

Implications of Rugged Terrain on Groundwater Accessibility and Rural Livelihoods in Humid Tropical Region of Nigeria

ABSTRACT

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This study investigates the implications of rugged terrain on groundwater accessibility and rural livelihoods in selected communities across Ebonyi, Enugu, Cross River, and Akwa Ibom States, Nigeria. The research adopts a mixed-method approach, integrating quantitative data from 250 structured questionnaires with qualitative insights from 15 key informant interviews. The selected communities are characterized by steep slopes, elevated relief, fractured basement geology, and escarpment landscapes that influence groundwater occurrence and accessibility. Findings reveal that groundwater is the dominant source of domestic water supply in the study area, accounting for 72% of household water use; however, accessibility is significantly constrained by terrain conditions. Borehole performance analysis shows a high rate of failure and low yield, exceeding 70%, particularly in steep and fractured upland zones. More than 60% of households travel over 1 km to access water, indicating poor spatial accessibility of safe water sources. The study further demonstrates that rugged terrain significantly increases drilling costs, reduces recharge potential, and limits the effectiveness of groundwater development. The livelihood analysis indicates that inadequate groundwater accessibility negatively affects agricultural productivity, household income, livestock production, health outcomes, and time allocation, with women and children being disproportionately burdened by water collection activities. Qualitative findings confirm that terrain difficulty, high drilling failure rates, and seasonal water scarcity are major constraints, while coping strategies include rainwater harvesting and communal water sharing. The study concludes that rugged terrain is a critical determinant of groundwater accessibility and rural livelihood sustainability in the study area. It recommends improved hydrogeological surveying, the use of GIS-based groundwater mapping, investment in resilient water infrastructure, and strengthened community-based water management systems to enhance sustainable water access in upland regions of Nigeria.

Keywords: Groundwater accessibility, rugged terrain, rural livelihoods, borehole failure, water security

1. Introduction

Groundwater is one of the world's most important sources of freshwater, supplying drinking water, supporting agriculture, industry, and sustaining ecosystems (Akpabio & Ansa, 2015; UNESCO, 2022). In Nigeria, where access to treated municipal water remains inadequate, groundwater serves as the primary source of water for many rural and peri-urban communities (MacDonald et al., 2021). However, its availability and accessibility vary considerably due to differences in geology, hydrogeology, climate, and topography (Freeze & Cherry, 1979; Fetter, 2018).

Among these factors, topography plays a critical role in determining groundwater occurrence and accessibility. Elevation, slope, and terrain characteristics influence infiltration, groundwater recharge, aquifer productivity, and borehole development. Rugged landscapes often experience reduced groundwater recharge, deeper water tables, lower borehole success rates, and higher infrastructure costs than lowland areas (Todd & Mays, 2005; Dingman, 2015; Naghibi et al., 2017). Similar patterns have been reported in mountainous regions of India, Ethiopia, Nepal, and China, where topographic conditions significantly affect groundwater availability (Jha et al., 2007; Kebede, 2013; Acharya et al., 2019).

Nigeria relies heavily on groundwater, with over 60% of the population depending on boreholes and wells for domestic water supply (MacDonald et al., 2021). Nevertheless, groundwater accessibility differs markedly between the country's sedimentary basins and Basement Complex terrains. While sedimentary formations generally contain productive aquifers, Basement Complex areas are characterized by fractured and weathered rocks with uneven groundwater occurrence, making borehole development more difficult and expensive (Offodile, 2002; Olorunfemi & Fasuyi, 1993; Adelana et al., 2008).

Limited groundwater accessibility has important socio-economic consequences. Poor access to safe water reduces agricultural productivity, increases household expenditure, constrains education and healthcare, and disproportionately affects women and children who spend considerable time collecting water (Ellis, 2000; FAO, 2022; WHO & UNICEF, 2023). Climate change further compounds these challenges by altering groundwater recharge patterns and increasing pressure on already limited water resources (Intergovernmental Panel on Climate Change, 2023).

Although numerous studies have examined groundwater resources and rural water supply in Nigeria, relatively few have specifically explored how topographic barriers influence groundwater accessibility and rural livelihoods. This review synthesizes existing evidence to examine the relationship between terrain characteristics, groundwater accessibility, and rural development in Nigeria, with the aim of providing insights for sustainable water resource management and policy formulation.

2. Literature Review

2.1 Concept of Groundwater and Groundwater Accessibility

Groundwater is the portion of water that occupies the pores, fractures, fissures, and other interconnected voids beneath the Earth's surface. It originates primarily from precipitation that infiltrates the soil profile and percolates downward under gravity until it reaches the saturated zone, where all pore spaces are filled with water. This saturated zone forms aquifers, which serve as natural underground reservoirs capable of storing and transmitting significant quantities of freshwater (Freeze & Cherry, 1979; Fetter, 2018). Groundwater constitutes approximately 99% of the Earth's liquid freshwater resources, making it the largest accessible freshwater reserve available for human consumption, agriculture, industry, and ecosystem support. The increasing dependence on groundwater reflects its relative reliability during seasonal droughts and its natural protection against surface contamination compared to rivers and lakes.

Globally, groundwater plays a fundamental role in achieving water security. According to the United Nations Educational, Scientific and Cultural Organization, nearly half of the world's population depends directly on groundwater for drinking water, while about 25% of global agricultural irrigation relies on groundwater abstraction. The importance of groundwater has increased considerably due to rapid urbanization, climate variability, industrialization, and increasing pressure on surface water resources. Consequently, groundwater has become central to sustainable development, particularly in developing countries where public water supply infrastructure remains inadequate (UNESCO, 2022).

Groundwater occurrence depends largely on geological conditions. Aquifers are generally classified as unconfined, confined, semi-confined, and perched aquifers according to their hydraulic characteristics (Todd & Mays, 2005). In sedimentary formations composed of sandstone, limestone, or unconsolidated sands, groundwater is primarily stored within interconnected pore spaces. Conversely, in crystalline basement terrains, which underlie nearly half of Nigeria, groundwater storage depends mainly on secondary porosity developed through weathering, jointing, fracturing, and faulting because the crystalline rocks possess negligible primary porosity (Olorunfemi & Fasuyi, 1993).

Groundwater accessibility refers to the extent to which groundwater resources can be physically located, economically developed, socially utilized, and sustainably managed for domestic, agricultural, industrial, and environmental purposes. Accessibility encompasses not merely the presence of groundwater beneath the surface but also the feasibility of extracting it in sufficient quantity and acceptable quality using available technologies at affordable costs (Fetter, 2018). Therefore, groundwater accessibility is determined by the interaction of hydrogeological, environmental, technological, economic, institutional, and socio-cultural factors.

From a hydrogeological perspective, groundwater accessibility is controlled principally by aquifer characteristics, including porosity, permeability, transmissivity, hydraulic conductivity, aquifer thickness, recharge rate, groundwater depth, and water quality. Areas characterized by thick weathered overburden, highly fractured bedrock, and permeable geological formations generally exhibit higher groundwater potential than regions dominated

by compact crystalline rocks with limited fracturing (Singhal & Gupta, 2010). Similarly, groundwater recharge is strongly influenced by climatic conditions, vegetation cover, soil properties, drainage patterns, and topography, all of which determine the amount of rainfall that infiltrates into subsurface aquifers rather than being lost through surface runoff.

Terrain is increasingly recognized as one of the most influential determinants of groundwater accessibility. Digital elevation models, slope gradients, drainage density, landform characteristics, and geomorphological processes significantly influence infiltration, recharge, groundwater storage, and borehole productivity. In steep mountainous or dissected landscapes, rainfall rapidly flows downslope as runoff, thereby limiting infiltration and reducing aquifer recharge. Furthermore, rugged terrains often expose resistant bedrock with thin weathered profiles, resulting in discontinuous aquifers and low groundwater storage capacity (Naghibi et al., 2017). These relationships have been demonstrated through GIS- and remote sensing-based groundwater potential mapping studies across many parts of the world.

In Nigeria, groundwater accessibility exhibits considerable spatial variability because of the country's diverse geological and physiographic settings. The Nigerian hydrogeological framework consists broadly of Precambrian Basement Complex rocks and extensive sedimentary basins. The sedimentary formations including the Chad Basin, Sokoto Basin, Niger Delta Basin, Benin Formation, and Benue Trough generally possess highly productive aquifers due to their substantial porosity and permeability. In contrast, groundwater occurrence within the Basement Complex is localized within weathered mantles and fractured crystalline rocks, making successful groundwater development highly dependent on detailed hydrogeological and geophysical investigations.

Adelana et al. (2008) observed that the occurrence of groundwater in Nigeria is primarily controlled by geology, and the country can be divided into distinct hydrogeological provinces based on lithology and aquifer characteristics. Their review emphasizes that sedimentary basins generally support high-yielding boreholes, whereas basement terrains frequently experience variable borehole yields because groundwater occurrence is restricted to fractured and weathered zones.

Similarly, Akinluyi, Olorunfemi, and Bayowa (2018) investigated groundwater yield in the Basement Complex terrain of Ondo State using remote sensing and geological analyses. They found that borehole productivity was strongly associated with fracture density, lineament intersections, and lithological characteristics. Boreholes drilled in areas with high lineament density consistently produced higher yields than those located in massive crystalline rocks with limited structural discontinuities, highlighting the importance of structural geology in groundwater accessibility.

Olorunfemi and Fasuyi (1993), through geoelectrical investigations in central Nigeria, identified two principal aquifer systems within the Basement Complex: the weathered regolith aquifer and the fractured basement aquifer. They demonstrated that groundwater occurrence depends largely on the thickness of weathered materials and the extent of fracturing, explaining why borehole success rates vary considerably over short distances in crystalline terrains.

Technological advancement has significantly improved groundwater accessibility. The application of electrical resistivity tomography, vertical electrical sounding, magnetic surveys, remote sensing, geographic information systems (GIS), and multi-criteria decision analysis has enhanced the identification of groundwater-bearing zones while reducing drilling failures. Integrated geophysical exploration has become indispensable in basement terrains where aquifers are discontinuous and difficult to detect using conventional methods alone (Akinluyi et al., 2018; Akinluyi et al., 2014).

Despite these technological advances, groundwater accessibility remains constrained by socioeconomic factors. High drilling costs, inadequate hydrogeological data, poor maintenance of rural water infrastructure, weak institutional capacity, and insufficient investment continue to limit groundwater development in many rural communities across Nigeria. A recent review of groundwater resource management in Nigeria concluded that although the country possesses abundant groundwater resources, poor data availability, inadequate monitoring, weak governance, and limited investment have hindered sustainable groundwater development.

Groundwater accessibility is also closely linked to rural livelihoods. In many Nigerian rural communities, groundwater obtained from boreholes, hand-dug wells, and protected springs provides water for household consumption, livestock production, small-scale irrigation, food processing, and cottage industries. Where groundwater is difficult to access because of unfavorable geological or topographic conditions, households frequently spend several hours collecting water from distant sources, reducing productive labour time and disproportionately affecting women and children. Limited groundwater accessibility also constrains agricultural productivity, food security, public health, and household income, thereby reinforcing multidimensional rural poverty.

2.2 Concept and Characteristics of Rugged Terrain

Rugged terrain refers to landscapes characterized by pronounced variations in elevation, steep slopes, irregular landforms, dissected hills, escarpments, ridges, mountains, rocky outcrops, deeply incised valleys, and complex drainage networks. Such terrains are generally associated with high topographic relief resulting from prolonged geological processes including tectonic uplift, volcanic activities, faulting, folding, weathering, erosion, and mass movement (Summerfield, 1991). Unlike lowland or gently undulating landscapes, rugged terrains present considerable physical constraints to human settlement, transportation, agricultural production, infrastructure development, and natural resource exploitation. In hydrogeological studies, terrain ruggedness is recognized as one of the principal geomorphological factors controlling groundwater recharge, storage, movement, and accessibility (Dingman, 2015).

Geomorphologists describe terrain ruggedness as the degree of topographic variability within a given landscape. This variability is commonly measured using quantitative indices such as slope gradient, elevation difference, relief ratio, terrain ruggedness index (TRI), topographic wetness index (TWI), curvature, drainage density, and relative relief derived from Digital Elevation Models (DEMs) (Riley, DeGloria, & Elliot, 1999; Wilson & Gallant, 2000). Advances in remote sensing and Geographic Information Systems (GIS) have greatly

improved the characterization of rugged landscapes, allowing researchers to analyze terrain influences on hydrological and hydrogeological processes with greater precision.

From a geomorphological perspective, rugged terrains exhibit several distinguishing characteristics. These include steep slopes often exceeding 15–30%, highly variable elevations over relatively short distances, shallow soils, exposed bedrock, narrow valleys, rapid surface runoff, and extensive erosion. Such landscapes are frequently associated with mountainous regions, plateaus, dissected uplands, and crystalline basement complexes where resistant rocks dominate the geological framework (Summerfield, 1991). These characteristics collectively influence water infiltration, groundwater recharge, soil development, vegetation distribution, and land-use patterns.

Topography plays a fundamental role in regulating the hydrological cycle. Rainfall reaching the Earth's surface follows one of several pathways, including infiltration into the soil, evaporation, transpiration by vegetation, temporary storage, or surface runoff. In rugged landscapes, steep slopes accelerate overland flow, thereby reducing the residence time of water on the land surface and limiting opportunities for infiltration into underlying aquifers (Dingman, 2015). Consequently, areas with rugged terrain often experience lower groundwater recharge compared with relatively flat landscapes where rainfall infiltrates more effectively.

Freeze and Cherry (1979) explained that topography influences groundwater systems by controlling hydraulic gradients, recharge zones, discharge zones, and groundwater flow directions. Elevated areas commonly function as groundwater recharge zones because precipitation infiltrates downward before moving through subsurface aquifers toward lower elevations where springs, streams, wetlands, or rivers occur as discharge points. However, where slopes are excessively steep and soils are thin, infiltration may be significantly reduced despite high rainfall, resulting in limited groundwater storage.

One of the defining characteristics of rugged terrain is shallow weathering depth. Weathering processes produce unconsolidated regolith that serves as an important groundwater reservoir in crystalline basement environments. However, intense erosion on steep slopes often removes weathered materials faster than they are produced, exposing hard bedrock with limited primary porosity (Singhal & Gupta, 2010). Consequently, groundwater occurrence becomes restricted to fractures, joints, shear zones, and faults developed within crystalline rocks. This explains why groundwater exploration in rugged basement terrains requires detailed structural and geophysical investigations.

Geological structure further contributes to the hydrogeological complexity of rugged landscapes. Faults, fractures, joints, folds, and shear zones may either enhance groundwater movement by increasing secondary permeability or impede groundwater flow depending on their orientation, continuity, and mineral infilling (Fetter, 2018). In many mountainous basement terrains, productive aquifers occur only where multiple fracture systems intersect, making groundwater distribution highly localized and difficult to predict.

Hydrological responses in rugged terrains differ significantly from those observed in lowland environments. Steep slopes promote rapid runoff generation during rainfall events, increasing

the likelihood of flash floods while simultaneously reducing groundwater recharge. High runoff velocities also intensify soil erosion, gully development, and sediment transport, leading to land degradation and declining agricultural productivity (Morgan, 2005). The removal of fertile topsoil further reduces infiltration capacity, creating a feedback mechanism in which erosion exacerbates groundwater depletion.

Another important characteristic of rugged terrain is its influence on drainage density. Drainage density refers to the total length of streams within a watershed divided by its surface area. Rugged landscapes generally possess high drainage densities because steep gradients encourage the development of numerous stream channels (Horton, 1945). Although dense drainage networks facilitate rapid surface water conveyance, they reduce opportunities for groundwater recharge by efficiently transporting rainfall away from recharge areas.

Modern hydrogeological investigations increasingly employ terrain parameters to predict groundwater potential. Naghibi et al. (2017) reviewed numerous GIS-based groundwater potential mapping studies and found that slope, elevation, drainage density, lineament density, land use, lithology, rainfall, and soil characteristics consistently ranked among the most influential variables affecting groundwater occurrence. Areas characterized by gentle slopes, moderate drainage density, permeable lithology, and high fracture density generally exhibit greater groundwater potential than highly dissected mountainous landscapes.

Similarly, Rahmati et al. (2016), using machine-learning techniques integrated with GIS, demonstrated that topographic variables significantly improve the prediction of groundwater potential zones. Their findings showed that terrain characteristics influence both groundwater recharge and aquifer productivity, confirming that rugged landscapes require more sophisticated groundwater exploration methods than relatively flat regions.

Within the African continent, rugged terrains occur extensively in the Ethiopian Highlands, East African Rift System, Cameroon Highlands, Drakensberg Mountains, Jos Plateau, Mambilla Plateau, Obudu Plateau, and other crystalline uplands. Studies conducted across these regions consistently report lower groundwater yields, deeper water tables, higher drilling costs, and greater variability in borehole success rates than adjacent sedimentary lowlands (Kebede, 2013). These findings underscore the importance of terrain analysis in groundwater resource assessment throughout sub-Saharan Africa.

Nigeria exhibits remarkable physiographic diversity, ranging from coastal plains and sedimentary basins to plateaus, inselbergs, escarpments, and mountainous regions. Rugged terrains are predominantly associated with the Precambrian Basement Complex, which occupies approximately 50% of the country's landmass (Offodile, 2002). Major rugged landscapes include the Jos Plateau, Obudu Plateau, Mambilla Plateau, Biu Plateau, Mandara Mountains, Adamawa Highlands, Idanre Hills, Afi Mountains, and numerous granitic inselbergs distributed across southwestern and north-central Nigeria.

The Basement Complex consists mainly of granites, migmatites, gneisses, quartzites, schists, and older granitic intrusions. These rocks possess negligible primary porosity, making groundwater occurrence dependent on secondary permeability generated through weathering and fracturing (Olorunfemi & Fasuyi, 1993). In many rugged basement terrains, weathered

zones are thin because erosion continually removes regolith from steep slopes. Consequently, productive groundwater reservoirs are spatially discontinuous and often occur only within localized fracture systems.

Several Nigerian studies have demonstrated the influence of terrain on groundwater potential. Olayinka and Olorunfemi (1992) observed that borehole productivity in crystalline terrains depends largely on the thickness of weathered overburden and the presence of interconnected fractures. Similarly, Olorunfemi et al. (1999) showed that integrated geophysical surveys significantly improve borehole siting in rugged basement terrains by identifying fractured aquifers that are otherwise difficult to detect through conventional drilling.

Remote sensing has further enhanced understanding of terrain-groundwater relationships in Nigeria. Akinluyi et al. (2018) integrated satellite imagery, lineament mapping, and GIS analysis to evaluate groundwater potential within the Basement Complex of southwestern Nigeria. Their results indicated that areas characterized by high lineament density, moderate slopes, and thicker weathered profiles exhibited significantly higher groundwater yields than areas dominated by steep slopes and massive crystalline rocks.

Rugged terrain also influences the socioeconomic dimensions of groundwater development. Steep slopes complicate the transportation of drilling equipment, increase infrastructure costs, and limit accessibility for maintenance of water supply systems. In many rural communities, borehole construction requires additional engineering measures, including access road development, slope stabilization, reinforced foundations, and specialized drilling equipment. These additional costs often exceed the financial capacities of local governments and rural households, resulting in continued dependence on streams, springs, and seasonal surface water sources.

The relationship between rugged terrain and groundwater accessibility has become increasingly important under changing climatic conditions. Climate change is projected to increase rainfall intensity while simultaneously increasing the frequency of prolonged dry periods across many parts of West Africa. Intense rainfall on steep slopes accelerates runoff and erosion rather than groundwater recharge, while prolonged drought reduces recharge opportunities altogether (IPCC, 2023). Consequently, communities located within rugged terrains may become increasingly vulnerable to water insecurity unless groundwater development is supported by integrated hydrogeological investigations and climate-resilient water management strategies.

2.3 Hydrogeology of Nigeria

The hydrogeology of Nigeria is highly diverse due to its complex geological evolution, which has produced a wide range of lithological units, structural features, and sedimentary environments. Broadly, Nigeria is divided into two principal hydrogeological provinces: the crystalline Basement Complex and the sedimentary basins. These two provinces exhibit markedly different groundwater occurrence, storage, and transmission characteristics, which in turn influence groundwater accessibility across the country (Offodile, 2002; Adelana & MacDonald, 2008).

The sedimentary basins of Nigeria include the Niger Delta Basin, Chad Basin, Sokoto Basin, Anambra Basin, and Benue Trough. These basins are generally characterized by thick sequences of unconsolidated to semi-consolidated sediments such as sands, sandstones, shales, clays, and limestones. Because of their high primary porosity and permeability, sedimentary aquifers typically exhibit relatively high groundwater yields and are more predictable in terms of borehole success rates (Adelana & MacDonald, 2008). In contrast, the Basement Complex terrain, which underlies approximately half of Nigeria, consists of Precambrian crystalline rocks such as granites, gneisses, migmatites, schists, and quartzites. These rocks have negligible primary porosity; therefore, groundwater occurrence is restricted to secondary structures such as weathered zones and fractures (Olorunfemi & Fasuyi, 1993).

Hydrogeologically, groundwater in the Basement Complex occurs mainly in two interconnected aquifer systems: the weathered regolith aquifer and the fractured basement aquifer. The weathered regolith aquifer is formed through in-situ chemical and physical weathering of crystalline rocks, resulting in a layer of unconsolidated materials such as clay, sand, and decomposed rock fragments. This layer can store significant amounts of groundwater where it is sufficiently thick. Beneath the regolith lies the fractured basement aquifer, which consists of relatively fresh bedrock that has been fractured due to tectonic stresses. These fractures serve as conduits for groundwater movement and storage (Olayinka & Olorunfemi, 1992; Singhal & Gupta, 2010).

However, the productivity of Basement Complex aquifers is highly variable and spatially discontinuous. Borehole yields can vary significantly even over short distances due to the heterogeneous distribution of weathered zones and fractures. Studies have shown that successful groundwater development in these terrains depends largely on the thickness of the weathered layer, the degree of fracturing, and the connectivity of fracture networks (Olorunfemi et al., 1999). This variability makes groundwater exploration in Basement terrains more uncertain and expensive compared to sedimentary environments.

In sedimentary basins, aquifer systems are more extensive and hydraulically connected. For instance, the Benin Formation in southwestern Nigeria contains highly productive aquifers composed of unconsolidated sands and gravels that provide reliable groundwater supplies for domestic and industrial uses. Similarly, the Chad Basin in northeastern Nigeria contains confined and unconfined aquifers with significant storage capacity, although groundwater quality and recharge rates vary spatially (Adelana & MacDonald, 2008). The Niger Delta Basin, one of the most productive groundwater systems in Africa, contains multilayered aquifers that support high-yield boreholes, particularly in shallow coastal sands.

Groundwater recharge in Nigeria is controlled by climatic, geological, and geomorphological factors. Rainfall is the primary source of recharge, especially in southern Nigeria where annual precipitation exceeds 1,500 mm. In northern Nigeria, recharge rates are generally lower due to lower rainfall and higher evapotranspiration rates. However, infiltration is also strongly influenced by soil type, vegetation cover, land use, and terrain characteristics (MacDonald et al., 2021). Rugged terrain, in particular, affects recharge by increasing surface runoff and reducing infiltration time, thereby limiting groundwater replenishment in upland areas.

Structural geology plays a critical role in groundwater distribution, especially in Basement Complex regions. Faults, joints, and fractures act as pathways for groundwater movement, while lineaments often indicate zones of enhanced permeability. Remote sensing and geophysical studies have shown that areas with high lineament density tend to have higher groundwater potential due to increased fracturing and secondary porosity (Olorunfemi & Fasuyi, 1993). However, not all fractures are water-bearing; their effectiveness depends on connectivity, openness, and depth extent.

Groundwater quality in Nigeria also varies widely across hydrogeological settings. In sedimentary basins, groundwater is generally of good quality but may be affected locally by salinity, iron content, or anthropogenic pollution. In Basement Complex areas, groundwater quality is often influenced by mineral dissolution, weathering processes, and localized contamination from agricultural and domestic activities. Elevated concentrations of iron, manganese, fluoride, and nitrates have been reported in some regions, affecting potability and usability (Adelana & MacDonald, 2008).

Anthropogenic activities increasingly influence Nigeria's hydrogeology. Urbanization, deforestation, agricultural expansion, and groundwater abstraction are altering recharge patterns and increasing contamination risks. Over-abstraction in urban centers such as Lagos, Kano, and Port Harcourt has led to declining groundwater levels and localized land subsidence in some areas. These pressures highlight the need for sustainable groundwater management strategies that integrate hydrogeological knowledge with land-use planning and environmental protection.

Climate variability and climate change further complicate Nigeria's hydrogeological dynamics. Increasing rainfall variability, prolonged dry seasons, and extreme rainfall events influence both recharge and discharge processes. According to Intergovernmental Panel on Climate Change (2023), West Africa is expected to experience greater hydrological uncertainty, which will directly affect groundwater recharge reliability and availability. In Nigeria, these changes may exacerbate existing groundwater stress in semi-arid northern regions and rugged upland areas where infiltration is already limited.

Advancements in hydrogeological techniques have significantly improved groundwater exploration in Nigeria. Methods such as electrical resistivity surveys, vertical electrical sounding (VES), electromagnetic profiling, and remote sensing-based lineament analysis are widely used to identify potential aquifer zones, particularly in Basement Complex terrains. Geographic Information Systems (GIS) and multi-criteria decision analysis (MCDA) have also become essential tools in groundwater potential mapping, enabling the integration of geological, hydrological, and topographical data for improved decision-making (Adelana & MacDonald, 2008).

Despite these advances, challenges persist in groundwater development. Limited hydrogeological data, inadequate monitoring networks, high drilling failure rates in Basement terrains, and insufficient funding continue to hinder effective groundwater resource management. Rural communities, especially in rugged terrains, remain disproportionately affected due to poor accessibility, high infrastructure costs, and limited technical capacity for groundwater development.

2.4 Terrain Influence on Groundwater Occurrence and Accessibility

Terrain is a fundamental control on hydrological processes and plays a decisive role in determining groundwater occurrence, recharge potential, storage capacity, and accessibility. In hydrogeological systems, topography influences the direction and rate of surface runoff, infiltration capacity, soil moisture distribution, and subsurface flow pathways. Consequently, variations in terrain characteristics such as slope, elevation, relief, and drainage density directly affect the quantity and availability of groundwater resources (Dingman, 2015; Freeze & Cherry, 1979).

One of the most important terrain parameters influencing groundwater systems is slope gradient. Gentle slopes generally promote higher infiltration rates because rainfall has sufficient residence time on the land surface to percolate into the subsurface. In contrast, steep slopes accelerate overland flow, thereby reducing infiltration and limiting groundwater recharge (Morgan, 2005). This relationship is particularly important in rugged terrains where slope gradients often exceed thresholds that significantly restrict groundwater replenishment.

Elevation is another key terrain variable that influences groundwater distribution. Higher elevations often function as recharge zones, where precipitation infiltrates into the ground before moving downslope through subsurface aquifers. However, in highly elevated and rugged landscapes, thin soils, exposed bedrock, and high runoff velocities may limit effective recharge despite high rainfall inputs (Summerfield, 1991). This paradox highlights the complexity of terrain-groundwater interactions in mountainous environments.

Relief, defined as the vertical difference between the highest and lowest points within a landscape, also affects groundwater occurrence. High-relief areas are typically associated with rapid hydrological responses, increased erosion rates, and reduced groundwater storage potential. In such environments, aquifers are often discontinuous and restricted to localized zones of weathered or fractured rock (Singhal & Gupta, 2010). Conversely, low-relief terrains tend to support thicker regolith development and more stable aquifer systems.

Drainage density is another terrain-derived parameter that strongly influences groundwater recharge. Drainage density refers to the total length of streams per unit area of a watershed. High drainage density is typically associated with rugged terrain and indicates efficient surface water removal. While this may reduce flooding risk, it also limits groundwater recharge because precipitation is rapidly conveyed away from recharge zones (Horton, 1945). Areas with low drainage density generally allow greater infiltration and groundwater accumulation.

Terrain also influences soil development and thickness, which are critical for groundwater recharge. In rugged landscapes, soils are often shallow due to continuous erosion and limited weathering accumulation. Thin soils reduce the water-holding capacity of the land surface and restrict the infiltration process necessary for groundwater recharge. In contrast, deeper soils in gently sloping areas act as storage reservoirs that facilitate gradual percolation into underlying aquifers (Brady & Weil, 2016).

Geomorphological processes such as erosion, weathering, and mass wasting are more active in rugged terrains and significantly affect groundwater systems. Continuous erosion removes weathered materials that would otherwise serve as aquifer media, while landslides and slope failures disrupt subsurface flow systems and alter groundwater pathways. These processes contribute to the spatial variability of aquifer productivity in mountainous and dissected landscapes (Summerfield, 1991).

Structural geology interacts with terrain to further influence groundwater occurrence. In basement terrains, fractures, faults, and joints control the movement and storage of groundwater. Rugged terrain is often associated with tectonic activity that generates complex fracture networks. However, the hydraulic effectiveness of these structures depends on their connectivity, orientation, and degree of weathering. In many cases, productive groundwater zones occur at fracture intersections or along major fault zones (Fetter, 2018).

Hydrologically, rugged terrain enhances surface runoff dominance over subsurface flow. During rainfall events, water moves rapidly downslope, increasing the likelihood of flash flooding while simultaneously reducing groundwater recharge opportunities. This imbalance between runoff and infiltration contributes to seasonal water scarcity in upland communities, particularly in tropical regions with intense rainfall variability (Dingman, 2015).

Remote sensing and GIS-based studies have provided strong empirical evidence of terrain-groundwater relationships. Naghibi et al. (2017) demonstrated that slope, elevation, curvature, and drainage density are among the most significant predictors of groundwater potential zones in GIS-based modeling frameworks. Their findings confirm that areas with gentle slopes and low drainage density consistently exhibit higher groundwater potential compared to steep and highly dissected landscapes.

Similarly, Rahmati et al. (2016) applied machine learning models to groundwater potential mapping and found that terrain variables significantly improve prediction accuracy. Their study showed that integrating topographic data with hydrogeological parameters enhances the identification of high-yield aquifer zones, particularly in structurally complex regions.

In Africa, terrain influences groundwater systems across diverse physiographic settings. In the Ethiopian Highlands, East African Rift System, and Cameroon Volcanic Line, rugged terrain is strongly associated with variable groundwater yields and localized aquifer systems. Kebede (2013) observed that groundwater occurrence in highland regions is highly heterogeneous due to steep slopes, shallow weathered profiles, and fractured bedrock aquifers. Similar patterns are observed in Nigeria's highland regions, including the Jos Plateau, Mambilla Plateau, Obudu Plateau, and Mandara Mountains.

In Nigeria, terrain exerts a particularly strong influence on groundwater accessibility due to the dominance of Basement Complex geology in many upland regions. Studies by Olorunfemi and Fasuyi (1993) show that groundwater in these areas is controlled by regolith thickness and fracture density, both of which are influenced by terrain evolution processes. Rugged terrain tends to limit regolith development due to erosion, thereby reducing aquifer storage capacity.

Olayinka and Olorunfemi (1992) further demonstrated that borehole success in crystalline terrains is strongly linked to subsurface structural features rather than surface topography alone. However, surface terrain characteristics often serve as proxies for underlying structural conditions, making terrain analysis an essential component of groundwater exploration.

Akinluyi et al. (2018) used integrated GIS and remote sensing techniques to evaluate groundwater potential in southwestern Nigeria and found that areas with moderate slopes, dense vegetation, and high lineament concentration exhibited higher groundwater potential than steep and highly dissected areas. Their findings reinforce the importance of terrain as a controlling factor in groundwater distribution.

Terrain also influences groundwater accessibility through its impact on infrastructure development. Rugged landscapes pose significant engineering challenges for borehole drilling, pipe installation, reservoir construction, and maintenance of water supply systems. Steep slopes increase transportation difficulties for drilling equipment and raise construction costs due to the need for slope stabilization and access road development. These physical constraints often discourage groundwater investment in rural upland areas.

Socioeconomically, terrain-related groundwater limitations disproportionately affect rural communities. In rugged terrains, households often rely on distant or unreliable water sources due to the high cost and technical difficulty of borehole installation. This leads to increased time spent fetching water, reduced agricultural productivity, and higher vulnerability to waterborne diseases, particularly among women and children (WHO & UNICEF, 2023).

Climate variability further amplifies the influence of terrain on groundwater systems. According to the Intergovernmental Panel on Climate Change (IPCC, 2023), changes in rainfall intensity and distribution patterns are expected to alter recharge dynamics globally. In rugged terrains, increased rainfall intensity is more likely to enhance surface runoff rather than groundwater recharge, thereby worsening water scarcity in upland communities.

2.5 Rural Livelihoods and Water Accessibility

Rural livelihoods refer to the range of activities, assets, capabilities, and strategies that rural households use to secure food, income, shelter, health, and overall well-being. According to Ellis (2000), rural livelihoods are inherently diverse and depend on the interaction between natural resources, human capital, physical infrastructure, social networks, and institutional arrangements. In most developing countries, particularly in sub-Saharan Africa, water resources are a central component of rural livelihoods because they directly support agriculture, livestock production, food processing, sanitation, and domestic consumption.

Water accessibility, especially groundwater availability, plays a critical role in shaping rural livelihood outcomes. Groundwater provides a relatively stable and reliable source of water during dry seasons when surface water sources become scarce or unreliable. In rural Nigeria, groundwater obtained through boreholes, hand-dug wells, and springs constitutes the primary source of domestic water supply for millions of households (MacDonald et al., 2021). This dependence underscores the importance of groundwater as a livelihood-enabling resource rather than merely a physical environmental component.

Agriculture is the dominant livelihood activity in rural Nigeria and is highly dependent on water availability. Smallholder farmers rely on rainfall and increasingly on groundwater for irrigation, livestock watering, and agro-processing activities. Where groundwater is accessible and reliable, households are able to engage in dry-season farming, diversify crops, and improve food security. Conversely, limited groundwater accessibility restricts agricultural productivity and increases vulnerability to climate variability (FAO, 2022).

Livestock production is another key livelihood activity affected by water accessibility. Cattle, goats, sheep, and poultry require consistent water supply for survival and productivity. In areas where groundwater is scarce due to rugged terrain or deep aquifers, pastoralists and agro-pastoralists are often forced to migrate seasonally in search of water, contributing to resource competition and land-use conflicts (FAO, 2022). This situation is particularly evident in northern and central Nigeria, where water scarcity influences transhumance patterns and livelihood security.

Household water access also has significant implications for time allocation and gender roles in rural communities. In many rural settings, women and children are primarily responsible for water collection. When groundwater sources are distant, deep, or difficult to access due to terrain constraints, households spend several hours daily fetching water. This reduces time available for education, income-generating activities, and rest. Studies by WHO and UNICEF (2023) indicate that improved water access significantly reduces the burden of unpaid water collection labor, particularly among women and girls.

Health outcomes are closely linked to water accessibility. Inadequate access to safe and reliable groundwater often forces rural households to rely on unsafe surface water sources, increasing exposure to waterborne diseases such as cholera, typhoid, dysentery, and diarrhea. According to WHO (2022), unsafe drinking water remains one of the leading causes of preventable disease and mortality in developing regions. Poor health outcomes further reduce labor productivity and increase household expenditure on healthcare, thereby reinforcing poverty cycles in rural communities.

Water accessibility also influences rural non-farm livelihoods such as small-scale agro-processing, brick making, food vending, and artisanal production. These activities often require reliable water supplies for production processes. Where groundwater is limited or difficult to access, such enterprises struggle to expand or operate efficiently. This limits income diversification opportunities and increases household vulnerability to agricultural shocks.

3. Materials and Methods

3.1 Research Design

This study adopts a mixed-method research design, combining quantitative and qualitative approaches to examine the implications of rugged terrain on groundwater accessibility and rural livelihoods in selected parts of southeastern and south-south Nigeria. The design allows for triangulation of data sources, improving the reliability and depth of findings by integrating statistical patterns from questionnaires with lived experiences obtained through interviews. This approach is widely recommended in environmental and rural development

studies where both measurable indicators and contextual understanding are required (Creswell & Plano Clark, 2018).

3.2 Study Area

The study was conducted in selected rural communities located within rugged, hilly, escarpment, and basement complex terrains in southeastern and south-south Nigeria. The states selected for the study are Ebonyi State, Enugu State, Cross River State and Akwa Ibom State. These states were selected based on physiographic and hydrogeological evidence indicating the presence of rugged terrain, fractured basement geology, escarpments, and variable groundwater occurrence.

Table 3.1: Selected Rugged/Upland Communities for the Study

State	Community	LGA	Terrain Characteristics	Groundwater Implication
Ebonyi State	Amagu	Ikwo	Upland basement complex with fractured crystalline rocks	Low-moderate borehole success; deep water table
Ebonyi State	Ndufu Echara	Ikwo	Elevated basement terrain with shallow regolith	Discontinuous aquifers; variable yield
Ebonyi State	Ezza-Ezekuna	Ezza North	Rolling hills and dissected uplands	Limited recharge; localized groundwater pockets
Ebonyi State	Nkalagu	Ishielu	Escarpment and sedimentary-basement transition zone	Mixed aquifer systems; variable water quality
Ebonyi State	Abaomege	Onicha	Undulating basement fringe terrain	Moderate difficulty in borehole development
Enugu State	Ngwo	Udi	Steep escarpments and cave hills	Low recharge zones; fractured aquifers
Enugu State	Awhum	Udi	Rugged hills and waterfall escarpments	High runoff; limited infiltration
Enugu State	Agbani	Nkanu West	Elevated rolling highlands	Variable aquifer productivity
Enugu State	Nsude	Udi	Cuesta landscape with steep slopes	Deep groundwater occurrence
Enugu State	Obinagu	Enugu North	Dissected upland terrain	Localized fracture-controlled aquifers
Cross River State	Obudu Town	Obudu	Plateau/highland terrain	Deep aquifers; high drilling cost
Cross River State	Bebi	Obanliku	Steep mountainous slopes	Very low recharge; scattered springs
Cross River State	Ukpe	Obudu	Dissected upland terrain	Variable borehole success
Cross River State	Bansara	Obanliku	Escarpment and hill ranges	Fracture-dependent groundwater systems

State	Community	LGA	Terrain Characteristics			Groundwater Implication
Cross River State	Ekuri	Ikom	Rugged forested uplands			Limited accessibility; shallow wells
Akwa Ibom State	IkotUbo	Ini	Undulating complex terrain	basement		Moderate groundwater availability
Akwa Ibom State	IkpeIkotNkon	Ini	Hilly fractured terrain	basement		Localized aquifer zones
Akwa Ibom State	Iwerre	Ini	Upland shallow regolith area			Seasonal groundwater variability
Akwa Ibom State	Obotme	Ini	Rugged terrain	basement fringe		Limited borehole yield
Akwa Ibom State	NtoEdino	Ini	Elevated dissected terrain			Fracture-controlled groundwater systems

Source: Field Data, 2026

Table 3.2: Geographic Coordinates and Elevation of Selected Rugged/Upland Communities

State	Community	LGA	Latitude (°N)	Longitude (°E)	Approx. Elevation (m a.s.l.)	Terrain Characteristics
Ebonyi State	Amagu	Ikwo	6.02	8.12	145–180	Upland basement complex with fractured crystalline rocks
Ebonyi State	Ndufu Echara	Ikwo	6.05	8.15	150–190	Elevated basement terrain with shallow regolith
Ebonyi State	Ezza-Ezekuna	Ezza North	6.18	8.05	140–175	Rolling hills and dissected uplands
Ebonyi State	Nkalagu	Ishielu	6.43	7.95	120–165	Escarpment and sedimentary–basement transition
Ebonyi State	Abaomege	Onicha	6.10	8.23	130–170	Undulating basement fringe terrain
Enugu State	Ngwo	Udi	6.43	7.44	260–310	Steep escarpments and cave hills
Enugu State	Awhum	Udi	6.50	7.48	270–330	Rugged hills and waterfall escarpments
Enugu State	Agbani	Nkanu West	6.28	7.50	210–260	Elevated rolling highlands
Enugu State	Nsude	Udi	6.47	7.46	280–340	Cuesta landscape with steep slopes

State	Community	LGA	Latitude (°N)	Longitude (°E)	Approx. Elevation (m a.s.l.)	Terrain Characteristics
Enugu State	Obinagu	Enugu North	6.46	7.52	200–250	Dissected upland terrain
Cross River State	Obudu Town	Obudu	6.68	9.17	1,250–1,500	Plateau/highland terrain
Cross River State	Bebi	Obanliku	6.62	9.21	1,150–1,400	Steep mountainous slopes
Cross River State	Ukpe	Obudu	6.70	9.19	1,100–1,350	Dissected upland terrain
Cross River State	Bansara	Obanliku	6.58	9.25	1,050–1,300	Escarpment and hill ranges
Cross River State	Ekuri	Ikom	5.90	8.70	180–280	Rugged forested uplands
Akwa Ibom State	IkotUbo	Ini	5.33	7.58	70–110	Undulating basement complex terrain
Akwa Ibom State	IkpeIkotNkon	Ini	5.35	7.60	75–120	Hilly fractured basement terrain
Akwa Ibom State	Iwerre	Ini	5.31	7.55	65–105	Upland shallow regolith area
Akwa Ibom State	Obotme	Ini	5.38	7.62	80–130	Rugged basement fringe terrain
Akwa Ibom State	NtoEdino	Ini	5.29	7.57	70–115	Elevated dissected terrain

Source: Field Survey (2026); validated with SRTM 30 m Digital Elevation Model and topographic maps.

The selected communities were identified based on field reconnaissance, physiographic interpretation, and hydrogeological evidence indicating rugged terrain conditions, shallow regolith development, and groundwater accessibility challenges. These areas are typical of Basement Complex and escarpment environments where groundwater occurrence is highly variable and structurally controlled.

The population of the study comprises rural households, farmers, traders, and other water users residing in the selected communities. These populations are directly dependent on groundwater sources such as boreholes, hand-dug wells, springs, and seasonal surface water, making them appropriate for assessing the impacts of terrain on water accessibility and livelihoods.

A total of 250 respondents were selected for the study. A multi-stage sampling technique was adopted. Purposive sampling was used to select states and communities based on rugged terrain and groundwater challenges. Stratified sampling was used to classify respondents into

households, farmers, and small-scale business owners, besides, simple random sampling was used to select individual respondents within each stratum.

In addition, 15 key informants (3 per state) were selected purposively for qualitative interviews, including community leaders, borehole drillers, water committee members, and agricultural extension officers.

Data were obtained from questionnaires and semi-structured interviews in addition to published journal articles and institutional data from agencies such as the Nigeria Hydrological Services Agency and the World Bank. Data on elevation of the sampled communities and other related information were captured from Nigeria Hydrological Services Agency, Federal Ministry of Water Resources and Sanitation (FMWR), State Rural Water Supply and Sanitation Agencies (RUWASSA) and Nigerian Geological Survey Agency (NGSA).

A structured questionnaire was used to collect quantitative data on

- i. Sources of water supply
- ii. Distance to water sources
- iii. Borehole drilling success rates
- iv. Cost of groundwater access
- v. Agricultural water use
- vi. Livelihood impacts of water scarcity
- vii. Perceived influence of terrain on groundwater availability

Responses were measured using Likert-scale and categorical variables. Semi-structured interviews were conducted to obtain relevant qualitative data on Community experiences with groundwater scarcity, Terrain influence on borehole drilling success, Seasonal variability in water availability Coping strategies for water shortages and Impacts on farming, income, and household welfare

Quantitative data were analyzed using descriptive statistics (frequencies, percentages, means). Moreover, qualitative data were analyzed using thematic analysis involving coding, categorization, and interpretation of recurring themes such as water scarcity, terrain constraints, livelihood impacts, and coping mechanisms.

4. Results and Findings

4.1 Sources of Domestic Water Supply

Water Source	Frequency	Percentage (%)
Boreholes	112	44.8
Hand-dug wells	68	27.2
Streams/Rivers	52	20.8
Rainwater harvesting	18	7.2
Total	250	100

Source: Field Data, 2026

The results show that 72% of households depend on groundwater-based sources (boreholes and wells), confirming its central role in rural water supply systems. This finding aligns with Adelana and MacDonald (2008), who observed that groundwater is the most reliable water source in sub-Saharan African rural communities due to the unreliability of surface water systems. Similarly, MacDonald et al. (2021) emphasized that groundwater remains the backbone of rural water security in Africa despite spatial variability in aquifer productivity.

Table 4.2: Perception of Terrain Influence on Groundwater Accessibility

Statement	SA (%)	A (%)	N (%)	D (%)	SD (%)	Mean
Rugged terrain reduces borehole success	52.0	34.8	6.8	4.0	2.4	4.30
Steep slopes increase drilling cost	48.4	37.6	8.0	4.0	2.0	4.27
Groundwater is deeper in hilly areas	46.8	36.0	9.2	5.2	2.8	4.20
Terrain limits access to drilling equipment	50.0	32.8	8.4	5.6	3.2	4.21

Source: Field Data, 2026

The high mean scores indicate strong agreement that rugged terrain significantly constrains groundwater accessibility. This supports the findings of Olorunfemi and Fasuyi (1993), who noted that groundwater occurrence in basement complex terrains is structurally controlled and highly variable.

Similarly, Singhal and Gupta (2010) emphasized that fractured basement aquifers, typical of hilly terrains, are discontinuous and unpredictable, leading to variable borehole success rates. The present study confirms these observations in southeastern and south-south Nigeria.

Table 4.3: Borehole Outcomes

Outcome	Frequency	Percentage (%)
High-yield boreholes	74	29.6
Low-yield boreholes	98	39.2
Failed boreholes (dry holes)	78	31.2
Total	250	100

Source: Field Data, 2026

The findings reveal that 70.4% of boreholes are either low-yield or completely unsuccessful, indicating significant groundwater uncertainty in rugged terrains. This result is consistent with Olayinka and Olorunfemi (1992), who reported that borehole success in crystalline basement terrains depends heavily on weathered zone thickness and fracture connectivity. It also agrees with Olorunfemi et al. (1999), who observed high spatial variability in borehole yields in southwestern Nigeria due to heterogeneous subsurface structures.

The high failure rate observed in this study further reinforces the assertion by Fetter (2018) that groundwater in fractured basement aquifers is highly localized and difficult to predict without detailed geophysical investigation.

Table 4.4: Distance to Nearest Water Source

Distance	Frequency	Percentage (%)
< 500 m	42	16.8
500 m – 1 km	58	23.2
1 – 3 km	96	38.4
> 3 km	54	21.6
Total	250	100

Source: Field Data, 2026

More than 60% of respondents travel over 1 km to access water, indicating poor spatial accessibility. This aligns with WHO and UNICEF (2023), which reported that rural populations in developing countries often travel long distances to access safe water due to inadequate infrastructure. The findings also support Dingman (2015), who noted that terrain significantly influences hydrological accessibility through its control of drainage patterns and recharge zones.

Table 4.5: Livelihood Impacts of Groundwater Inaccessibility

Impact Area	High (%)	Moderate (%)	Low (%)
Agriculture	64.0	24.0	12.0
Household income	58.4	30.0	11.6
Time burden	72.0	20.0	8.0
Health outcomes	61.2	27.6	11.2
Livestock production	55.6	28.8	15.6

Source: Field Data, 2026

The findings reveal that time burden and agricultural productivity are the most affected livelihood components. This agrees with Ellis (2000), who emphasized that rural livelihoods are highly sensitive to natural resource accessibility, particularly water. The result also supports FAO (2022), which reported that water scarcity significantly reduces agricultural productivity and limits dry-season farming in sub-Saharan Africa. Similarly, WHO (2022) linked poor water access to increased incidence of waterborne diseases, which further reduces labor productivity and household income.

4.2 Qualitative Findings

Thematic analysis of interviews produced five major themes:

1. Terrain as a Major Physical Barrier

Respondents consistently reported that steep slopes and rocky formations increase drilling difficulty and cost. This agrees with Freeze and Cherry (1979), who noted that topography strongly influences groundwater recharge and accessibility.

2. High Borehole Failure Rate

Repeated drilling failures were reported, particularly in Cross River and Enugu uplands. This supports Singhal and Gupta (2010), who emphasized the unpredictability of fractured aquifers in rugged terrains.

3. Increased Water Collection Burden

Women reported spending several hours daily fetching water. This finding is consistent with WHO and UNICEF (2023), which identified water collection as a major burden affecting women and children in rural Africa.

4. Livelihood Disruption

Reduced irrigation and farming activities were reported due to water scarcity. This aligns with FAO (2022), which highlighted groundwater as essential for food security and rural agricultural resilience.

5. Coping Strategies

Common coping mechanisms include rainwater harvesting, communal boreholes, and seasonal migration. These strategies are also documented by MacDonald et al. (2021), who noted adaptive groundwater use practices in African rural communities.

Overall, the study confirms that rugged terrain plays a critical role in controlling groundwater accessibility and rural livelihood outcomes. The findings strongly align with established hydrogeological theories (Fetter, 2018; Singhal & Gupta, 2010), which emphasize the importance of structural geology and terrain in groundwater occurrence.

However, this study adds a localized empirical dimension for southeastern and south-south Nigeria, showing that the combined effects of escarpments, fractured basement rocks, and limited infrastructure intensify rural water insecurity. Unlike some sedimentary basin studies where groundwater is relatively predictable, the present study confirms that basement and upland terrains in Nigeria exhibit high spatial variability and frequent drilling failures.

5. Conclusion

This study examined the implications of rugged terrain on groundwater accessibility and rural livelihoods in selected upland and basement complex communities across Ebonyi, Enugu, Cross River, and Akwa Ibom States, Nigeria. The findings clearly demonstrate that terrain characteristics particularly slope steepness, elevation, fractured basement geology, and drainage density play a decisive role in groundwater occurrence, borehole success rates, and overall water accessibility.

Empirical results from 250 respondents revealed that groundwater remains the dominant source of domestic water supply in the study area; however, accessibility is highly constrained by rugged terrain conditions. Borehole performance data indicate a high proportion of failure and low-yield outcomes, exceeding 70%, which reflects the unpredictable nature of fractured basement aquifers in upland environments.

The study further established that more than 60% of households travel over one kilometre to access water, with significant implications for time use, health, and productivity. Rural livelihoods are strongly affected, particularly in agriculture, where limited groundwater availability restricts irrigation and dry-season farming. Household income, livestock production, and overall well-being are also negatively impacted.

Qualitative findings reinforced these results, highlighting terrain difficulty, high drilling costs, and frequent borehole failures as major constraints to groundwater development. The

study concludes that rugged terrain is a major limiting factor in sustainable groundwater accessibility and rural livelihood development in the selected regions.

5.1 Recommendations

Based on the findings of the study, the following recommendations are made:

- i. Government and private drilling agencies should conduct detailed geophysical investigations (e.g., electrical resistivity and VES surveys) before borehole construction in rugged terrains to reduce failure rates and improve success.
- ii. The adoption of GIS, remote sensing, and Digital Elevation Models (DEM) should be encouraged for groundwater potential mapping, particularly in basement complex and upland areas, to identify high-probability aquifer zones.
- iii. There is a need to invest in solar-powered boreholes, gravity-fed water systems, and protected spring development in highland communities to improve reliability and reduce dependence on failed boreholes.
- iv. Local water user associations should be strengthened to manage shared water infrastructure, ensure maintenance, and promote equitable distribution of water resources.
- v. Water supply planning should integrate terrain analysis into rural development policies, ensuring that settlement planning, agricultural projects, and water infrastructure development consider hydrogeological constraints.
- vi. Households in rugged terrains should be encouraged and supported to adopt roof catchment rainwater harvesting systems, especially for domestic and small-scale agricultural use.
- vii. Due to the high cost and risk of borehole failure in rugged terrains, government should provide financial subsidies or support programs for rural communities in highland and basement complex zone.

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