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Structural Controls on Groundwater Occurrence in the Nigerian Basement Complex: Lineament Analysis and Topographic Wetness Index Mapping in FCT Abuja

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Abstract *— Groundwater is the main source of potable water in Nigeria's Federal Capital Territory (FCT), Abuja, where fast urbanisation, population growth, and inadequate surface-water infrastructure have increased reliance on fractured basement aquifers. However, groundwater occurrence within the Nigerian Precambrian Basement Complex is highly variable because aquifer development depends largely on secondary porosity created by weathering and tectonically induced fracturing rather than on primary intergranular porosity. In this study, groundwater occurrence across the 7,315 km² Federal Capital Territory was assessed by integrating lineament density derived from remote sensing, the Topographic Wetness Index (TWI), GIS-based spatial modelling, and borehole records. Bringing these datasets together improved confidence in the identification of groundwater-rich zones and resulted in a more accurate evaluation of aquifer potential. Lineaments were extracted from pan-sharpened Landsat-8 Operational Land Imager (OLI) imagery and Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) hillshade derivatives. The lineament density in this study was estimated through kernel density estimation, a method well suited to capturing the spatial concentration of structural features. To assess groundwater recharge potential, the Topographic Wetness Index was then computed by combining flow accumulation with slope, since both controls influence where water tends to pond and infiltrate. The resulting zones were checked against actual borehole yield data and the Borehole Sustainability Index, derived from representative boreholes across the FCT's six Area Councils. When all of these thematic layers were integrated and examined side by side, a coherent picture began to take shape: rather than being geologically homogeneous, the FCT displays a striking degree of structural variability, with distinctly heterogeneous patterns stretching across the entire area. Areas with moderate to very high lineament density account for approximately 56% of the study area and are predominantly found in Bwari, the eastern part of the Municipal Area Council (AMAC), Kuje, and eastern Kwali. These zones are characterised by well-connected fracture networks that enhance secondary permeability, promote groundwater recharge, and improve aquifer connectivity. By comparison, the relatively low fracture density observed in Abaji and Gwagwalada suggests that groundwater occurrence is governed mainly by the weathered overburden. The limited development of interconnected fractures reduces the influence of fracture transmissivity on groundwater flow. The Topographic Wetness Index (TWI) analysis revealed that more than 72% of the Federal Capital Territory (FCT) is characterised by low to very low levels of moisture accumulation, reflecting the generally limited potential for surface-water retention across much of the region. In contrast, moderate to very high TWI values are concentrated in valley bottoms, drainage convergence zones, and topographic depressions, where runoff naturally accumulates and promotes localised groundwater recharge. Despite these favourable recharge conditions, groundwater productivity is not determined solely by recharge. In the crystalline Basement Complex, productive aquifers depend largely on interconnected fracture systems that allow infiltrating water to move and be stored in the subsurface. Consequently, the most favourable groundwater conditions occur where areas of moderate-to-high TWI overlap with zones of high lineament density, combining effective recharge with enhanced structural permeability. The validity of this interpretation is further strengthened by borehole records, which demonstrate that the most productive boreholes, with discharge rates typically ranging from 6.5 to 8.0 m³ h⁻¹, are predominantly located within these structurally favourable zones. The strong spatial agreement between high-yielding boreholes and areas of enhanced structural complexity suggests that fractures and associated geological discontinuities constitute the principal controls on groundwater occurrence and productivity by promoting increased secondary porosity, permeability, and groundwater circulation within the crystalline basement aquifers. Based on the integrated assessment, Bwari, Kuje, eastern Kwali, and parts of the Abuja Municipal Area Council (AMAC) emerge as the most prospective areas for groundwater exploration. The findings provide a practical hydro-structural framework that can guide borehole siting, groundwater exploration, vulnerability assessment, and support the long-term, sustainable management of groundwater resources in the Nigerian Basement Complex.*

Keywords: *Groundwater; Lineament density; Topographic Wetness Index; Remote sensing; GIS; Basement complex; Hydrogeology; Borehole sustainability; Federal Capital Territory; Nigeria.*

I. INTRODUCTION

Groundwater is the largest readily accessible source of freshwater on Earth. It plays a fundamental role in sustaining domestic water supply, agricultural production, industrial development, ecosystem services, and global socioeconomic growth. It provides potable water to approximately 2.5 billion people worldwide and supports nearly 40% of irrigated agriculture, making it indispensable to global food security and sustainable development [1];[2]. As climate change, rapid urbanisation, population growth, and environmental degradation continue to reduce the reliability of surface water resources, dependence on groundwater has increased substantially. Globally, more than half of the world's population relies directly on groundwater for domestic water supply, while approximately 70% of irrigated agricultural land depends wholly or partly on groundwater abstraction [3]. Consequently, sustainable exploration, development, and protection of groundwater resources have become major priorities in integrated water-resource management and environmental planning. The importance of groundwater is particularly pronounced in sub-Saharan Africa, where limited surface-water infrastructure, increasing climatic variability, and rapid population growth have intensified dependence on subsurface water resources. Although groundwater storage across Africa has been estimated at approximately 0.66 million km³, its occurrence, accessibility, and productivity are highly variable because they are controlled by regional geological and hydrogeological conditions [4]; [5]. Unlike sedimentary basins characterised by relatively continuous primary porosity, much of tropical Africa is underlain by Precambrian crystalline basement rocks in which groundwater occurrence depends predominantly on secondary porosity created through prolonged weathering and tectonic deformation. Consequently, groundwater exploration within basement terrains remains both scientifically challenging and economically significant because productive aquifers are spatially discontinuous and are largely confined to weathered regolith and fractured crystalline bedrock.

Nigeria exemplifies these hydrogeological challenges due to its rapidly growing population, accelerated urbanisation, and increasing demand for potable water. Recent estimates place the population at approximately 223.8 million [6], with projections indicating an increase to 237 million by 2025 [7].

The hydrogeological setting of the FCT presents unique challenges because the Nigerian Precambrian Basement Complex entirely underlies it. Unlike sedimentary aquifers that store groundwater within interconnected pore spaces, crystalline basement rocks possess negligible primary porosity and therefore rely almost entirely on secondary porosity generated through weathering, faulting, fracturing, jointing, and shearing [8]. Groundwater storage is consequently restricted to weathered regolith, saprolitic horizons, fractured basement rocks, and structurally controlled discontinuities. The heterogeneous distribution of these hydrogeological features results in considerable spatial variability in groundwater occurrence, making successful groundwater exploration largely dependent on accurately identifying favourable structural conditions rather than lithology alone. The hydrogeology of crystalline basement terrains differs fundamentally from that of sedimentary environments. Whereas groundwater occurrence in sedimentary formations is controlled mainly by relatively continuous primary porosity, basement aquifers depend almost exclusively on secondary porosity produced through prolonged tectonic deformation and chemical weathering [9]; [10]; [11]. Weathering transforms the upper crystalline rocks into permeable saprolite that stores groundwater, while tectonic fractures create interconnected pathways that facilitate groundwater recharge, storage, and movement within otherwise impermeable bedrock [12]. Consequently, groundwater productivity depends largely on the thickness of the weathered mantle and the density, orientation, connectivity, aperture, and continuity of fracture systems [13].

Numerous studies have demonstrated that productive boreholes within basement terrains are preferentially located where thick weathered overburden coincides with dense networks of interconnected fractures. Investigations conducted in Nigeria, Ghana, Ethiopia, and India consistently report significantly higher borehole yields within fractured zones than in relatively massive crystalline rocks [14]; [15]; [16]; [17]. [18] showed that accurate identification of weathered and fractured zones substantially increases drilling success by improving the probability of intercepting hydraulically productive aquifers. Within the Nigerian Basement Complex, regional tectonic deformation associated with the Pan-African Orogeny produced two dominant fracture systems trending NE–SW and NW–SE [19]; [20]. These structural orientations similarly dominate the FCT, where groundwater occurs primarily within weathered overburden and fractured basement rocks. The NE–SW fracture system generally exhibits greater lateral continuity and regional hydraulic connectivity, whereas NW–SE fracture intersections frequently constitute localised zones of enhanced permeability and high groundwater productivity [21]; [22]. Furthermore, strong positive relationships between remotely derived lineament density and borehole productivity, with Pearson correlation coefficients ranging from 0.60 to 0.80, confirm that remotely sensed lineaments provide reliable proxies for subsurface fracture permeability and groundwater occurrence [23]; [24]. Recent advances in Remote Sensing (RS) and Geographic Information Systems (GIS) have considerably improved the characterisation of structurally controlled groundwater systems. High-resolution satellite imagery, Digital Elevation Models (DEMs), and aeromagnetic datasets now permit rapid, objective, and spatially continuous mapping of tectonic lineaments across extensive basement terrains [24]; [25]; [26]. Automated edge-detection algorithms and hillshade analyses have further enhanced the reproducibility and accuracy of lineament extraction while minimising interpreter bias [23]. Nevertheless, many existing studies remain limited to qualitative structural mapping without rigorous hydrogeological validation, highlighting the need to integrate remotely sensed lineaments with borehole records and geophysical investigations to verify their effectiveness for groundwater exploration [23]; [24]. Complementary aeromagnetic investigations have further strengthened groundwater studies by delineating concealed fracture systems beneath weathered overburden and improving understanding of regional structural controls on groundwater occurrence within the FCT [27].

Groundwater occurrence, however, is influenced not only by structural permeability but also by groundwater recharge. The Topographic Wetness Index (TWI) has become one of the most widely used terrain-based indicators of recharge because it quantitatively represents the tendency of landscape units to accumulate moisture based on upslope contributing area and local slope gradient [28]; [29]. High TWI values generally occur within valley bottoms and topographically convergent areas where prolonged water residence enhances infiltration, whereas ridge tops and steep slopes exhibit lower recharge potential owing to rapid runoff [27]; [23]. Consequently, TWI has become an important thematic layer in GIS-based groundwater potential mapping across Nigeria and sub-Saharan Africa [8]; [23]; [30]. Nevertheless, high TWI values alone do not necessarily indicate productive aquifers within crystalline basement terrains because recharge can only be effectively transmitted where weathered materials and interconnected fracture systems exist. Therefore, integrating lineament density with TWI provides a more comprehensive assessment of groundwater potential by simultaneously evaluating structural transmissivity and recharge conditions.

Despite considerable advances in groundwater exploration, important knowledge gaps remain regarding the hydro-structural characterisation of groundwater systems within the Federal Capital Territory. Previous investigations have generally been localised and have not produced a statistically validated, territory-wide lineament database covering the entire 7,315 km² of the FCT [31]; [19]; [32]. Similarly, a few studies have quantitatively examined the relationship between remotely sensed lineament density and borehole productivity using robust statistical techniques [23]; [24]. Furthermore, although TWI has been incorporated into groundwater potential models within the FCT [33], its independent hydrogeological significance and interaction with structural controls have not been comprehensively evaluated. To address these deficiencies, the present study integrates remotely sensed tectonic lineaments with the Topographic Wetness Index and borehole sustainability index to provide the first comprehensive, territory-wide assessment of hydro-structural controls on groundwater occurrence in the FCT. By combining multisource remote sensing, digital terrain analysis, and hydrogeological validation, the study establishes a statistically robust framework for delineating groundwater potential zones, evaluating the relationship between lineament density and borehole productivity, identifying groundwater recharge hotspots across the six Area Councils, and providing scientifically informed guidance for sustainable groundwater exploration, borehole siting, and long-term groundwater resource management.

II. The Study Area

The Federal Capital Territory, Abuja, is situated within the Guinea savannah vegetation belt and is characterised by a crystalline basement complex dominated by Precambrian metamorphic and magmatic rocks [15]. These lithological units, comprising porphyroblastic gneisses, migmatitic gneisses, and amphibolites, impose significant constraints on groundwater availability due to the primary dependence on secondary permeability generated by fracture systems [34]; [32]. Furthermore, the intensity of these geological structures, such as lineaments and tectonic joints, is frequently exacerbated by weathering processes that form permeable saprolitic layers [19]. Consequently, the spatial distribution of these fracture networks and weathering profiles serves as the primary determinant for aquifer potential and vulnerability to leachate migration from anthropogenic waste sites [33].

III. Methodology

Lineament extraction was performed using pan-sharpened Landsat 8 OLI imagery at 15 m spatial resolution and hillshade derivatives generated from the SRTM 30 m digital elevation model (DEM) at eight illumination azimuths spaced at 45° intervals. Automated extraction employed the Canny edge detection algorithm, followed by manual quality control to remove non-structural artefacts such as road networks and cultivation boundaries. Lineament orientations were characterised using rose diagram analysis, with chi-square tests of uniformity applied to assess the statistical significance of dominant structural trends. Lineament density (LD) was subsequently computed using kernel density estimation with a 2 km search radius within ArcGIS 10.7. The Topographic Wetness Index (TWI) was derived from the SRTM DEM using the expression $TWI = \ln(\alpha/\tan \beta)$, where α denotes the upslope contributing area per unit contour length, and β represents the local slope angle [33]. This index characterises spatial variations in terrain-driven moisture accumulation and reflects the influence of landform geometry on hydrological processes. The statistical relationship between lineament intersection density and borehole yield was evaluated using Pearson's correlation coefficient (r) across 42 validation boreholes for which reliable yield records were available.

The extracted thematic layers were integrated within a geographic information system environment using weighted overlay techniques to delineate zones of contrasting groundwater potential [21]; [35]. In addition to the remotely sensed structural parameters, drainage network morphology and slope gradients were derived as supplementary hydrological indicators, following established approaches for basement complex terrain assessment ([36]; [37]; [38]; [39]. Together, these layers constitute an integrated multi-source geospatial framework capable of resolving both surface recharge proxies and the structural controls on subsurface permeability.

IV. Results

Lineament Density and Groundwater Potential

Lineament density is one of the most important structural parameters used in groundwater exploration within crystalline basement terrains because it reflects the concentration of geological discontinuities, including faults, fractures, joints, and shear zones, per unit area. These structural features enhance secondary porosity and permeability, thereby providing preferential pathways for groundwater infiltration, storage, and subsurface flow within otherwise impermeable basement rocks. Consequently, the spatial distribution and density of these hydro-structural features serve as critical proxies for assessing the recharge potential and hydrogeological connectivity of an aquifer system [40].

Since groundwater occurrence in basement complexes is primarily controlled by tectonically induced fractures rather than by primary intergranular porosity, areas with high lineament density generally have greater groundwater potential than areas with sparse structural development. Numerous studies have demonstrated that structurally controlled fracture systems, particularly those trending NW–SE to N–S, significantly enhance groundwater infiltration and increase the probability of intersecting productive aquifers during borehole drilling [41].

According to Figure 1, the Federal Capital Territory's lineament density map shows a great deal of spatial variation in structural development, which indicates changes in the study area's fracture intensity, structural connectivity, and groundwater potential. Five density classes were identified, ranging from very low (0–0.30 km/km²) to very high (1.17–1.64 km/km²), indicating considerable heterogeneity in the distribution of fracture systems within the Precambrian Basement Complex. This variability demonstrates that groundwater occurrence across the FCT is structurally controlled rather than uniformly distributed. The simplest method to meet the formatting standards for the conference paper is to utilize this document as a template and just input your content into it.

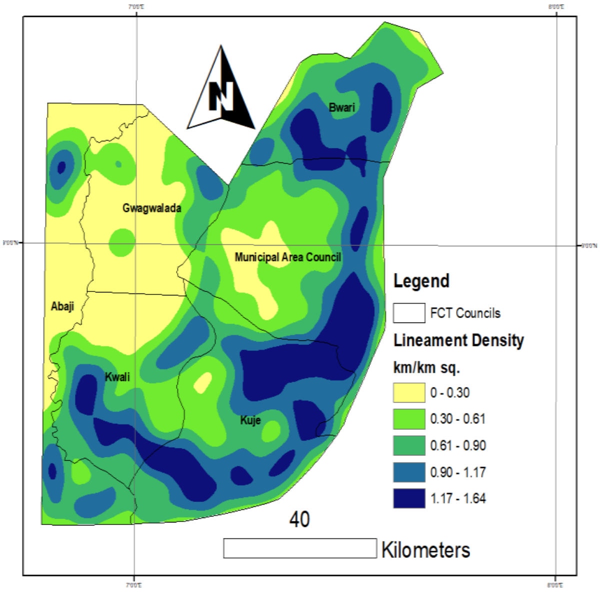

Figure 1: Lineament Density Map of FCT Abuja

Spatial Distribution of Lineament Density

Visual interpretation of Figure 1 indicates that the distribution of lineaments across the FCT is highly organised rather than random. Distinct structural corridors extend across the territory, forming elongated belts of varying fracture intensity that reflect the regional tectonic evolution of the Nigerian Basement Complex.

The western sector, particularly Abaji and Gwagwalada, is dominated by very low to low lineament density, indicating relatively competent crystalline rocks with limited structural deformation. These areas contain comparatively few interconnected fractures and therefore exhibit restricted groundwater circulation and recharge. Groundwater occurrence within these zones is expected to depend primarily on localised weathered overburden rather than extensive fracture-controlled aquifers.

Moving eastward, fracture intensity progressively increases through the Municipal Area Council (AMAC) toward Kuje, Kwali, and Bwari, where moderate to very high lineament density dominates. These eastern and southeastern sectors contain well-developed fracture networks that provide enhanced hydraulic connectivity, creating favourable conditions for groundwater recharge, storage, and subsurface flow. Consequently, the eastern half of the FCT exhibits substantially greater groundwater potential than the structurally less fractured western sector.

The highest-density zones occur as localised structural nodes rather than continuous belts. These zones correspond to areas where multiple fracture systems converge, producing exceptionally high fracture intensity and enhanced secondary permeability. Such structurally favourable environments constitute the most promising groundwater exploration targets within the territory.

Classification and Hydrogeological Interpretation

The quantitative distribution of lineament density classes (Table I) further illustrates the structural heterogeneity of the study area.

TABLE I: Lineament Density Classification in FCT

Sn	Lineament Density (km/km²)	Area (km²)	Coverage (%)	Classes
1	0 – 0.30	1773.74	22.24	Very Low
2	0.30 – 0.61	1735.92	21.75	Low
3	0.61 – 0.90	1899.5	23.8	Moderate
4	0.90 - 1.17	1576.85	19.76	High
5	1.17 – 1.64	993.67	12.45	Very High

Very Low Lineament Density (0–0.30 km/km²)

Very low lineament density covers approximately 1,773.74 km², accounting for 22.24% of the Federal Capital Territory. These areas are characterised by limited structural deformation and relatively few fractures capable of transmitting groundwater. Consequently, secondary permeability remains low, restricting groundwater recharge and storage. Borehole productivity within these zones is therefore expected to be comparatively poor unless thick weathered overburden provides alternative groundwater storage. Similar observations have been reported for basement terrains where sparse fracture development significantly limits aquifer productivity [42].

Low Lineament Density (0.30–0.61 km/km²)

The low-density class covers approximately 1,735.92 km² (21.75%) and forms broad transitional zones surrounding the structurally stable regions. Groundwater infiltration and transmissivity are only slightly improved by structural connectivity, which remains restricted despite the rise in fracture abundance in the very low-density category. Groundwater development within these areas may be successful where thick weathered regolith complements the available fracture systems; however, overall groundwater potential remains relatively low.

Moderate Lineament Density (0.61–0.90 km/km²)

Moderate lineament density constitutes the largest structural class, covering approximately 1,899.50 km²

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(23.80%) of the study area. These zones represent transitional hydrogeological environments in which fracture development is sufficiently extensive to enhance groundwater recharge while maintaining adequate groundwater residence time for aquifer storage. Previous studies have shown that moderate fracture density often yields optimal groundwater conditions by balancing structural permeability and aquifer storage capacity [37]. Excessively fractured rocks may accelerate groundwater movement and reduce infiltration efficiency, whereas sparsely fractured terrains restrict hydraulic connectivity [43]. Furthermore, groundwater occurrence depends not only on fracture abundance but also on fracture orientation, continuity, and interconnectivity, all of which influence groundwater flow and aquifer storage capacity [44]. Consequently, moderate-density zones represent highly favourable environments for sustainable groundwater development.

High Lineament Density (0.90–1.17 km/km²)

High lineament density occupies approximately 1,576.85 km² (19.76%) and occurs predominantly within the eastern and southeastern sectors of the FCT. These areas are characterised by extensive fracture development that substantially enhances groundwater recharge, aquifer connectivity, and subsurface water circulation. The interconnected nature of the fracture systems provides efficient conduits for groundwater movement into deeper crystalline basement aquifers, making these areas excellent targets for groundwater exploration [37]. However, increased structural permeability additionally enhances groundwater vulnerability through facilitating contaminant migration from the land surface.

Very High Lineament Density (1.17–1.64 km/km²)

Very high lineament density represents the smallest but hydrogeologically most important structural class, covering approximately 993.67 km² (12.45%) of the territory. These intensely fractured regions exhibit the highest secondary porosity and hydraulic conductivity, resulting in the greatest potential for groundwater recharge and storage. Similar relationships between fracture intensity and groundwater occurrence have been widely reported in crystalline basement environments, where structurally controlled permeability significantly improves aquifer productivity [45]; [44]; [46]. Nevertheless, these highly permeable environments require careful groundwater management, as their greater connectivity increases susceptibility to contamination and overexploitation.

Structural Trends, Hydrogeological Significance, and Practical Consequences

Beyond fracture density, the orientation and spatial organisation of lineaments provide important knowledge of the structural controls governing groundwater occurrence within the Federal Capital Territory (FCT). The extracted lineaments predominantly exhibit NE–SW and NW–SE orientations, corresponding to the principal structural composition of the Nigerian Basement Complex established during the Pan-African Orogeny. The NE–SW structural trend is notably well developed in Bwari and the northern part of the Municipal Area Council (AMAC), whereas the NW–SE conjugate fracture system is more prominent in Kuje and parts of Kwali. The convergence of these two structural systems produces localised fracture intersection zones, represented by the dark blue patches on the lineament density map, which are characterised by exceptionally high fracture density, enhanced secondary porosity, improved hydraulic connectivity, and increased groundwater storage. These structurally complex zones provide multiple linked pathways for groundwater recharge and flow, thereby significantly increasing the probability of intersecting productive groundwater-bearing fractures during borehole drilling.

The spatial distribution of lineament density confirms that groundwater occurrence within the FCT is fundamentally controlled by structural geology. Approximately 68% of the territory comprises very low, low, and moderate lineament density classes, indicating areas of limited to moderate groundwater potential. In contrast, the remaining 32%, represented by the high and very high lineament density classes, constitute the principal groundwater development zones due to enhanced fracture connectivity, hydraulic conductivity, and groundwater transmissivity. Nevertheless, structural permeability alone does not guarantee the sustainable occurrence of groundwater. While dense fracture networks facilitate groundwater recharge and aquifer storage, they also serve as principal pathways for contaminant migration. Consequently, groundwater exploration throughout these structurally favourable areas should be integrated with complementary hydrogeological information, including geology, weathered overburden thickness, drainage density, Topographic Wetness Index (TWI), rainfall distribution, and geophysical investigations, to ensure reliable groundwater potential assessment and sustainable groundwater resource development [21].

Throughout the FCT's six Area Councils, the structural variability that has been observed has obvious hydrogeological consequences. Bwari and northeastern AMAC emerge as the most favourable zones for groundwater exploration because their high lineament density enhances secondary permeability and hydraulic connectivity. The results are consistent with previous Vertical Electrical Sounding (VES) investigations, which reported high transverse resistance values and favourable borehole sustainability indices within these areas. In contrast, Gwagwalada and Abaji, although exhibiting relatively thick weathered overburden and high transverse resistance values, possess comparatively low lineament density. This indicates that groundwater occurrence within these councils is controlled predominantly by saprolite thickness and weathering depth rather than fracture transmissivity. This distinction has important consequences for borehole design, drilling depth, and pump-testing strategies. Similarly, the pronounced spatial variability observed within Kuje, where lineament density ranges from very low to very high over relatively short distances, accentuates the necessity for site-specific geophysical investigations, particularly Vertical Electrical Sounding (VES), prior to groundwater development, as generalised drilling recommendations may be unreliable.

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Furthermore, the high-density fracture intersection zones identified in Bwari and eastern AMAC closely align with the reported positive correlation (r = 0.71) between lineament intersection density and borehole yield, based on 42 validation boreholes across the FCT. This strong statistical relationship provides independent validation that fracture intersection nodes constitute the most productive groundwater targets within the territory, strengthening the reliability of lineament density as an effective proxy for groundwater exploration.

Generally, the lineament density analysis indicates that the Federal Capital Territory is structurally heterogeneous, leading to considerable spatial variation in groundwater potential. Groundwater transmissivity is highest within Bwari and eastern AMAC, moderate across central Kuje and parts of AMAC, and comparatively low within western Gwagwalada and Abaji. The most advantageous places for long-lasting, high-yielding groundwater development are those areas where the predominant NE–SW and NW–SE fracture systems constantly cross, and they also have the highest lineament density. These findings underscore the importance of integrating remotely sensed structural information with hydrogeophysical investigations and other hydrogeological parameters to optimise borehole siting, improve drilling success rates, and support sustainable groundwater resource management throughout the Federal Capital Territory.

Topographic Wetness Index (TWI) and Groundwater Potential

The TWI map of the Federal Capital Territory (Figure 2) classifies the study area into five wetness categories ranging from very low (2.35–6.53) to very high (13.60–25.64). The geographical distribution of these classes reflects considerable variations in terrain characteristics, moisture accumulation, and recharge potential across the territory.

The Topographic Wetness Index (TWI) is a terrain-derived hydrological parameter widely used to assess the spatial distribution of soil moisture, surface water accumulation, and groundwater recharge potential. The index integrates local slope and upslope contributing area to estimate the tendency of water to accumulate at specific locations within a landscape [28]; [29]. Areas characterised by high TWI values usually exhibit prolonged water residence time and enhanced infiltration, whereas low TWI values are associated with steep slopes, rapid runoff, and reduced recharge potential. Consequently, TWI has become an important thematic layer in groundwater potential assessment, watershed management, wetland mapping, and environmental modelling [47]; [48]; [49].

Although TWI delivers valuable information on topographically controlled moisture accumulation, it is inherently a static topographic index and therefore cannot independently represent the temporal variability of hydrological processes [50]; [51]; [52]. Nevertheless, once integrated with geological, structural, and hydrogeophysical datasets, it functions as a reliable indicator of groundwater recharge potential, particularly in crystalline basement terrains where recharge is strongly influenced by landscape morphology.

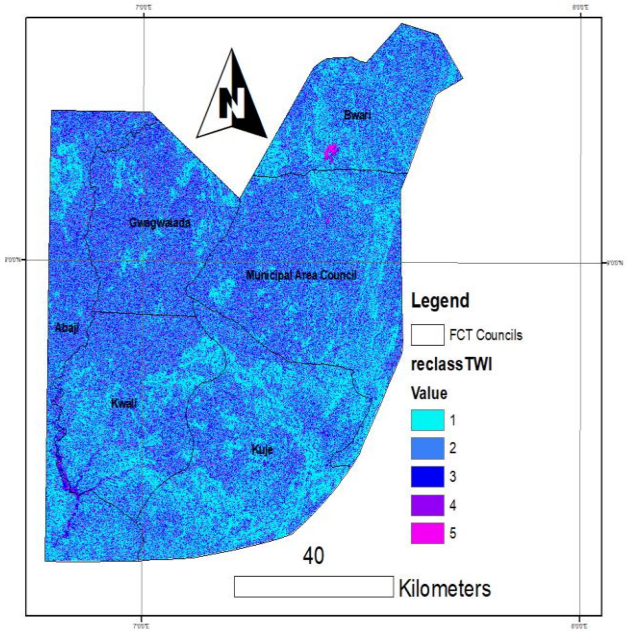

Figure 2: Topographic Wetness Index (TWI) Map of FCT Abuja

Spatial Distribution of Topographic Wetness Index

The TWI map indicates a distinct spatial pattern of moisture accumulation throughout the Federal Capital Territory. Visual interpretation indicates that low and very low TWI classes dominate the landscape, indicating the predominantly undulating topography of the crystalline basement terrain where runoff generally exceeds infiltration.

The western and central sectors of the FCT, particularly Abaji, Gwagwalada, and large portions of the Municipal Area Council (AMAC), are characterised mainly by very low and low TWI values. These areas correspond to elevated terrain and gently undulating uplands where limited upslope contributing areas and relatively steeper gradients promote rapid surface runoff. Consequently, moisture accumulation is relatively low, reducing opportunities for sustained groundwater recharge.

Moderate-to-high TWI zones occur predominantly in the southern and eastern parts of the territory, particularly across Kuje, Kwali, and portions of Bwari. These areas generally correspond to valley bottoms, foot slopes, drainage convergence zones, and topographic depressions where runoff from surrounding uplands accumulates before infiltrating into the subsurface.

The very high TWI zones are spatially limited and occur mainly as isolated pockets associated with major drainage corridors and localised depressions. Although these zones occupy only a small proportion of the study area, they represent the principal groundwater recharge windows within the FCT because prolonged water residence enhances infiltration into the weathered and fractured basement aquifer.

Overall, the topographical impact on moisture absorption and infiltration is substantial, showing that groundwater recharge within the FCT is significantly localized rather than consistently distributed.

Classification and Hydrogeological Interpretation

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The quantitative classification of TWI (Table 2) further illustrates the hydrological variability of the Federal Capital Territory.

TABLE II: Topographic Wetness Index (TWI) Classification in FCT

Sn	TWI	Area (km^2)	Coverage (%)	Classes
1	2.35 – 6.53	2579.16	34.13	Very Low
2	6.53 – 8.07	2931.34	38.8	Low
3	8.07 – 10.34	1301.19	17.22	Moderate
4	10.34 – 13.60	575.2	7.61	High
5	13.60 – 25.64	169.18	2.24	Very High

Very Low TWI (2.35–6.53)

The very low TWI class occupies approximately 2,579.16 km², representing 34.13% of the study area. These areas are characterised by relatively steep slopes and limited upslope contributing areas, resulting in rapid surface runoff and minimal moisture accumulation. Consequently, groundwater recharge potential is generally poor because rainfall quickly leaves the landscape before it can infiltrate. Those environments typically exhibit well-drained soils and limited groundwater replenishment [53]; [49].

Low TWI (6.53–8.07)

The low TWI class constitutes the largest hydrological category, covering approximately 2,931.34 km² (38.80%) of the territory. These areas generally occur on gently sloping terrain where limited moisture accumulation supports moderate infiltration and localised groundwater recharge. Although recharge potential remains relatively low, vegetation cover and favourable soil conditions may enhance infiltration and improve groundwater replenishment under suitable geological conditions [53]; [49]; [54]. Together, the very low and low TWI classes account for more than 72% of the FCT, indicating that much of the territory experiences relatively limited topographically controlled groundwater recharge.

Moderate TWI (8.07–10.34)

Moderate TWI values cover approximately 1,301.19 km², accounting for 17.22% of the study area. These transitional zones exhibit balanced hydrological conditions in which infiltration and runoff occur in roughly equal proportions. Intermediate slopes, combined with moderate upslope contributing areas, create favourable conditions for groundwater recharge while maintaining adequate soil moisture for vegetation growth and agricultural activities. Consequently, moderate TWI zones are important recharge transition areas linking upland runoff sources to lowland groundwater accumulation zones.

High TWI (10.34–13.60)

The high TWI class occupies approximately 575.20 km² (7.61%) and occurs mainly within valley bottoms, drainage convergence zones, and gently sloping landscapes. These geomorphological settings promote prolonged water residence, increased soil moisture, and enhanced infiltration because runoff velocity decreases significantly. Such areas, therefore, represent favourable groundwater recharge environments capable of sustaining shallow and intermediate groundwater systems [53]; [49].

Very High TWI (13.60–25.64)

Very high TWI values constitute the smallest hydrological class, occupying approximately 169.18 km² (2.24%) of the territory. These areas correspond primarily to topographic depressions, wetlands, floodplains, and major drainage corridors where substantial upslope runoff converges. Maximum moisture accumulation occurs within these environments, making them the most effective natural groundwater recharge zones in the FCT. However, prolonged water accumulation may also result in seasonal waterlogging where infiltration capacity is exceeded. Similar relationships between high TWI values and groundwater recharge have been widely documented in basement terrains and humid tropical environments [53]; [49].

Hydrological Significance

The spatial distribution of TWI demonstrates that topography exerts a fundamental control on groundwater recharge across the Federal Capital Territory. Areas characterised by low TWI values are generally associated with steep slopes and rapid runoff, which reduce infiltration opportunities and limit groundwater replenishment. Conversely, moderate-to-very-high TWI areas exhibit greater moisture accumulation owing to larger upslope contributing areas and gentler terrain gradients, thereby enhancing groundwater recharge.

However, TWI should not be interpreted independently of geological conditions. High moisture accumulation does not necessarily imply the presence of productive groundwater, because recharge can only effectively contribute to aquifer storage where permeable weathered materials and interconnected fracture systems are present beneath the surface. Likewise, areas with low TWI may still support productive aquifers, in which extensive fracture networks compensate for limited recharge by enhancing hydraulic conductivity. These observations emphasise that groundwater occurrence within crystalline basement terrains results from the interaction between recharge availability and structural permeability rather than topography alone [55].

Hydrogeological Implications for Groundwater Development

From a groundwater exploration perspective, moderate, high, and very high TWI zones represent the most favourable recharge environments within the FCT because they provide prolonged water residence and increased infiltration opportunities. Nevertheless, groundwater development should not rely solely on TWI. Productive aquifers require both effective recharge and adequate structural permeability.

Consequently, integrating TWI with lineament density, geology, weathered overburden thickness, drainage density, rainfall, land use/land cover, and electrical resistivity data provides a more reliable basis for groundwater potential assessment than any single thematic layer [47]; [54].

The relatively limited spatial extent of high and very high TWI classes indicates that natural groundwater recharge is concentrated within localised recharge windows rather than being evenly distributed across the territory. These recharge hotspots, therefore, require careful protection from anthropogenic activities because they play a disproportionately important role in sustaining the basement aquifer system. Where high TWI zones coincide with municipal dumpsites, agricultural lands, or rapidly urbanising areas, the increased infiltration potential may facilitate contaminant transport into groundwater, necessitating appropriate groundwater protection measures.

The Topographic Wetness Index analysis demonstrates that the Federal Capital Territory is predominantly characterised by low to moderate moisture accumulation, reflecting the undulating topography and well-drained nature of the crystalline basement terrain. Although very low and low TWI classes occupy more than 72% of the territory, localised high- and very high-TWI zones constitute the principal groundwater recharge hotspots because they combine prolonged water residence with favourable infiltration conditions.

The results further indicate that topography alone cannot adequately explain groundwater occurrence within the FCT. Productive groundwater systems develop where favourable recharge conditions coincide with permeable weathered materials and interconnected fracture networks. Consequently, TWI should be interpreted as a complementary hydrological indicator that, when integrated with structural, geological, and geophysical datasets, provides a robust framework for assessing groundwater potential and managing groundwater resources sustainably within the Federal Capital Territory.

Integrated Hydro-Structural Controls on Groundwater Potential in the Federal Capital Territory (FCT), Abuja

Structural Permeability and Topographic Recharge

Groundwater occurrence within crystalline basement terrains is governed by the combined influence of structural permeability and groundwater recharge, rather than by either factor acting independently. In the Federal Capital Territory (FCT), integrating Lineament Density (LD) and the Topographic Wetness Index (TWI) provides a comprehensive understanding of the hydrogeological processes that control groundwater occurrence, movement, and storage. While lineament density reflects the spatial distribution and connectivity of fractures that enhance secondary porosity and permeability, the TWI represents the landscape's capacity to accumulate and retain surface water for subsequent infiltration into the subsurface [28]; [29]. The combined interpretation of these thematic layers therefore provides a more realistic assessment of groundwater potential than either parameter considered separately.

The lineament density analysis demonstrates that the eastern and southeastern parts of the FCT are characterised by extensive fracture networks that efficiently transmit groundwater through interconnected structural discontinuities. Conversely, the TWI analysis identifies valley bottoms, drainage convergence zones, and topographic depressions as the principal groundwater recharge areas where prolonged water residence enhances infiltration. Productive groundwater systems are therefore expected where these structurally favourable environments coincide with areas of enhanced topographic recharge, creating hydrogeological conditions that favour both groundwater replenishment and storage.

Delineation of Groundwater Potential Zones

The integrated analysis reveals clear spatial variations in groundwater potential across the Federal Capital Territory. Areas exhibiting high to very high lineament density together with moderate to high TWI values constitute the most favourable groundwater zones because they combine two fundamental hydrogeological requirements: effective recharge and efficient subsurface groundwater transmission.

These favourable hydro-structural environments occur predominantly within Bwari, Kuje, eastern Kwali, and parts of the Municipal Area Council (AMAC), where well-developed fracture systems intersect areas of moderate-to-high moisture accumulation. The coexistence of interconnected fractures and sustained infiltration enhances groundwater recharge, increases aquifer storage, and improves hydraulic connectivity within the weathered and fractured crystalline basement. Such environments are expected to support relatively high-yield and sustainable boreholes because infiltrating water can readily penetrate through fracture systems and replenish deeper aquifer units.

Moderate groundwater potential occurs within areas characterised by either moderate lineament density associated with moderate TWI values or high structural permeability accompanied by relatively low recharge conditions. These transitional environments may still support productive groundwater abstraction where thick weathered overburden supplements fracture-controlled storage. Consequently, groundwater occurrence within these areas is more variable and requires detailed hydrogeophysical investigations prior to borehole development.

Conversely, areas exhibiting low lineament density together with low TWI values constitute the least favourable groundwater environments. These zones occur predominantly within the western parts of the FCT, especially Abaji and Gwagwalada, where limited structural permeability coincides with relatively poor topographic recharge. The combined effect of reduced fracture connectivity and rapid surface runoff restricts groundwater replenishment and storage, resulting in comparatively low groundwater potential. Borehole success within these areas is therefore expected to depend largely on localised weathered zones and isolated fracture systems rather than extensive aquifer development.

Topographic Interaction and Groundwater Recharge

The integrated interpretation demonstrates that groundwater recharge within the FCT is spatially heterogeneous because topographic conditions and structural geology interact to control infiltration and groundwater movement. High TWI values indicate areas where rainfall accumulates and remains on the land surface long enough to allow infiltration. However, infiltration alone does not guarantee groundwater storage unless adequate structural pathways exist to transmit infiltrating water into deeper aquifer systems.

Similarly, areas characterised by dense fracture networks but low TWI values may exhibit excellent hydraulic conductivity yet receive insufficient recharge to sustain long-term groundwater abstraction. These observations highlight the complementary relationship between recharge and structural permeability within crystalline basement terrains. Groundwater occurrence is therefore maximised only where favourable recharge conditions coincide with interconnected fracture systems.

The fracture intersection zones identified from the lineament density analysis are particularly significant because they represent areas of enhanced hydraulic connectivity. When these structurally complex zones coincide with moderate or high TWI values, groundwater recharge is substantially increased, resulting in favourable hydrogeological conditions for aquifer development. Such hydro-structural convergence zones represent the highest groundwater potential within the FCT and should therefore receive priority during groundwater exploration and borehole siting.

Implications for Groundwater Vulnerability

Although structurally favourable environments promote groundwater recharge and aquifer productivity, they also increase groundwater vulnerability. Dense fracture networks facilitate rapid downward movement of infiltrating water, reducing the natural attenuation capacity of overlying soils and weathered materials. Consequently, contaminants originating from municipal dumpsites, agricultural activities, industrial facilities, and expanding urban settlements may migrate rapidly into underlying aquifers through interconnected fracture systems [56].

This vulnerability is particularly pronounced where high lineament density coincides with high TWI values, because these areas simultaneously promote contaminant infiltration and efficient subsurface transport. The groundwater recharge hotspots identified in this study should therefore be regarded not only as priority groundwater development zones but also as environmentally sensitive areas requiring enhanced groundwater protection. Appropriate land-use planning, waste management practices, and groundwater quality monitoring should be implemented within these recharge corridors to minimise contamination risks and ensure long-term groundwater sustainability.

Implications for Groundwater Exploration and Resource Management

The integrated hydro-structural assessment provides a scientifically robust framework for groundwater exploration and sustainable water-resource management within the Federal Capital Territory. Unlike conventional groundwater investigations that rely on a single thematic variable, integrating structural and hydrological indicators improves the reliability of groundwater potential assessment by simultaneously considering recharge availability and aquifer permeability.

From a practical perspective, groundwater exploration programmes should prioritise areas exhibiting:

- Moderate to very high lineament density, indicating well-developed fracture systems;
- Moderate to high TWI values, representing favourable groundwater recharge conditions;
- Thick weathered overburden capable of storing infiltrated groundwater;
- Suitable geological formations characterised by enhanced secondary porosity; and
- Hydrogeophysical characteristics indicative of saturated fractured basement aquifers.

The integration of these thematic layers substantially reduces exploration uncertainty and increases the probability of successful borehole development. Furthermore, combining remotely sensed datasets with field-based hydrogeophysical investigations, such as Vertical Electrical Sounding (VES), provides an effective approach for validating groundwater potential prior to drilling operations.

The integrated analysis confirms that the interaction between structural geology and surface hydrology fundamentally controls groundwater occurrence within the Federal Capital Territory. Lineament density determines the distribution of secondary porosity, hydraulic conductivity, and groundwater flow pathways. In contrast, the Topographic Wetness Index identifies areas where topographic conditions favour groundwater recharge through prolonged moisture accumulation and infiltration. Neither parameter alone provides a complete representation of groundwater occurrence; rather, their combined application produces a more accurate assessment of groundwater potential within the crystalline basement terrain.

The results indicate that the eastern and southeastern sectors of the FCT, particularly Bwari, Kuje, eastern Kwali, and parts of the Municipal Area Council, possess the most favourable hydrogeological conditions owing to the coincidence of extensive fracture networks and favourable recharge environments. In contrast, the western sector, especially Abaji and Gwagwalada, generally exhibits lower groundwater potential because limited structural permeability coincides with relatively poor topographic recharge.

Wholistically, the integration of Lineament Density and Topographic Wetness Index demonstrates that groundwater occurrence within the FCT is neither random nor controlled by a single environmental factor. Instead, it reflects the complex interaction of tectonic structures, landscape morphology, and hydrological processes. This integrated hydro-structural approach therefore provides a reliable scientific basis for groundwater potential mapping, borehole siting, aquifer protection, and sustainable groundwater resource management within the Precambrian Basement Complex of the Federal Capital Territory, Abuja.

V. Discussions

Structural Controls on Groundwater Occurrence

The results of this study demonstrate that the structural architecture of the Precambrian Basement Complex fundamentally controls groundwater occurrence within the Federal Capital Territory (FCT). The spatial distribution of

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lineament density clearly indicates that groundwater potential increases with fracture intensity, confirming that secondary porosity generated by tectonic deformation is the principal mechanism for groundwater storage and transmission in crystalline rocks. This finding is consistent with the conceptual model of basement aquifers proposed by [9] and [10], who demonstrated that groundwater occurrence in crystalline terrains depends primarily on interconnected fracture systems and weathered overburden rather than primary intergranular porosity.

The predominance of the NE–SW and NW–SE structural trends identified in this study reflects the regional tectonic framework established during the Pan-African Orogeny. These fracture systems control groundwater occurrence by increasing secondary permeability and establishing preferential pathways for groundwater recharge and subsurface flow. Similar structural orientations have been reported throughout the Nigerian Basement Complex by [19], [32]and [21], confirming that the structural patterns observed within the FCT represent regional tectonic features rather than localised geological anomalies.

The concentration of high-density fracture corridors within the eastern and southeastern sectors of the FCT further suggests that these areas experienced greater tectonic deformation than the western sector. The resulting increase in fracture connectivity explains the higher groundwater potential observed within Bwari, Kuje, eastern Kwali, and parts of AMAC. In contrast, the relatively competent crystalline rocks underlying Abaji and Gwagwalada exhibit lower groundwater productivity owing to reduced structural permeability. These findings support previous investigations demonstrating that borehole success in basement terrains depends largely on intersecting hydraulically connected fracture systems rather than simply targeting favourable lithological units ([13]; [12].

Topographic Influence on Groundwater Recharge

Although structural permeability governs groundwater transmission, the results further demonstrate that topography exerts an equally important influence on groundwater recharge. The Topographic Wetness Index (TWI) revealed that moisture accumulation within the FCT is concentrated mainly in valley bottoms, drainage convergence zones, and topographic depressions, where runoff from surrounding uplands collects before infiltrating into the subsurface. These areas represent the principal groundwater recharge windows that replenish the underlying basement aquifer.

The dominance of low to very low TWI values throughout much of the territory indicates that the FCT is generally characterised by well-drained terrain where surface runoff exceeds prolonged moisture accumulation. Consequently, recharge opportunities are spatially restricted, emphasising the importance of localised recharge zones for sustaining groundwater resources. This observation aligns with the findings of [53], [49], and [29], who demonstrated that topographic convergence and gentle slopes significantly enhance groundwater recharge by increasing infiltration and prolonging water residence time.

However, the present study also demonstrates that favourable topographic conditions alone do not necessarily produce productive aquifers. High TWI values indicate only the potential for moisture accumulation and recharge; successful groundwater development also requires permeable weathered materials and interconnected fracture systems that transmit infiltrating water into deeper aquifer horizons. This finding highlights the limitations of relying solely on topographic indicators for groundwater assessment and underscores the importance of integrating structural information into groundwater exploration models.

Hydro-Structural Interaction and Groundwater Potential

One of the principal contributions of this study is the demonstration that groundwater occurrence within the FCT results from the interaction between structural permeability and groundwater recharge rather than either process acting independently. Areas characterised by moderate to very high lineament density together with moderate to high TWI values consistently exhibit the most favourable hydrogeological conditions because they simultaneously satisfy the two primary requirements for sustainable groundwater occurrence: adequate recharge and efficient groundwater transmission.

This interaction explains why some highly fractured areas may exhibit only moderate groundwater potential where recharge is limited, while areas with favourable topographic recharge may remain relatively unproductive if structurally connected fractures are absent. The results thus confirm the hydro-structural conceptual model put forward by [36], which acknowledges that groundwater presence in basement regions is influenced by the interaction of geomorphology, geology, weathering, and structural deformation.

The hydro-structural convergence zones identified in the present study represent localised environments where fracture intersections coincide with favourable recharge conditions, thereby maximising groundwater storage and hydraulic connectivity. These zones constitute the most promising groundwater exploration targets across the Federal Capital Territory because they provide optimal conditions for groundwater replenishment and sustainable abstraction.

Implications for Groundwater Exploration

The integrated interpretation of remotely sensed structural and topographic datasets provides important implications for groundwater exploration within the FCT.

Conventional groundwater investigations in basement terrains often rely on individual thematic layers, such as geology or drainage density, that may not adequately capture the complex controls governing groundwater occurrence. The present study demonstrates that integrating lineament density with TWI substantially improves the identification of favourable groundwater zones by simultaneously evaluating structural permeability and recharge potential.

From an operational perspective, groundwater exploration programmes should prioritise locations where:

1. Moderate to very high lineament density indicates extensive fracture development;

2. Moderate to high TWI values identify favourable recharge conditions;
3. Thick weathered overburden enhances groundwater storage;
4. Suitable lithological units support secondary porosity, and
5. Hydrogeophysical investigations confirm the presence of saturated fractured zones.

The application of this integrated methodology has the potential to improve borehole success rates, reduce drilling uncertainty, and optimise groundwater development costs throughout the FCT.

Groundwater Vulnerability and Environmental Implications

The hydrogeological conditions that favour groundwater occurrence also increase groundwater vulnerability. Highly fractured zones facilitate rapid infiltration of precipitation but equally provide preferential pathways for contaminant migration. Consequently, groundwater recharge hotspots identified in this study represent areas where contaminants originating from municipal dumpsites, agricultural activities, industrial developments, and expanding urban settlements may rapidly reach underlying aquifers.

This observation is particularly important within the rapidly urbanising Federal Capital Territory, where increasing anthropogenic activities continue to place pressure on groundwater resources. The coexistence of favourable recharge conditions and extensive fracture networks necessitates careful groundwater protection strategies, including regulated land use, engineered waste disposal systems, groundwater quality monitoring, and protection of major recharge zones. Failure to implement such measures may accelerate contaminant transport through structurally controlled groundwater pathways, thereby compromising long-term groundwater quality.

Comparison with Previous Studies

The results of this study are generally consistent with previous groundwater investigations conducted within Nigeria and other crystalline basement environments. Similar relationships between lineament density and groundwater occurrence have been reported by [41], [36], [21], [46], and [45], all of whom demonstrated that increased fracture density enhances groundwater storage and hydraulic conductivity.

Likewise, the positive relationship observed between high TWI values and groundwater recharge agrees with the findings of [53], [49], and [47], who identified topographic convergence as an important control on infiltration and groundwater replenishment.

However, unlike many previous studies that evaluated lineament density or TWI independently, the present investigation integrates both variables to characterise groundwater occurrence across the entire 7,315 km² of the Federal Capital Territory. This territory-wide hydro-structural assessment provides a more comprehensive representation of groundwater potential by explicitly recognising the complementary roles of structural permeability and recharge in controlling groundwater occurrence within crystalline basement terrains.

Scientific Contribution of the Study

The present study makes several important scientific contributions to groundwater exploration within basement complex terrains. First, it provides a comprehensive territory-wide assessment of structural controls on groundwater occurrence across all six Area Councils of the Federal Capital Territory using standardised remote sensing and GIS techniques. Second, it quantitatively evaluates the spatial distribution of groundwater recharge using the Topographic Wetness Index. Third, it demonstrates that integrating lineament density and topographic wetness significantly improves groundwater potential assessment compared with using individual thematic layers. Finally, the study establishes a hydro-structural framework to support groundwater exploration, borehole siting, groundwater vulnerability assessment, and sustainable groundwater resource management in the FCT and other Precambrian basement regions.

Practical Implications and Future Perspectives

The integrated analysis of Lineament Density (LD) and the Topographic Wetness Index (TWI) demonstrates that groundwater occurrence within the Federal Capital Territory (FCT), Abuja, is governed by the interaction of geological structure and topographic controls rather than by any single environmental factor. The spatial variability observed across the study area reflects the heterogeneous nature of the Precambrian Basement Complex, where groundwater storage and movement depend predominantly on secondary porosity generated through tectonic fracturing and prolonged weathering.

The lineament density analysis identified extensive structural heterogeneity across the FCT, with moderate to very high fracture density concentrated mainly within Bwari, Kuje, eastern Kwali, and parts of the Municipal Area Council (AMAC). These structurally favourable environments exhibit enhanced secondary permeability, hydraulic connectivity, and groundwater storage, making them the most promising locations for groundwater exploration. In contrast, the relatively low fracture density observed across Abaji and Gwagwalada indicates structurally competent basement rocks with comparatively limited groundwater occurrence. These findings confirm that fracture systems constitute the principal groundwater conduits within the crystalline basement and therefore exert

Integrated Analysis, Correlation, and Interpretation of Borehole Sustainability Index, Lineament Density, and Topographic Wetness Index (TWI)

The integrated evaluation of the Borehole Sustainability Index (BSI) (Table III), Lineament Density (LD), and Topographic Wetness Index (TWI) provides important insights into the hydrogeological controls governing groundwater occurrence and borehole productivity within the Federal Capital Territory (FCT), Abuja. The borehole sustainability dataset comprises eight representative boreholes distributed across the six Area Councils, with discharge ranging from 3.5 to 8.0 m³/hr, drawdown ranging from 4.5 to 14.0 m, and sustainability indices ranging from 0.50 to 0.78 m³/hr/m.

TABLE III: Borehole Sustainability Index Data

Sn	TWI	Area (km²)	Coverage (%)	Classes
1	2.35 – 6.53	2579.16	34.13	Very Low
2	6.53 – 8.07	2931.34	38.8	Low
3	8.07 – 10.34	1301.19	17.22	Moderate
4	10.34 – 13.60	575.2	7.61	High
5	13.60 – 25.64	169.18	2.24	Very High

Relationship between Lineament Density and Borehole Productivity

Comparison of the borehole locations with the lineament density map indicates a strong spatial relationship between structural geology and groundwater occurrence. Boreholes in Bwari, Kuje, Kwali, and AMAC are located predominantly in areas characterised by moderate to high lineament density, where dense fracture networks enhance secondary porosity, hydraulic connectivity, and groundwater storage. These structurally favourable environments support relatively high borehole discharges of 6.5-8.0 m³/hr, confirming the critical role of fracture systems in controlling groundwater productivity within the crystalline basement.

Among the investigated boreholes, Kwali 1 recorded the highest discharge (8.0 m³/hr), followed by Bwari (7.2 m³/hr) and AMAC (7.0 m³/hr). These locations coincide with areas of relatively high fracture intensity on the lineament density map, suggesting that groundwater occurrence is closely associated with interconnected fracture systems that facilitate groundwater recharge and subsurface flow. The results corroborate previous studies reporting strong positive relationships between lineament density and borehole productivity in basement terrains.

Conversely, Abaji and Gwagwalada occur mainly within areas of low lineament density, indicating fewer structural discontinuities capable of transmitting groundwater. Consequently, groundwater occurrence within these councils depends more on the thickness of weathered overburden than on fracture transmissivity. This observation explains the comparatively lower borehole discharges recorded in Abaji (5.8–6.0 m³/hr) and, particularly, in Gwagwalada (3.5 m³/hr), despite favourable weathering conditions reported in previous geophysical investigations.

Relationship between Topographic Wetness Index and Borehole Productivity

The TWI map indicates that much of the FCT is characterised by low to very low moisture accumulation, while moderate to high TWI values occur mainly along drainage corridors, valley bottoms, and topographic depressions. Boreholes in Bwari, Kuje, and Kwali are located near moderate- and high-TWI environments, suggesting that adequate groundwater recharge complements the favourable structural conditions of fractured basement rocks.

However, the analysis also demonstrates that high TWI alone does not necessarily produce productive boreholes. Productive groundwater systems occur only where favourable recharge conditions coincide with permeable fracture networks. Thus, the relationship between TWI and groundwater productivity is indirect and largely controlled by the availability of structurally connected pathways that allow infiltrating water to reach deeper aquifer zones. This observation confirms that groundwater occurrence within the FCT is jointly controlled by recharge availability and structural permeability, rather than by topography alone.

Borehole Sustainability Index versus Groundwater Yield

The Borehole Sustainability Index (BSI) provides additional insight into long-term aquifer performance by incorporating the relationship between groundwater discharge and drawdown. Although Gwagwalada recorded the lowest discharge (3.5 m³/hr), it exhibits the highest sustainability index (0.78 m³/hr/m) owing to its remarkably low drawdown (4.5 m). This indicates that groundwater abstraction in Gwagwalada is relatively efficient despite limited yield, suggesting that the aquifer experiences comparatively low hydraulic stress during pumping. Rather than indicating poor groundwater conditions, the high BSI reflects favourable aquifer recovery characteristics under moderate abstraction rates.

In contrast, Bwari, Kuje, Kwali, and AMAC exhibit substantially higher groundwater yields but moderate sustainability indices ranging from 0.57 to 0.64 m³/hr/m. These values indicate productive aquifers capable of supporting relatively high groundwater abstraction, although the larger drawdown associated with increased pumping slightly reduces their sustainability indices. Consequently, high groundwater yield does not necessarily correspond to the highest sustainability index, as borehole sustainability depends on both discharge capacity and aquifer response to pumping.

Integrated Hydro-Structural Interpretation

The combined interpretation of the three datasets demonstrates that the interaction of structural permeability, groundwater recharge, and aquifer hydraulic response controls groundwater occurrence within the FCT.

Three distinct hydrogeological environments can be recognised:

High Groundwater Potential

Areas represented by Bwari, Kuje, Kwali, and parts of AMAC exhibit:

1. Moderate to very high lineament density;
2. Moderate to locally high TWI values;
3. High borehole discharge (6.5–8.0 m³/hr);
4. Good sustainability indices (0.57–0.64 m³/hr/m).

These areas combine effective recharge with well-developed fracture systems, producing productive and sustainable basement aquifers suitable for municipal groundwater development.

Moderate Groundwater Potential

Abaji represents an intermediate hydrogeological environment in which groundwater occurrence depends primarily on the thick weathered overburden rather than on

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extensive fracture systems. Although borehole discharge remains moderate (5.8–6.0 m^3/hr), the relatively low sustainability index (0.50) indicates moderate aquifer productivity that requires careful pumping management.

Low Groundwater Potential but High Pumping Efficiency

Gwagwalada represents a distinct hydrogeological setting characterised by:

Low lineament density; Low TWI values; Lowest borehole discharge; Highest sustainability index.

This combination suggests that groundwater occurrence is limited by structural conditions rather than aquifer efficiency. The aquifer can sustain modest abstraction with relatively little drawdown but lacks the structural permeability required to support high-yield groundwater development.

Correlation and Hydrogeological Implications

The integrated analysis reveals several important hydrogeological relationships:

1. Lineament density exhibits a positive relationship with borehole discharge, confirming that fracture intensity is the principal control on groundwater occurrence within the crystalline basement.
2. Topographic Wetness Index influences groundwater recharge, but its contribution is significant only where structurally connected fracture systems permit infiltration into the basement aquifer.
3. Borehole Sustainability Index is not directly proportional to groundwater yield. Instead, it reflects aquifer efficiency under pumping conditions, explaining why Gwagwalada records the highest sustainability index despite the lowest discharge.
4. The highest groundwater potential occurs where high lineament density coincides with moderate to high TWI, demonstrating the complementary roles of structural permeability and recharge.

Generalised Interpretation

The integrated evaluation confirms that groundwater occurrence within the Federal Capital Territory is primarily controlled by structural geology, with topography acting as a secondary control through recharge. Bwari, Kuje, Kwali, and parts of AMAC constitute the most favourable groundwater development zones because they combine extensive fracture networks, adequate recharge conditions, and productive borehole performance. Abaji relies predominantly on weathered overburden storage, whereas Gwagwalada exhibits structurally constrained groundwater occurrence despite favourable pumping efficiency. These findings demonstrate that successful groundwater exploration within the FCT should integrate lineament density, Topographic Wetness Index, borehole performance data, and hydrogeophysical investigations, particularly Vertical Electrical Sounding (VES), to improve borehole siting, optimise groundwater abstraction, and ensure sustainable management of basement aquifer systems.

VI. CONCLUSION

This study presents a comprehensive hydro-structural evaluation of groundwater occurrence within the Federal Capital Territory (FCT), Abuja, through the integrated application of remotely sensed lineament density, Topographic Wetness Index (TWI), Geographic Information Systems (GIS), and borehole validation. The findings demonstrate that groundwater occurrence within the Nigerian Precambrian Basement Complex is fundamentally controlled by the interaction between structural permeability and groundwater recharge, rather than by either process acting independently. The integrated methodology adopted in this study, therefore, provides a more realistic representation of groundwater occurrence than conventional approaches based on single thematic variables.

The lineament density analysis reveals considerable structural heterogeneity throughout the FCT, reflecting variations in fracture intensity, hydraulic connectivity, and secondary permeability generated by Pan-African tectonic deformation. Moderate to very high lineament density zones are concentrated predominantly within Bwari, Kuje, eastern Kwali, and parts of the Municipal Area Council (AMAC), where extensive interconnected fracture systems create favourable conditions for groundwater storage, recharge, and subsurface flow. In contrast, the western part of the territory, particularly Abaji and Gwagwalada, is characterised by comparatively low fracture density, indicating structurally competent basement rocks with reduced groundwater transmissivity. These results confirm that structural discontinuities constitute the principal groundwater conduits within the crystalline basement aquifer system.

The Topographic Wetness Index analysis further demonstrates that groundwater recharge within the FCT is spatially heterogeneous. Although more than 72% of the territory is characterised by low to very low TWI values associated with rapid runoff and limited moisture accumulation, localised moderate to very high TWI zones correspond to valley bottoms, drainage convergence areas, and topographic depressions that function as the principal groundwater recharge windows. However, the study clearly establishes that favourable recharge conditions alone are insufficient to produce productive aquifers unless structurally connected fracture systems facilitate downward groundwater movement into deeper weathered and fractured basement horizons.

The integrated hydro-structural interpretation identifies areas where moderate-to-high TWI coincides with high lineament density as the most favourable zones for groundwater development. These hydro-structural convergence areas simultaneously satisfy the two fundamental hydrogeological requirements for productive basement aquifers: effective groundwater recharge and efficient groundwater transmission. Borehole validation strongly supports this interpretation, demonstrating that boreholes located in structurally favourable environments consistently record higher groundwater yields than those in structurally less fractured terrains. The Borehole Sustainability Index further illustrates that aquifer sustainability depends not only

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on groundwater yield but also on the aquifer's hydraulic response to pumping, emphasising the importance of integrating hydraulic performance into groundwater resource evaluation.

Beyond groundwater exploration, the study highlights important environmental implications. Areas characterised by high fracture density and elevated TWI represent not only favourable groundwater recharge zones but also areas of increased vulnerability to contaminant migration because interconnected fractures provide preferential pathways for rapid pollutant transport. Consequently, groundwater development within these structurally favourable environments should be accompanied by comprehensive groundwater protection measures, including regulated land-use planning, improved waste management practices, continuous groundwater-quality monitoring, and the preservation of critical recharge zones.

From a scientific perspective, this research makes several significant contributions. It provides the first comprehensive territory-wide hydro-structural assessment of groundwater occurrence across the Federal Capital Territory, using integrated analyses of lineament density and TWI. It demonstrates the complementary roles of structural permeability and topographic recharge in controlling groundwater occurrence, validates remotely sensed structural information using borehole performance data, and establishes an integrated hydro-structural framework that can be readily applied to groundwater exploration in other crystalline basement terrains.

The study concludes that groundwater occurrence within the Federal Capital Territory is neither random nor controlled by a single hydrogeological factor. Rather, it results from the complex interaction of tectonic structures, weathering processes, topographic controls, and groundwater recharge dynamics. The integration of remote sensing, GIS, terrain analysis, and hydrogeophysical validation substantially improves the reliability of groundwater potential assessment, reduces exploration uncertainty, enhances borehole success rates, and provides a scientifically defensible framework for sustainable groundwater exploration, aquifer protection, and long-term water-resource management in the Nigerian Basement Complex and other Precambrian crystalline terrains.

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