HYDROGEOLOGICAL COMPLEXITY AND WATER GOVERNANCE IN NIGERIA: ADVANCING INTEGRATED WATER RESOURCES MANAGEMENT THROUGH PROVISIONS OF ACHIEVABLE SOLUTIONS

Shuaibu, A. M.[1] and Musa, K. O.[1]

[1]*Department of Geology, Faculty of Physical Science, Federal University Lokoja, Kogi State, Nigeria*

Cite this article as: Shuaibu, A. M., & Musa, K. O. (2026). Hydrogeological complexity and water governance in Nigeria: Advancing integrated water resources management through provisions of achievable solutions. Journal of Interdisciplinary Postgraduate Research, 1(2), 196–203.

Abstract

Sustainable water resources management in Nigeria remains a significant challenge despite the country's abundant surface and groundwater reserves. This study assesses the status, constraints, and prospects of Integrated Water Resources Management as a vehicle for addressing the widening imbalance between water demand and supply under mounting socio-economic and environmental pressure. The analysis reveals strong spatial variability in water availability, persistent climatic uncertainty, and the widespread occurrence of low-yielding crystalline basement aquifers. Water scarcity in the northern regions, particularly within the Sokoto-Rima, Chad, and Hadejia-Jamare basins, is intensified by high evapotranspiration, rapid population growth, weak infrastructure, and ineffective governance. Several systemic limitations are identified, among them fragmented institutional structures, an entrenched supply-oriented management posture, inadequate data, and limited technical capacity. Hydrogeological and geophysical evidence underscores the importance of aquifer characterisation and recharge assessment for sustainable groundwater development, while water budget analysis clarifies the regional water balance. Advances in hydrological modelling, embracing both numerical and data-driven approaches, strengthen predictive capacity and support informed decision-making, and the integration of remote sensing, geographic information systems, and machine learning improves groundwater potential mapping in data-scarce settings. The study concludes that durable water security in Nigeria requires a decisive shift toward an integrated and adaptive management framework underpinned by institutional reform, technological innovation, and genuine stakeholder engagement.

Keywords: *integrated water resources management, hydrogeology, groundwater, basement complex, water governance, Nigeria*

1. Introduction

Integrated evaluation of water resources constitutes a comprehensive approach to harmonising the development and management of water, land, and associated natural systems in order to enhance economic and social benefit. The approach places sustainability, equity, and the protection of critical ecosystems at its centre, ensuring that resource use does not erode environmental integrity (Ezenwaji et al., 2015; Shuaibu et al., 2022a). It offers a structured framework for reconciling competing demands while encouraging cooperation among governing bodies and stakeholders. Although technological innovation contributes substantially to groundwater assessment, its value depends ultimately on sound implementation and disciplined management.

The evaluation of water resources typically begins with the acquisition of basin-scale data encompassing both physical and socio-economic variables, followed by the development of conceptual and numerical models that represent the hydrological, geological, and hydraulic systems. A critical review of governance structures is equally essential for identifying gaps and proposing improvements aligned with prevailing legal and institutional frameworks (Lanini et al., 2004). In Nigeria, water supply systems are increasingly strained by rapid urban growth, constrained finance, and concerns over equitable access. A substantial portion of the country lies within the crystalline hydrogeological province of the Sudano-Sahelian zone, where evapotranspiration frequently exceeds precipitation and water scarcity is correspondingly acute (Shuaibu et al., 2022a).

Adopting an integrated perspective for groundwater entails balancing extraction, in both quantity and quality, against demand driven by population growth and economic activity (Aksever et al., 2015). A well-formulated management plan evaluates availability and quality while promoting the protection and sustainable use of freshwater systems, and it serves additionally as an instrument for raising public awareness of the dynamic character of aquatic ecosystems (Schoeneich, 2007). Groundwater systems are central to supply for both ecological sustainability and human consumption, and may be regarded as renewable where recharge and abstraction remain in equilibrium (Shuaibu and Murana, 2023).

The demand for potable water in Nigeria is expected to rise markedly with continued population expansion and economic development. The Water Resources Act of 2004 provides the principal legislative instrument guiding planning and management, yet domestic supply remains inadequate across much of the country, evidenced by dry taps, declining yields in hand-dug wells, and the failure of boreholes. In per capita terms, renewable resources are estimated at roughly 2,514 cubic metres per year, while only about sixty-nine percent of the population enjoys basic supply services (FAO, 2003). This situation contrasts sharply with countries such as Tunisia, which, despite far lower endowment, have attained near-universal coverage (UNICEF, 2019), a disparity that points unmistakably to systemic inefficiency rather than absolute scarcity. Accordingly, this study examines the prevailing condition of water resources management in Nigeria, its implications for national development, and the contribution that a fully operational integrated framework could make to sustainable development.

2. Nigeria's Water Resources Potential

The sustainable stewardship of water constitutes a foundational pillar of socio-economic development, linking domestic supply, commerce, industry, agriculture, and recreation to public health, food security, and productivity. Historical evidence from industrialised economies demonstrates that sustained investment in infrastructure, coupled with robust institutions and governance capacity, has been instrumental in achieving reliable supply and long-term security (Grey and Sadoff, 2006). Nigeria, in common with many developing countries, continues to contend with inadequate infrastructure, fragile institutions, and ineffective governance, which together undermine efficient utilisation (Abdullahi et al., 2014).

Nigeria's endowment is nonetheless substantial and diverse. The country is bordered by an extensive southern coastline and encompasses major hydrological systems, including the Lake Chad Basin in the north and the great river systems of the Niger and Benue with their numerous tributaries. Climatically, the country exhibits pronounced spatial variability, with annual precipitation ranging from approximately 4,000 millimetres along the coastal belt to about 500 millimetres in the far north and a national mean near 1,200 millimetres (Nigerian Meteorological Agency, 2020). This gradient produces distinct hydro-climatic zones and uneven surpluses and deficits across the territory (Olayinka and Adebayo, 2014). The national hydrological framework is depicted in Figure 1.

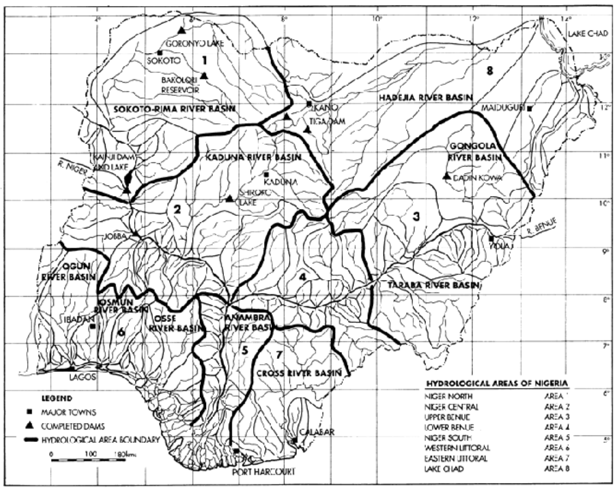

Figure 1. Hydrological map of Nigeria showing the principal river basins and hydrological areas.
Source: FAO (2001).

Nigeria's hydrological regime is strongly seasonal, with more than eighty percent of annual rainfall concentrated within the wet period from April to September. A fraction of this precipitation infiltrates to replenish aquifers, while the larger share is conveyed as surface runoff or returned to the atmosphere through evapotranspiration (Ezeabasili et al., 2014). Despite these losses, groundwater constitutes a substantial component of national reserves, with early estimates suggesting that storage may exceed surface flows by up to an order of magnitude (Orjiako, 2000; Nwankwoala, 2011). National assessments reinforce this picture: the Japan International Cooperation Agency (1995) reported annual renewable yields of approximately 267.30 billion cubic metres for surface water and 51.9 billion cubic metres for

Journal of Interdisciplinary Postgraduate Research 2026,Vol. 1 (2) DOI: 10.61955/CBZWPW

groundwater, while the updated Water Resources Master Plan (JICA, 2013) placed total surface water potential near 333 billion cubic metres per year and overall renewable resources, including transboundary inflows, at about 375 billion cubic metres per year.

Hydrogeological conditions exert fundamental control over groundwater occurrence and productivity. The juxtaposition of sedimentary basins and crystalline Basement Complex terrains produces marked spatial disparity in aquifer performance. Sedimentary formations typically host productive aquifers, whereas the Basement Complex, which underlies nearly half of the country, generally exhibits low potential owing to limited primary porosity, with occurrence restricted to weathered and fractured zones (Ayoade, 2012; Offodile, 2002). The geological framework is summarised in Figure 2.

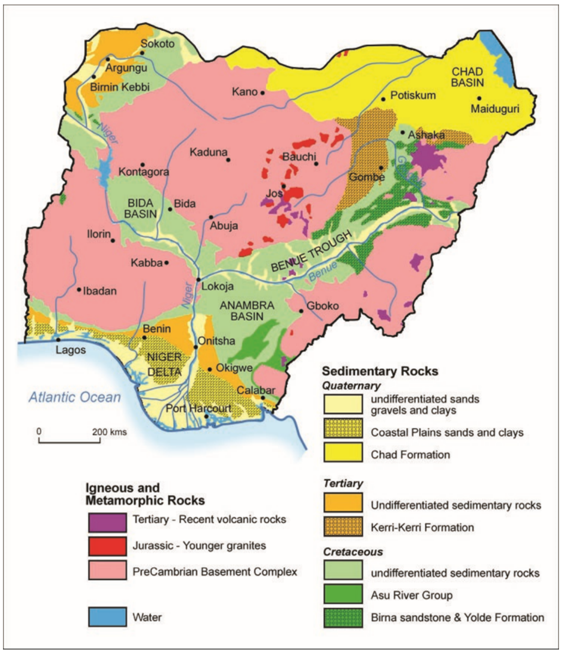

Figure 2. Geological map of Nigeria showing the major geological components.
Source: MacDonald et al. (2005).

2.1 Water Supply versus Demand

Water resources management may be understood fundamentally as the task of ensuring a reliable and continuous supply of freshwater in the face of rising demand (Muller et al., 2009). In Nigeria, practice has historically been skewed toward supply expansion rather than demand regulation, with priority given to new infrastructure and comparatively little attention to efficiency (Ezenwaji et al., 2015). With the population growing at an estimated 2.6 percent per year, demand across domestic, municipal, agricultural, and industrial sectors continues to rise, even as available resources are strained by climate variability, excessive withdrawal, and pollution. The regional distribution of surface and groundwater across the eight hydrological areas is presented in Table 1 and visualised in Figure 3.

Table 1. The Eight Hydrological Areas of Nigeria and their Water Resources Potential

Hydrological Area	River Basin	Area (10^3 km^2)	Surface (10^9 m^3)	Ground (10^9 m^3)
HA-I	Sokoto-Rima	131.6	22.4	4.30
HA-II	Upper/Lower Niger	158.1	32.6	8.18
HA-III	Upper Benue	158.9	55.0	6.99
HA-IV	Lower Benue	73.0	28.0	4.32
HA-V	Anambra-Imo & Niger Delta	53.9	20.0	7.15
HA-VI	Ogun-Oshun & Benin-Owena	100.9	35.4	9.02
HA-VII	Cross-River	59.8	65.7	6.28
HA-VIII	Hadejia-Jamare & Chad	188.0	8.20	5.58
Total		923.8	267.3	51.93

Source: Federal Ministry of Water Resources (2013).

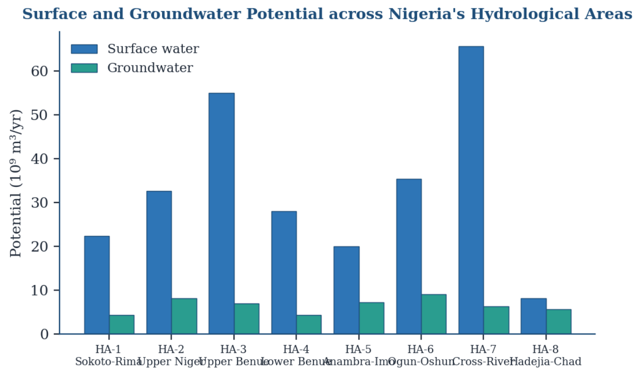

Figure 3. Comparison of surface and groundwater potential across the eight hydrological areas.
Source: Authors' analysis of data in Table 1.

The regime exhibits pronounced spatial heterogeneity. Internally generated renewable resources in the northern zones generally fall below 10 billion cubic metres per year, whereas the southern zones exceed 50 billion cubic metres per year, a stark north-south gradient that reflects the combined influence of rainfall distribution and geological control on recharge. Per capita availability varies by more than an order of magnitude across the areas; the national mean stood near 1,800 cubic metres per person per year in 2010 and is projected to decline to about 1,100 cubic metres by 2030, with critically low values in the north. This trajectory is depicted in Figure 4.

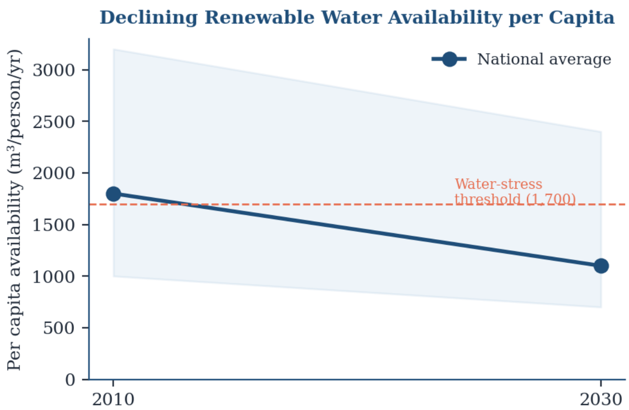

Figure 4. Projected decline in renewable water availability per capita, 2010 to 2030.
Source: Authors' analysis based on national assessments.

Despite the considerable aggregate endowment, access to safe water and sanitation remains inadequate. National estimates indicate that only about fifty-eight percent of the population has access to improved supply, while sanitation coverage lags near thirty-two percent, leaving close to one hundred million people without reliable potable water. The public health consequences are severe, with waterborne disease remaining a leading cause of mortality among young children. Socio-economic inequality further shapes access, since piped networks predominantly serve high-income neighbourhoods while poorer households depend on vendors at significantly higher cost. The coverage record is summarised in Table 2 and Figure 5.

Table 2. Level of Improved Water Supply and Sanitation in Nigeria (millions of persons with access)

Population with Access	JMP 1990	JMP 2008	NDHS	WSSBS 200
Improved water — Rural	30	42	43.8	49.9
Improved water — Urban	79	75	79.7	69.3
Improved water — National	48	58	55.8	54.3
Improved sanitation — Rural	36	28	28.1	59.6
Improved sanitation — Urban	39	36	37.5	85.2
Improved sanitation — National	37	32	31.2	65.6

Source: Federal Ministry of Water Resources (2013).

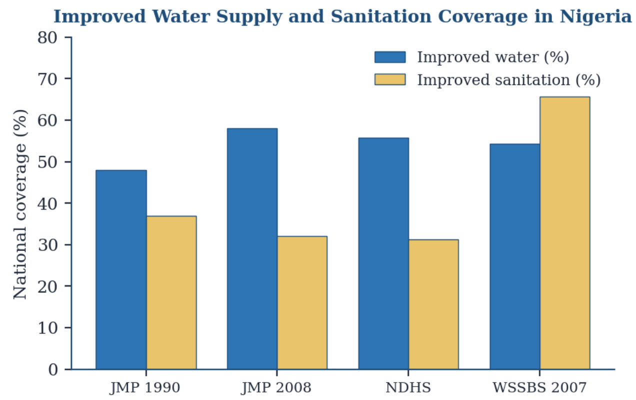

Figure 5. National improved water supply and sanitation coverage across survey instruments.
Source: Authors' analysis of data in Table 2.

Freshwater accessible to rural and peri-urban communities is increasingly compromised by human-induced pressure, of which pollution is the most pervasive. Contaminants ranging from pathogenic microorganisms and suspended sediment to sewage effluent and industrial residue degrade both surface and groundwater. During microbial degradation, heterotrophic organisms consume dissolved oxygen, and where concentrations fall below roughly two milligrams per litre, hypoxic conditions emerge that constrain aquatic survival and destabilise ecosystem function (Galadima et al., 2011; Shuaibu et al., 2022c). Direct consumption of untreated water, still prevalent in many communities, facilitates the transmission of typhoid, dysentery, cholera, and hepatitis, compounding the burden of infectious disease.

3. The Nature and Assessment of IWRM in Nigeria

Decisions to initiate new water projects in Nigeria have frequently been shaped more by political interest than by technical judgement (Okereke et al., 2000). This has encouraged a preference for capital-intensive infrastructure over non-structural strategies such as policy reform and institutional strengthening. Further weaknesses are evident in the absence of effective cost-recovery mechanisms, reliance on outdated irrigation techniques, and limited stakeholder inclusion, each of which sits uneasily with the principles of the Sustainable Development Goals (Emenike et al., 2017; Solomon, 2011). Integrated Water Resources Management in Nigeria is often perceived as an externally driven framework promoted by international institutions, and critics contend that its implementation has emphasised demand management, supply augmentation, and cost recovery at the expense of long-term sustainability, including ecosystem restoration and aquifer recharge.

Assessments of implementation progress place Nigeria, in common with many African countries, within a moderate-to-low performance band of roughly 31 to 50 percent, with about 41 percent of components formally established (Cardwell et al., 2006). South Africa, by contrast, occupies a higher band of 51 to 70 percent, suggesting a stronger prospect of meeting the 2030 targets (Allouche, 2016). This comparative position is summarised in Figure 6. Scholars such as Akpabio et al. (2007) and Biswas (2004) argue that Nigeria's heterogeneity, expressed in cultural diversity, uneven resource distribution, and institutional complexity, poses a significant obstacle to the adoption of any uniform framework.

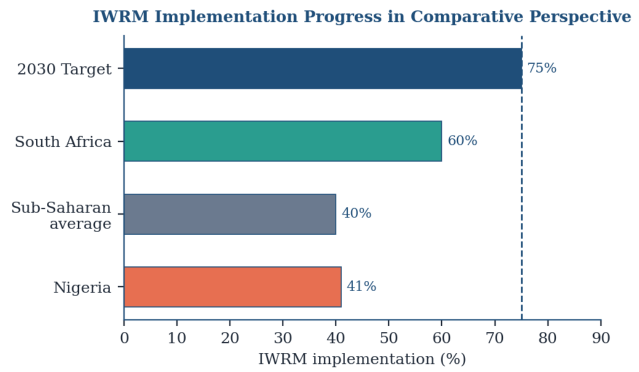

Figure 6. IWRM implementation progress in comparative perspective.
Source: Authors' synthesis of assessment literature.

The development of integrated management in Nigeria can be traced to the establishment of the early River Basin Development Authorities, the creation of the Federal Ministry of Water Resources in 1970, and the subsequent expansion of the authorities across the country (Ezenwaji et al., 2015). Although early policy did not reference integrated management explicitly, the concept was formally acknowledged in the National Water Policy of 2004. The authorities remain central to practical implementation, since river basins are widely regarded as the most appropriate spatial units, yet empirical evidence indicates that they often struggle to fulfil their mandates owing to inadequate funding and limited technical capacity, particularly in data acquisition (Akpabio et al., 2007).

A constructive illustration is offered by the Northeast, where acute scarcity is compounded by insecurity. Within the Sahelian zone, Lake Chad has contracted dramatically, declining from about 25,000 square kilometres to roughly 2,000 square kilometres over three decades through the combined effect of recurrent drought and extensive irrigation withdrawal. In response, the early 2000s saw targeted interventions that disseminated assessment findings, removed obstructions impeding river flow, enhanced flood early-warning systems, and established state-level committees to coordinate management. These efforts contributed to a marked decline in water-related conflict, with reports indicating a ninety percent reduction in cases reaching the courts by 2006, and culminated in the establishment of the national commission in 2008 (Benson et al., 2015).

4. The IWRM Conceptual Framework

Resolving the demand-supply imbalance requires a holistic framework that simultaneously enhances supply, manages demand, strengthens institutions, and protects the environment. The operational pillars of such a framework are set out in Figure 7. Rather than treating water as a sector-specific resource, integrated management promotes coordinated planning across sectors, scales, and stakeholders, ensuring through basin-wide planning and equitable allocation that economic efficiency, social equity, and environmental protection are held in balance. A simple expression of the regional water balance, which underpins such planning, is given in Equation 1, where recharge R is the residual of precipitation P after evapotranspiration ET, surface runoff Q, and the change in storage are accounted for.

$$R = P - ET - Q - \Delta S \quad (1)$$

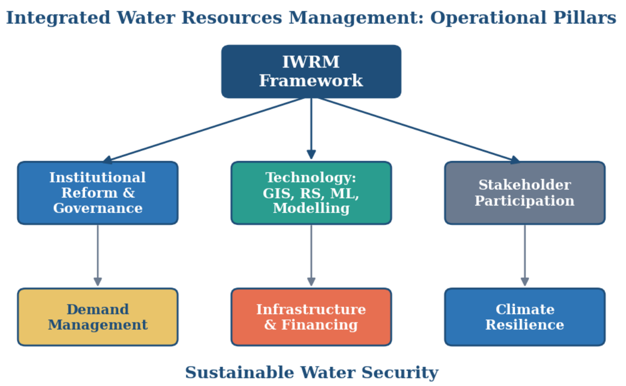

Figure 7. Operational pillars of integrated water resources management.
Source: Authors' conceptualisation.

Complementing governance reform, investment in storage and the rehabilitation of ageing distribution systems would improve supply reliability and reduce physical loss. Equally, demand-side management offers a cost-effective means of narrowing the gap through water-saving technology, appropriate tariff structures, and the reduction of non-revenue water. Given the uncertainty introduced by climate change, planning must incorporate adaptive and resilience-based strategies, strengthening recharge, protecting watersheds, and integrating climate projections into decision-making. Sustainable financing, drawing where feasible on public-private partnership and cost recovery, together with genuine community participation, completes the framework.

5. Hydrogeology of the Sokoto Basin

Hydrogeological research within the Sokoto Basin can be traced to the foundational geological mapping of Jones (1948) and Parker (1965), followed by the regional appraisal of Anderson and Ogilbee (1973), which remains a pivotal early account of the basin's framework. Recent synthesis by Shuaibu et al. (2022b), drawing on seventy boreholes across the crystalline basement terrains of northern Nigeria, highlights the inherent limitation of groundwater occurrence in such settings. Approximately one-third of the boreholes were dry, and productive wells were largely restricted to zones where secondary porosity, in the form of fractures and weathered horizons, was sufficiently developed. Boreholes completed in fresh granite or gneiss typically yielded negligible quantities. A representative cross-section through the basin is presented in Figure 8.

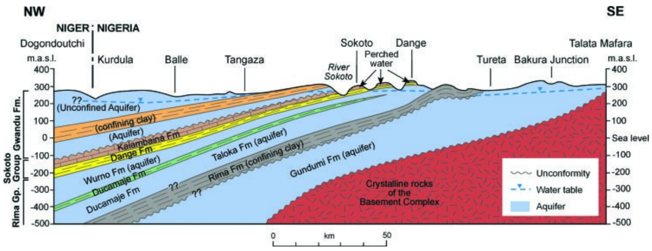

Figure 8. Hydrogeological cross-section through the Sokoto Basin, north-west Nigeria.
Source: Modified after Anderson and Ogilbee; Adelana et al. (2008).

Early pumping-test investigation revealed relatively low transmissivity for basement aquifers, ranging from approximately 1.58 to 38.59 square metres per day, values one to two orders of magnitude lower than those of adjacent sedimentary formations (JICA, 1990). Localised structural features such as fractures, weathered zones, and quartz veins can nonetheless enhance occurrence appreciably. Within the Sokoto-Rima basin, groundwater accounts for roughly seventy percent of rural water provision, and alluvial deposits within floodplain fadama systems often represent more viable targets owing to their higher permeability and storage (Eduvie and Garba, 2017). The most recent assessments report high transmissivity for these alluvial aquifers, ranging from 200 to 5,000 square metres per day, with storage coefficients between ten to the minus two and ten to the minus four.

5.1 Aquifers of the Basement Rocks

Groundwater in basement terrains is associated principally with two interconnected units, the weathered regolith and the underlying fractured crystalline bedrock, whose distribution is strongly governed by structural control (Shuaibu, 2024; Alagbe and Raji, 1990). Productivity is therefore a function of effective porosity, permeability, reservoir geometry, and lithology, with the most prospective zones associated with moderately thick weathered profiles underlain by well-developed fracture systems. Borehole yields commonly range between one and two litres per second, adequate for rural supply, while yields below half a litre per second are generally classified as non-viable (Hamidu et al., 2015). The distribution of yields across the relevant viability classes is shown in Figure 9.

Journal of Interdisciplinary Postgraduate Research 2026,Vol. 1 (2) DOI: 10.61955/CBZWPW

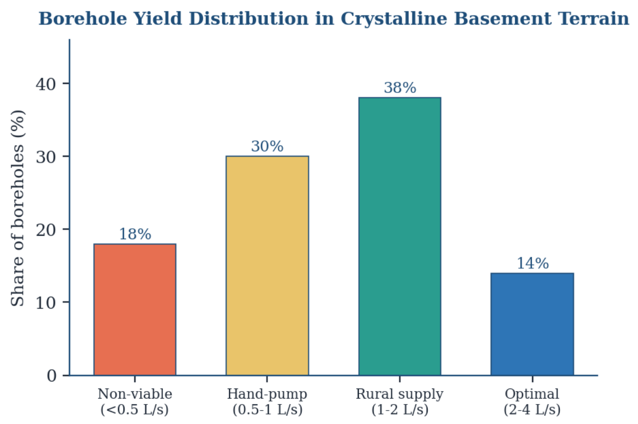

Figure 9. Borehole yield distribution and viability classes in crystalline basement terrain.
Source: Authors' synthesis after Hamidu et al. (2015).

5.2 Groundwater Evaluation Techniques

Hydrogeological conditions are governed fundamentally by the interplay of lithology and climate, and a comprehensive understanding therefore requires detailed characterisation of both geological architecture and hydroclimatic dynamics (Garba and Schoeneich, 2005; Shuaibu, 2024). Advances in geospatial technology have transformed investigation, with remote sensing supplying synoptic, multi-temporal data on lineament density, land cover, and drainage that serve as indirect indicators of occurrence and recharge. When integrated within a geographic information system, these layers can be weighted to generate groundwater potential maps of improved accuracy (Shuaibu and Umoru, 2025). Geophysical methods, including electrical resistivity tomography, vertical electrical sounding, and electromagnetic survey, remain indispensable for delineating aquifer geometry and zones of enhanced permeability, particularly in complex basement settings.

Beyond traditional methods, physically based numerical models such as MODFLOW and SWAT are now widely adopted for simulating flow, recharge, and surface-subsurface interaction (Shuaibu et al., 2026). Data-driven approaches that draw on artificial neural networks, random forests, and support vector machines are increasingly applied to potential mapping and recharge estimation, since they handle nonlinear relationships and large multi-source datasets effectively. Coupled with geographic information systems, these techniques enhance predictive accuracy and reduce the uncertainty associated with conventional empirical methods, a contribution of particular value in semi-arid and data-scarce regions.

6. Recommended Policy Matrix

To translate principle into practice, this study advances an implementable policy matrix for water demand management, summarised in Table 3. Its measures are organised across planning and analysis, legal and institutional reform, economic management, and projects and programmes, and are designed to facilitate consistent metering so that users pay in proportion to consumption.

Table 3. Recommended Policy Matrix for Water Resources Management in Nigeria

Domain	Representative Measures
Planning & analysis	Assess and develop resources; forecast population and demand; map users and consumption; monitor quantity and quality.
Legal & institutional	Establish protection zones; curb illicit connections; institute effective authorities; enforce licensing for drilling and abstraction.
Economic management	Introduce metering and volumetric tariffs; treat water as an economic good; provide targeted subsidy for vulnerable users.
Projects & programmes	Conduct hydrogeological surveys; rehabilitate deficient infrastructure; implement leak detection; sustain public education.

Source: Adapted by the authors after Federal Ministry of Water Resources (2013).

7. Conclusion

This study demonstrates that Nigeria possesses substantial surface and groundwater resources, and that the persistent mismatch between availability and access is primarily a consequence of systemic inefficiency rather than absolute scarcity. Fragmented institutions, inadequate infrastructure, weak governance, and the poor integration of management strategy have together constrained the effective use of available resources, while spatial and temporal variability, rapid population growth, environmental degradation, and climate variability intensify stress across the regions. Although the integrated framework has been adopted at the level of policy, its practical implementation remains limited, and the prevailing paradigm continues to privilege supply expansion over demand management and ecosystem preservation.

Achieving durable water security requires a decisive transition toward a fully operational and context-specific integrated framework. This entails strengthening institutional coordination, enhancing data-driven decision-making, and embedding modern geospatial and modelling tools within planning. Investment in resilient infrastructure, the adoption of demand-side management, and the pursuit of efficient use are each essential to bridging the widening gap, while climate-resilient approaches, genuine stakeholder participation, and sustainable financing will materially improve long-term outcomes. Aligning policy, technology, and governance within a single integrated framework offers the most credible pathway to optimising resource use, safeguarding ecosystem integrity, and supporting national development.

Declarations

Conflict of interest. The authors declare no competing interests. **Funding.** This review received no external funding. **Data availability.** All data discussed are drawn from the cited published sources.

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