REVIEW | OPEN ACCESS

Discovery Nature

A Comprehensive Review of Climate Change Catastrophy on Food Security with Groundwater abstraction and Drip Irrigation System as Viable Mitigation Measures: A Case Study of the 12 River Basins, Nigeria

Ibrahim OI[1]*, Abubakar SM[2], Abdullah MA[3], Davis O[4], Ojo OO[5], Eze CI[6]

To Cite:
Ibrahim OI, Abubakar SM, Abdullah MA, Davis O, Ojo OO, Eze CI. A Comprehensive Review of Climate Change Catastrophy on Food Security with Groundwater abstraction and Drip Irrigation System as Viable Mitigation Measures: A Case Study of the 12 River Basins, Nigeria. *Discovery Nature* 2025; 2: e9dn3127
doi: https://doi.org/10.54905/disssi.v2i4.e9dn3127

Author Affiliation:
[1]Design and Hydrogeology Units, Lower Niger River Basin Development Authority, Ilorin, Kwara state, Nigeria
[2]Head of Water Supply, Sanitation and Climate Change, Sokoto-Rima River Basin Development Authority, Sokoto state, Nigeria
[3]Deputy Director, Head of Drilling unit, Chad River Basin Development Authority, Maiduguri, Borno state, Nigeria
[4]Engineering Department, Cross River Basin Development Authority, Calabar, Nigeria
[5]Hydrology Department, Ogun-Oshun River Basin Development Authority, Abeokuta, Ogun State, Nigeria
[6]Hydrogeology Department, Anambra-Imo River Basin Development Authority, Owerri, Imo state, Nigeria

***Corresponding Author**
Ibrahim OI,
Design and Hydrogeology Units, Lower Niger River Basin Development Authority, Ilorin, Kwara state, Nigeria; Email: ibroibrahim72@gmail.com

Peer-Review History
Received: 05 May 2025
Reviewed & Revised: 14/May/2025 to 30/August/2025
Accepted: 09 September 2025
Published: 18 September 2025

Peer-Review Model
External peer-review was done through double-blind method.

Discovery Nature
pISSN 2319-5703; eISSN 2319-5711

DISCOVERY
SCIENTIFIC SOCIETY

ABSTRACT

Changing climate has drastically made the environment prone to uncertainty. This has further made man's habitation on earth to be non-conducive with earth temperature that keeps rising unpredictably and uncontrollably. The study delves into solutions to ameliorate this Pandemic with the adoption of groundwater exploitation and drip Irrigation Engineering technique as mitigative approach to reduce the impacts on food insecurity in Nigeria. The study was also corroborated by findings from 12 River Basin Development areas expected to respond swiftly to the changes. The specific problem has been largely traced to high (87%) dependence on surface water and rainfall agricultural system which has been with much more limited, unsustainable and unpredictable in volume with destructive tendencies to farmlands and other valuable properties. However, groundwater potential has been largely untapped for the purpose of irrigation, just as drip irrigation has shown to be much more effective for food security. The study has thus reviewed published articles and come to a common point that Nigeria will need shift to harnessing its groundwater potential for irrigation, especially during the dry season. The Alluvium is the largest untapped mapped aquifer system of 26% country's area, Basalt (14.12%), Banded Gneissic Complex (12.09%), Sandstone (23.21%), Shale (7.11%), Gneiss (4.08%), Schist (3.33%), Granite (3.18%), Charnockite (3.41%), Limestone (2.54%), Quartzite (1.48%) and Laterite (2.29%) systems. Water production capacity ranges between 0.98 to 5.1 liters/second in these aquifers across the River basins and Nigerian states. The study thus concludes that viable mitigation measures to reduce the impacts of climate change and enhance food security is to adopt climate resilient, smart-groundwater productivity and drip irrigation system.

Keywords: Groundwater, Alluvium, Basalt, Limestone, Aquifer system and Banded Gneissic Complex

1. INTRODUCTION

1.1. Background knowledge

Climate change with approximate 1°C temperature rise over the last half century globally and 1.55°C declared as earth temperature in recent year has not only made 2024 to be the hottest year ever, but has directly impacted the supply and production of freshwater through the amplification of precipitation extremes (Ibrahim et al 2025). This change is now more frequent and pronounced globally with floods and droughts, heatwaves, biodiversity loss, increasing evapotranspiration rates, rising sea levels, flooding of coastal communities, ocean acidification, desertification, changing precipitation, wildfire burning and meltwater regimes globally. Groundwater, the world's largest distributed store of freshwater is naturally well placed to play a vital role in enabling societies to adapt to this intermittent water shortages caused by the change. It is also essential to satisfy the increased demand for water in order to realize many of the United Nations' Sustainable Development Goals (SDGs), including no. 2 (zero hunger), 6 (water for all) and 13 (climate action). The impacts of climate change on terrestrial water balances can be further modified by human activity such as land use and land cover (LULC) change (Amanambu et al., 2020). Climate and land cover largely determine rates of precipitation (P) and evapotranspiration (ET), whereas the underlying soil and geology dictate whether water surplus (P - ET) can be transmitted to an underlying aquifer as previously attested in a published journal (Sultana et al 2015).

River Basins in Nigeria are saddled with the responsibility of responding swiftly to this adverse climate change effect by utilizing surface and groundwater resources to enhance domestic, industrial and agricultural activities. With this change ravaging the global communities in the name of drought, famine and flooding, the task of mitigating these effects on humanity greatly lies with an effective and efficient activities of the 12 River basins across Nigeria to respond swiftly to these catastrophic pandemic and strengthen food security in the country. Drip irrigation is globally accepted as one of the most efficient irrigation technique, as it allows high uniformity of water and nutrient application to farmland down to the root system. This study, thus, entail 2 critical components of groundwater abstraction as a tool to respond to the effects of climate change and drip irrigation system to improve agricultural products and enhance food security across the 12 River basins in Nigeria.

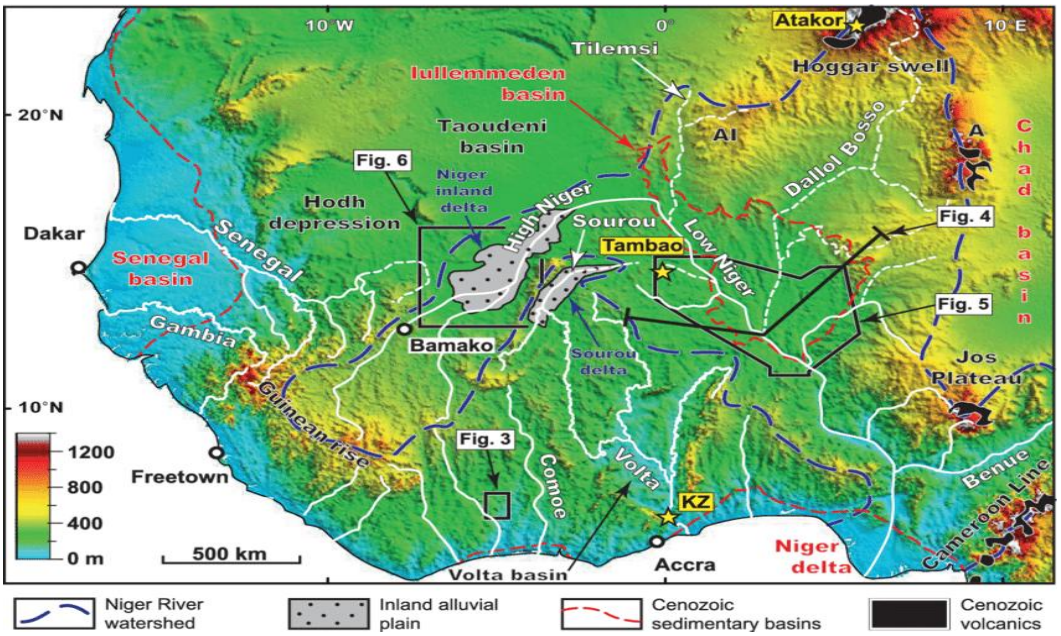

Fig. 1: Notable West African River Basins and the Geologic rock composition

1.2. Geomorphology of Nigeria and its waterways

Nigeria has a coordinate of Latitudes 4° and 14° North of the Equator and longitudes 3° and 15° East. It has a total land mass of about 924,000km^2 and a population density of about 220,000,000 people. Nigeria has two major rivers, the river Niger, after which the country is named and the Benue river with several tributaries. Nigeria has over 10,000 km of inland waterways. According to statistics from Nigerian Inland Waterways (NIWA), 28 of the 36 states of the Federation can be linked by water for more easier transportation of goods and services. River Niger (Fig. 2) is the main river of West Africa extending about 4,180 kilometres (2,600 miles). Its drainage basin is 2,117,700 km² (817,600 sq mi) in area. The Nigerian basement complex is one of the three major litho-petrological components that make up the Geology of Nigeria (Figs. 1 and 2). The SPIN ie Sustainable Power Irrigation in Nigeria is a welcome project to climate change pandemic, but it is expected to be incorporated with resilient smart-groundwater source for farmers to supplement the hydropower irrigation proposed by world bank group.

The Nigerian basement complex forms a part of the Pan-African mobile belt and lies between the West African and Congo Cratons (Fig. 1) and south of the Tuareg Shield. It is intruded by the Mesozoic calc-alkaline ring complexes (Younger Granites) of the Jos Plateau and is unconformably overlain by Cretaceous and younger sediments. The Nigerian basement (Fig.1) was affected by the 600 Ma Pan-African orogeny and it occupies the reactivated region which resulted from plate collision between the passive continental margin of the West African craton and the active Pharusian continental margin (Dada, 2006). The basement rocks are believed to be the results of at least four major orogenic cycles of deformation, metamorphism and remobilization corresponding to the Liberian (2,700 Ma), the Eburnean (2,000 Ma), the Kibaran (1,100 Ma), and the Pan-African cycles (600 Ma) (Lapworth et al 2017).

Fig. 2: Guinea upland as source of the River Niger through notable West Africa areas

Table 1: Groundwater roles in combating climate change pandemic

Groundwater systems

Provisioning services	Regulatory services	Supporting services	Cultural services
Domestic water	Buffering between wet and dry season periods	Springs	Mineral water
Agricultural water	Buffering the impacts of climate change	Baseflow of streams	Hotsprings
Industrial water	Reducing erosion and floods	Sustaining groundwater dependent wetlands and Phreatophytes	Sacred springs and wells
Recreation water	Buffering water chemistry and temperature	Sustaining subsurface life	Spiritual and healing values
	Water purification	Control of land surface stability	Leisure services

Its source of the river is in the Guinea Highlands (Fig. 2), South-eastern Guinea near the Sierra Leone border. It runs in a crescent shape through Mali, Niger (Fig. 2) on the border with Benin and then through Nigeria discharging through the Niger Delta into the Gulf of Guinea in the Atlantic Ocean. The river is the third-longest river in Africa, exceeded by the Nile and the Congo River.

1.3. Groundwater aquifer roles

Groundwater already plays a vital role in supporting food and energy security (Table 1), urban and (especially) rural settlements and industrial growth. It is an essential component for many healthily functioning ecosystems and offers exceptional prospects in terms of climate change cultural adaptation and mitigation. It plays 4 major roles in our society in mitigating climate change catastrophy (Ibrahim et al 2024a; Magesh et al 2021).

1.4. Aquifer resilience to climate change with Renewable Energy

In Nigeria, the utilization of groundwater as a viable source of irrigation of farmlands is still at its lowest ebb with farmers depending much more on rainfed irrigation system traced to lack of stakeholders assistance in drilling wells (deep or shallow) and affordable energy source to power such wells. Statistical record has shown that 87% of farmers are always waiting for rain that comes for just 3-4 months in recent years to have their planted crops irrigated with lots of destructive flooding tendencies on already cultivated farmlands.

This negative trend is just in the midst of abundant underground aquiferous water largely untapped and largely resilient to climate change especially in the rural areas where large food production takes place with abundant sunlight. A typical example is Kwara state under the Lower Niger River Basin Development Authority, Ilorin, where most farmlands are domiciled in Kwara North and Southern axes with attendant lack of irrigable water for the farmlands. This has caused severe strain on food security as most crops go bad without adequate irrigation infrastructure especially during the peak of dry season, where most river channels go dry to supply few existing dams. More recently, insecurity traced to banditry has also taken over notable farming areas and its reducing food output from the axes. Government and security agencies are currently battling hard to restore normalcy to affected communities as large farming population is already migrating out of these locations. Another major threat to food insecurity is high cost of diesel and gasoline with the current subsidy removal on the products. An estimated 67% of the irrigated area in India is currently served by groundwater (Shah, 2008) while in Nigeria less than 8% of such similar farmlands are served with irrigable underground water source. More importantly, Groundwater irrigation source has been instrumental to the success of the Green Revolution in India from the 1960s till date.

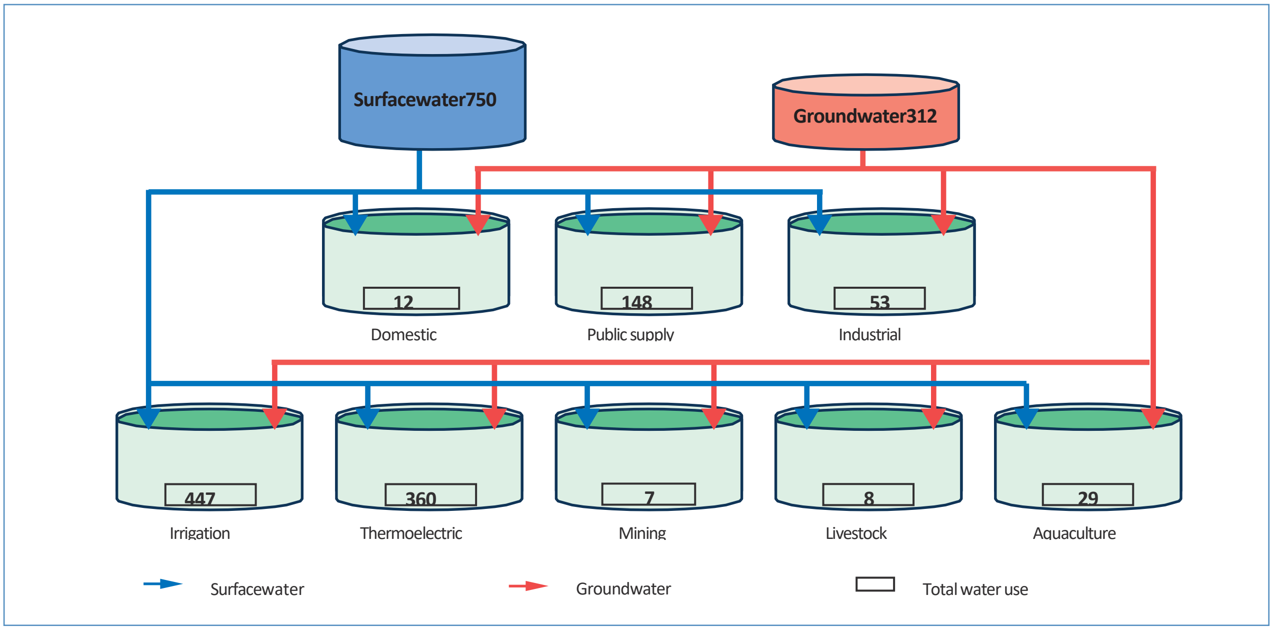

Fig. 3: Ground and surface water utilization potential across the river basins in Nigeria.

Groundwater abstraction and energy use are closely interrelated. Rural electrification has been a principal driver for groundwater development in India and most developing nations. Concentration of groundwater development is notable when rural power grids are extended into areas that would otherwise rely on diesel generation or wind energy, such as evidenced in Ethiopia, Kenya and South Africa (Villholth, 2013). Conversely, power utilities can face significant losses in revenue when declining groundwater levels and rising irrigation costs lead to diminishing pumping, as evidenced in the central USA. Nigeria blessed with abundant groundwater resources with vast amount of sunlight to power smart-irrigable groundwater will go a long way to mitigate the climate change effects on food security in the country.

The importance of groundwater as a vital buffer to the impacts of climate change, including not only droughts and increased ET (Fig. 3) but also more variable soil moisture and surface water, which is expected to increase in the coming decades. The 'green revolutions' in Asia have relied on the continued widespread use of shallow groundwater for dry-season irrigation by smallholder farmers and increased regional resilience to seasonal water availability. In tropical Africa there are growing calls (Cobbing, 2020) to draw from groundwater storage to improve the climate resilience of water and food supplies in pursuit of the SDGs 2, 6, and 13 among others. Adaptations to climate-driven shortages in water supplies to cities such as Dares Salaam (Tanzania) in 1997 and Cape Town (South Africa) in 2017 involved not only reductions in freshwater demand but also supply-side strategies that increasingly used groundwater as a climate-resilient source of freshwater that can be used collectively with surface water resources.

1.5. Managed aquifer recharge (MAR) strategies

Human responses to climate change employing groundwater-based adaptations include a range of managed aquifer recharge (MAR) strategies to augment freshwater availability with (Dillon et al. 2019). Categorization of the MAR strategies can be done in four broad branches: (a) streambed channel modification, (b) bank filtration, (c) water spreading and (d) recharge wells.

(A) Streambed channel modification

Streambed channel modification describes infrastructure such as small dams, ponds and tanks that detain surface runoff to supply drinking water and irrigation via directed infiltration, replenishing underlying aquifers. Application of this MAR strategy has a long history in hard-rock aquifers of Nigeria and alluvial plains of Nigeria and Rajasthan in northwest India (Dashora et al., 2018). Other examples include huge recharge dams in Oman that are operated in combination with water spreading in a series of connected recharge basins (Dillon et al., 2019).

(B) Bank filtration

Bank filtration refers to the process of enhancing infiltration of surface water through groundwater abstraction next to rivers and other surface water bodies so that the hydraulic gradient from surface water to the pumping well is increased (Dillon et al. 2019), the city of Budapest's water supply is sustained entirely by bank filtrate from the River Danube.

(C) Water Spreading

Spreading refers to the use of floodwaters to increase soil moisture for food production on dry cropping land. Water spreading projects employing flood discharges from the River Colorado in Arizona (USA) has shown increase in groundwater storage for dryland cities such as Phoenix and Tucson (Scanlon et al., 2006). In the Netherlands, treated river water from the Rhine is transported by pipeline to coastal dune areas where it is infiltrated as groundwater recharge in different basins.

(D) Recharge wells (aquifer storage and recovery, ASR)

Using recharge wells is the practice of injecting water into aquifers via wells which is often referred to as Aquifer Storage and Recovery (ASR) or Aquifer Storage Transfer and Recovery (ASTR) is gaining traction globally especially in northern Europe, seasonal (winter) surpluses in surface water collected in reservoirs are often transferred to shallow aquifers via injection wells to sustain anticipated increases in summer water demand. In coastal Bangladesh, the resilience of rural communities to increasing coastal salinity has been improved through the creation of freshwater lenses within shallow, partly saline, confined aquifers. This is achieved via the injection of seasonal pond water from flood discharges or rainwater harvested in wells under gravity drainage (Sultana et al., 2015). In Windhoek (Namibia), the resilience of the city's water supply to climate variability and change has been augmented through the transfer via injection wells of treated, seasonal surface water into the fractured quartzite aquifer system.

These are just few selected case studies globally among several others of groundwater mitigation strategy in combating climate change to address food security. In Nigeria, the utilization of these techniques to mitigate the climate problem is still at its lowest ebb, thus the need for stakeholders to look inward for ways to better add value to the underground water resources for the existence of humanity and to ameliorate climate change pandemic for sustainable food production.

2. DRIP IRRIGATION

2.1. Drip Irrigation Practice

Drip ie trickle irrigation is a type of micro-irrigation system that has the potential to save water and nutrients by allowing water to drip slowly to the roots of plants, either from above the soil surface or buried below the surface. The goal is to place water directly into the root zone and minimize evaporation linked to climate change. Drip irrigation systems distribute water through a network of valves, pipes, tubing and emitters (Fig. 4). Depending on how well designed, installed, maintained and operated, a drip irrigation system can be more efficient than other types of irrigation systems, such as surface irrigation or sprinkler irrigation. This irrigation technique is currently at its lowest ebb due to lack of proper utilization value it provides to combat and reduce the impacts of climate change to enhance food production.

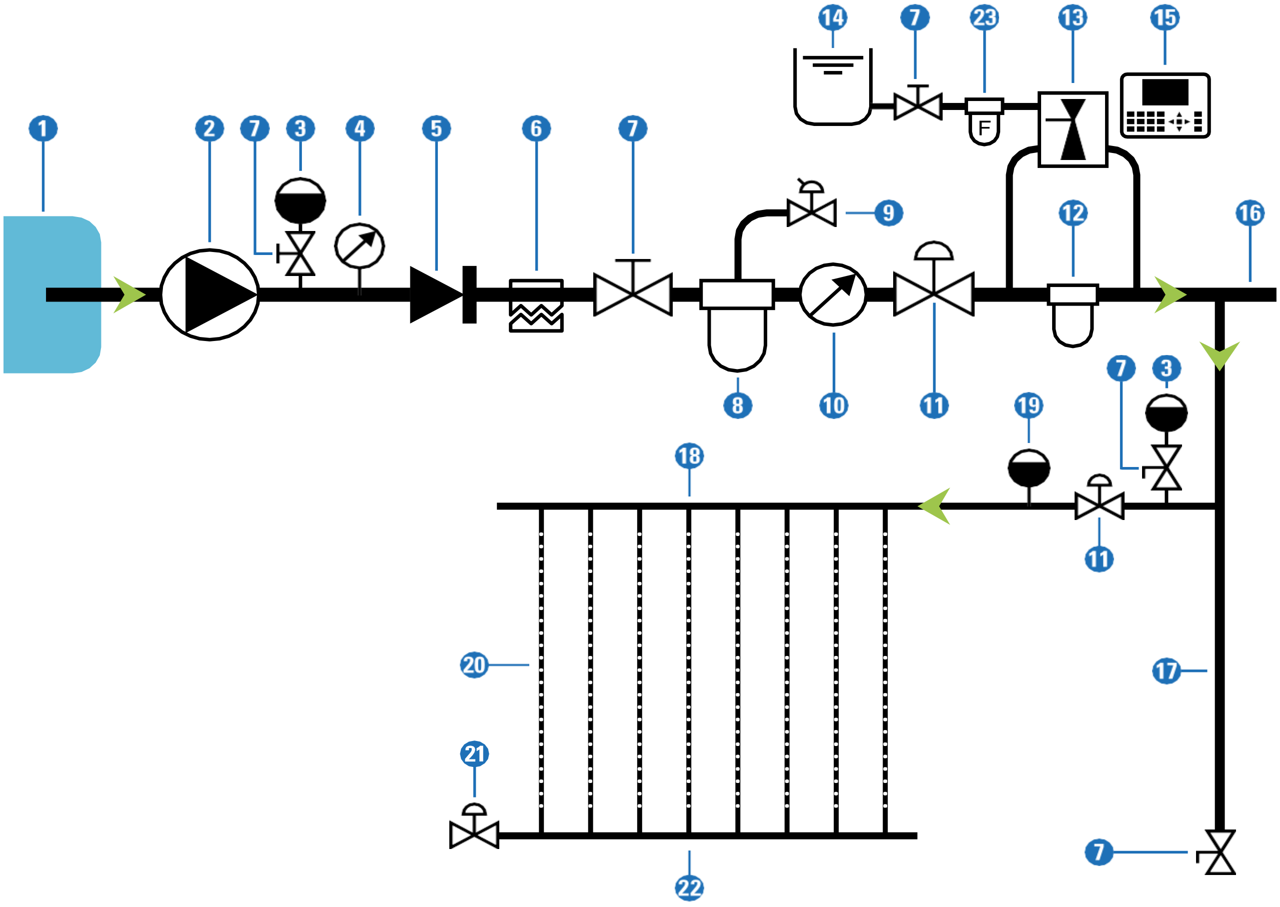

Fig. 4: Drip irrigation system and its functional components

① Water source ② Pumping station ③ Air valve ④ Pressure gauge ⑤ Check valve ⑥ Shock absorber ⑦ Manual valve ⑧ Main filtration unit ⑨ Main filtration automatic drainage valve ⑩ Water meter ⑪ Hydraulic valve ⑫ Secondary filtration unit ⑬ Dosing unit ⑭ Fertilizer tank ⑮ Irrigation controller ⑯ Main line ⑰ Sub-main line ⑱ Distribution line ⑲ Kinetic valve (vacuum breaker) ⑳ Dripperline ㉑ Flushing valve ㉒ Flushing manifold ㉓ Fertilizer filter

2.2. Structure of Drip irrigation system

A drip irrigation system is composed of many components (Figs. 4 and 5), each of which play an important role in the operation of the system. The structure of any irrigation scheme starts with the water source which is commonly surface (river) and groundwater sources to facilitate food security during the dry and rainy season. In essence, the article delves into the importance of groundwater to irrigate farmlands to ensure food security.

2.3. Maintenance of Drip Irrigation system

This entail inspecting the main, sub-main, distribution pipelines and dripperlines (Figs. 4 and 5) flushing manifolds for integrity, for leaks and for damage from agricultural machinery or from rodents and pests. Regular baseline readings and monitoring of flow, pressure and flush water condition will guide your maintenance scheduling. In addition to flow, pressure and condition of flush water, the overall condition of the pump station and distribution system, including control equipment engines, motors, reservoirs, injectors, pipelines, valves, fittings, flow meters and pressure gauges, should be routinely inspected and/or calibrated. Broken or dysfunctional equipment should be immediately repaired or replaced with the same or similar equipment that will perform the same function according to system design criteria. The maintenance is composed of the following

a) Visually inspect the pump for integrity and for leaks from its impeller chamber, inlet, outlet pipes and accessories.
b) Make sure the pump and its immediate environment are clean and free of any unrelated objects that might obstruct proper aeration of the pump's motor or block accessibility for maintenance.
c) Check the screen at the pump's inlet for clogging and rust.
d) Make sure the electrical supply to the pump is properly isolated and protected from moisture.
e) Make sure the pump starts smoothly (In the long term, start up vibrations might damage the pump).
f) Check that the pump sounds as usual, free of hiss or irregularity that might suggest stress or a mechanical problem within the pump.
g) Check the flow rate and the pressure at the pump's outlet and compare the results to the benchmark data

Table 2: Flushing frequency of drip irrigation system

Flushing frequency is too high	Flushing frequency is too low	Automatic flushing is not triggered
• The filtration unit or medium remains clogged after flushing. • The pressure range is incorrectly set in the controller. • Faults in automation or sensor.	• The filtration unit or medium is breached or leaking. • Faults in automation or sensor. • Mechanical failure.	• Faults in automation or sensor. • Mechanical failure.

2.4. Filter Precautionary steps

The maintenance of the filter must cause a loss of pressure in the system while filtering. This loss of pressure is demonstrated by the pressure differential across the filter (between the inlet and the outlet of the filter/filtration array). Most filters (Fig. 5 and Table 2) are subject to an increasingly higher pressure differential between inlet and outlet due to friction as the filter becomes clogged. Monitor the filter pressure differential frequently, especially as water conditions change in the course of the season. The pressure differential in a filter might be higher than the allowed maximum due to the development of biofilm, scale or mineral sedimentation in the filter. The pressure differential in a filter might be lower (Table 2) than the allowed minimum due to poor operation and maintenance practices or improper calibration of the automatic flushing control unit.

Table 3: Filter Gravel or sand, screen and disc of drip irrigation system

Filter	Higher than the maximum	Lower than the minimum
Gravel/sand	Partial or total clogging of medium	Tunnels in the medium or breakage and loss of medium
Screen	Screen clogging	Screen ripping or bursts through the screen (meat grinder)
Disc	Clogging of filtration grooves	Leakage through discs due to solids trapped between the discs (preventing the discs from being pressed closetogether and causing gaps in the disc array)

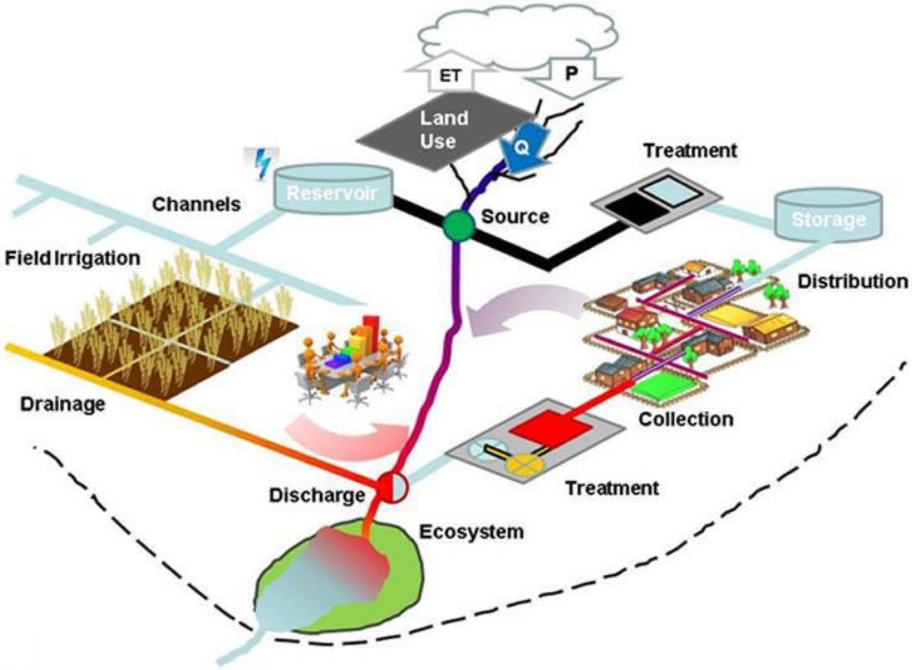

Fig. 5: Modern Drip field irrigation system that is climate resilient

The filter might lose some (Fig. 7 and Table 3) gravel/sand during the back-flush cycles, so even if the filter is in proper working order, it may require additional gravel/sand from time to time. While flushing, its good to check the water at the filter's drainage exit by touch to detect loss of gravel/sand medium. Take the screen out of the filter casing and clean it with pressurized water and brushes and visually inspect the screen for breaches, cracks and replace the screen if damaged. Open the filter's casing and release the piston holding the discs pressed close together. Take the discs out of the filter casing and thread the discs on an acid-resistant rope and tie the ends of the rope to form a loop (Fig. 6). Do not thread too many discs on one loop; it is important that the cleaning solution reaches all the disc surfaces. Lastly, it's good to soak the discs in this solution making sure the discs are loose and have good contact on both sides with the solution.

2.5. Drip irrigation system flushing

Filters whether disc, screen or media should be back-flushed periodically to clear out any precipitate of particulate or organic matter (Figs. 6 and 8). Clogged filters can reduce pressure to the system, lowering the water application rate. The filter's performance depends on the efficiency of its flushing and cleaning. Any accumulation of non-disposed material will eventually lead either to clogging of the filter or in a gravel/sand filter to the release of the filtering material along with the filtered water during irrigation. Many filter systems are automated and will self-clean via an electric or hydraulic 3-way back-flush valve when a pre-set filter pressure differential is reached.

2.6. Flushing of the irrigation system include the following 3 processes:

- Filter back-flushing
- Flushing main and sub-main lines
- Flushing dripperlines

Filter Flushing is performed during the filter's current operation. The automatic valve opens the drainage outlet which creates suction in the flushing axis. The motor rotates the flushing axis and moves it back and forth, drawing the dirt from the entire inside surface of the filtration screen (Figs. 7 and 8).

During current operation, the piston at the top of all the filters in the array holds the discs pressed close together. All the automatic inlet valves are open and the drainage valves are close. Water flows through the disks into the irrigation line.

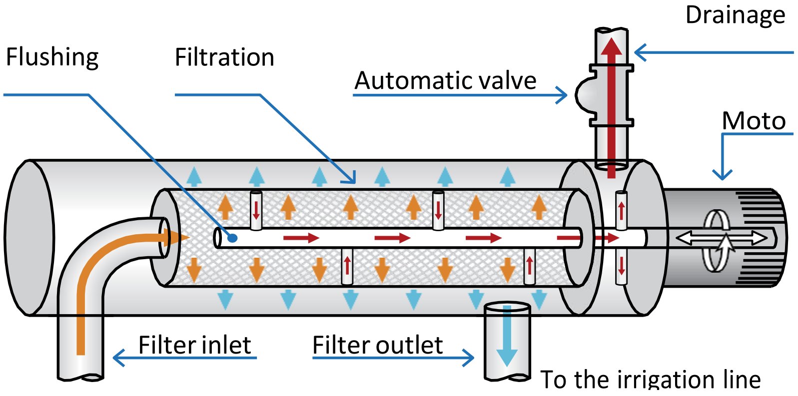

Fig. 6: The typical flushing mechanism during Drip irrigation

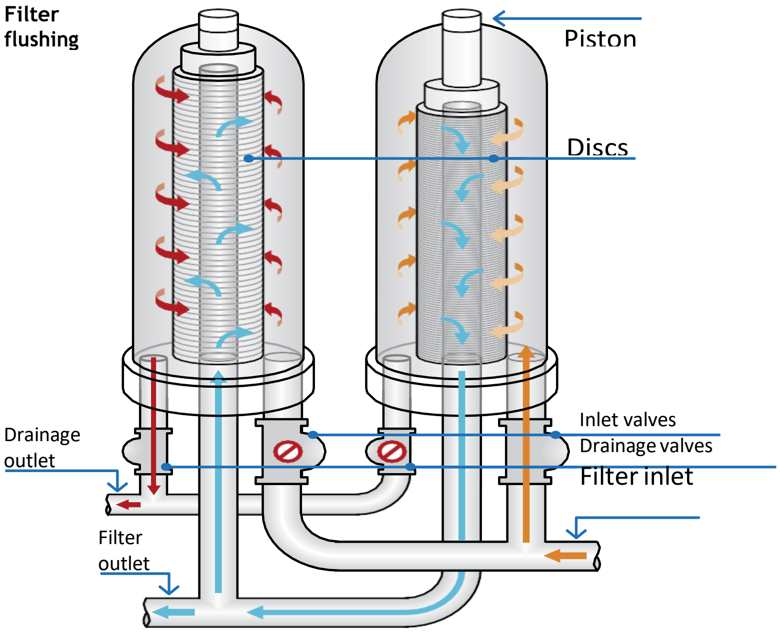

Fig. 7: Pistons position to pick up groove dirts during drip irrigation flushing

When filter flushing is performed, the automatic 3-way valve (Fig. 8) of one of the filters opens the drainage outlet while blocking the water inlet to the filter. The opened drainage outlet creates a pressure differential across the filter, allowing water to flow into the filter through its outlet and out of the drainage outlet, back-flushing the filter's gravel/sand medium. Gravel and sand filters in an array are flushed in such sequence.

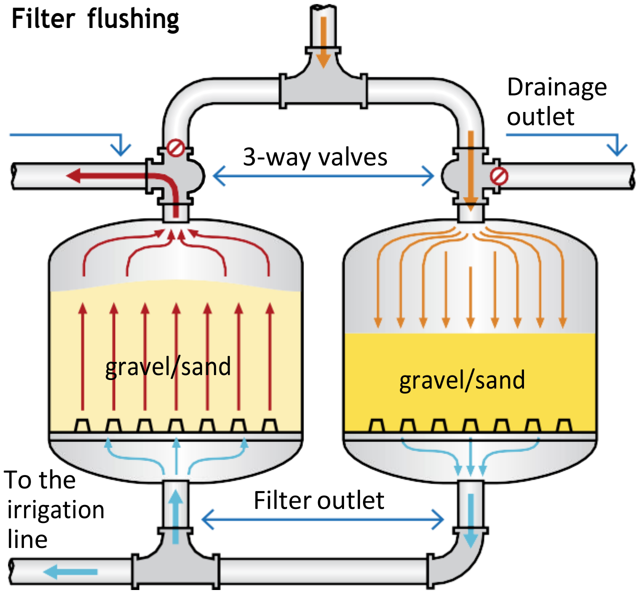

Fig. 8: 3 way valves connected to the main irrigation line

2.6. Main, sub-main and distribution line flushing

Flushing the main, sub-main and distribution lines will considerably reduce the accumulation of organic and mineral materials in the system. This will prevent those materials from reaching the drippers and eventually clogging them, thus minimizing the quantity of chemical products required to maintain the system. Regular flushing of the main, sub-main and distribution lines will result in a significant saving of labor, time and chemicals. The main, sub-main and distribution lines in the system should be flushed in sequence. Each one of them should be flushed for at least two minutes or until the flushed water runs clear. The process consists of the process of flushing the main, sub-main and distribution lines with two waves for each cycle:

- The first wave removes contaminants collected at the end of the pipe.
- The second wave removes contaminants from the pipe.

The color of the water will not be as dark as in the first wave, but the process takes more time. Flushing must be continued until the water is visually clean and crystal clear for the irrigation purpose.

2.7. Flushing the dripperlines

Dripperlines in both surface and SDI systems require periodic flushing to purge them of settled debris, organic or mineral and of any residues of chemicals injected into the system. Dripperline flushing must be given high priority since frequent dripperline replacement is impractical and dripperlines are expected to last up to 20 years or even longer (Tables 4 and 5). Even for short-term dripperline use, flushing is important to maintain irrigation uniformity. Flushing should be performed as often as needed to keep the dripperlines clean; this depends on seasonal water quality and the effectiveness of the system filter. All the dripperlines in a plot should be flushed in sequence in a single flushing event. Dripperlines should be flushed (Tables 4 and 5) until the flushed water runs clear. Flushed water should be disposed of properly to avoid deteriorating the system's inlet water quality and/or the quality of the environment surrounding the site. The flow rate is commonly a function of the thickness of the dripperline wall (Tables 4 and 5).

Calculating flow velocity in the dripperline pipes (V)

Velocity (speed) is the distance water passes in one unit of time in a pipe (meters per second)

$V = (Q / A) / 3600$

V = Velocity (m/sec)

Q = Flow rate ($m3/h$)

A = Area of the pipe inside cross-section (m^2)
3600 = Constant for conversion of the result from m/h to m/sec

The flow rate in a dripperline or indeed any pipe with no outlets is constant throughout the length of the pipe, and is independent of the pipe's diameter or of the area of the pipe's cross section. If the pipe's cross-section changes, the flow velocity changes accordingly, but the flow rate remains constant.

Consequently: $Q = A1 * V1 = A2 * V2 = A3 * V3 = \text{constant}$

Calculating the advancement time in a pipe

The time it takes for water to pass the length of a pipe segment (seconds).

At = L / V •
At = Advancement time (sec)
V = Velocity (m/sec)
L = Length of pipe segment (m)

Table 4: Dripperline models, specification and their corresponding properties

Dripperline model	Pipe's outside diameter (OD) (mm)*	Wall thickness		Max. working pressure (bar)	Max. flushing pressure (bar)
		(mm)	(mil)		
12010	12	1.00	39.0	3.5	4.6
16009	16	0.90	35.0	3.0	3.9
16010	16	1.00	39.0	3.5	4.6
16012	16	1.20	47.0	4.0	5.2
17012	17	1.20	47.0	4.0	5.2
20010	20	1.00	39.0	3.5	4.6
20012	20	1.20	47.0	4.0	5.2
23009	23	0.90	35.0	3.0	3.5
23010	23	1.00	39.0	3.0	3.5

Table 5: Dripperline models, specification and their corresponding properties (Contd).

Dripperline model	Pipe's inside diameter (ID) (mm)*	Wall thickness		Max. working pressure (bar)	Max. flushing pressure (bar)
		(mm)	(mil)		
12200	12	0.50	20.0	3.0	3.5
12250	12	0.63	25.0	3.5	4.6
16200	16	0.50	20.0	2.5	3.3
16250	16	0.63	25.0	2.8	3.6
16007	16	0.70	27.0	2.9	3.8
16008	16	0.80	32.0	3.0	3.9
22250	22	0.63	25.0	2.5	2.9

3. CASE STUDIES

3.1. Case studies in Nigeria

The average annual rainfall ranges from about 500mm in the north to over 2,000mm in the south. Uneven distribution of rainfall across Nigeria reflects a significant variation in the surplus when viewing different parts of the country. This rainfall distribution generates the arid and semi-arid conditions of the north, the wet south and the coastal aquifer environments of Nigeria. With consideration of the hydrologic cycle, each of these four major environments has their hydrological challenges. While the northern part of Nigeria is dominated by the problems of aridity–semi-aridity, which limits the volume of water available for recharge to the aquifers, the south is saddled with the problems of flooded terrains, saltwater intrusion, environmental and ground degradation due to the activities of the petroleum exploration and production activities (Shanono et al 2022).

3.2. Groundwater potential in Nigeria

Sedimentary terrains of Nigeria possess more groundwater potential than the established basement complex areas (Maduabuchi, 2004), (Ibrahim et al. 2024b) and various empirical figures which suggest high groundwater resources potential for Nigeria has been published. The nation's groundwater resource is abundant and of good quality and estimated at 52,000MCM out of which the sedimentary basins groundwater potential account for 67% (Tables 6 and 7).

Table 6: Groundwater potential across different zones of Nigeria

GPZ	N-W	N-E	N-C	S-S	S-W	S-E	TOTAL
URBAN GROUNDWATER SUPPLY							
Projected demand	1010	010 1	827 2	423 1	510 7	656 3	649 18
Actual supply capacity	250	344	516	161	988	379	2639
Deficit capacity	770 1	491 1	909 1	348 6	668 3	269 15	486
RURAL GROUNDWATER SUPPLY							
Projected demand	640	1069	705	909	916	1058	5197
Actual supply capacity	24	34	18	21	24	17	138
Deficit capacity	616	1035	687	888	792	1041	5059
TOTAL							
Projected demand	1	650 2	896 3	128 2	419 8	472 4	707 23
Actual supply capacity	275	378	534	182	1012	396	2777
Deficit capacity	1	386 2	525 2	597 2	236 7	460 4	310 20

The occurrence of groundwater is greatly influenced by the local geological conditions which ultimately control yield. The geological distribution of Nigeria is divided according to geology, river tributaries (Figs 9 and 10), basin aquifer occurrence and nature (Tables 6 and 7). Nigeria is located within the West African subcontinent, south of the Sahara, with the Atlantic Ocean bordering the southern coastal region (Fig.1). Geologically, Nigeria is made up of two major rock types ie Basement complex and Sedimentary formation. In the northern arid and semi-arid areas of the country, its greatly underlain by more basement crystalline rocks, groundwater is moderate with some areas known for good water potential. Also, exploration for water becomes more challenging in topographically rugged terrains of high relief. Such areas include Sokoto, Zamfara, Kastina, Kano, Kaduna, Niger, Adamawa, Bauchi, Bornu South, Taraba and Gombe states (Fig.10). Other semi-arid regions include Plateau, Nasarawa, Federal Capital Territory, Kogi, Kwara and Benue States that form the north-central Nigeria (Fig. 10). Other basement complex areas in the south-western and eastern Nigeria include parts of Oyo, Ondo, Osun, Ogun and Edo North. Groundwater production ranges between 0.6-15.1liters/second in this area with vast and extensive aquiferous fractures and microfractures.

Groundwater utilization in Nigeria for socio-economic activities including agricultural irrigation scheme is inevitable because most dams built to pump surface water hardly sustain 5% of the inhabitants for domestic, industrial or agricultural functions (Muhammed and Ibrahim 2025). Studies have also shown that most constructed dams also collapse in no time to construction date due to heavy downpour of rain, lack of technical knowledge of consultants, poor supervision, utilization of sub-standard construction materials and more importantly, infrastructural decay to pump such water (Shanono et al 2020 and 2022). Furthermore, the south-southern part of Nigeria form a large and extensive sedimentary aquiferous zones for groundwater production grossly untapped. In essence, states like Rivers, Bayelsa, Delta, Cross-River, Akwa-Ibom, Edo and some south-eastern part of Imo form excellent groundwater potential with the yield ranging between 0.9-4.1 liters/second production capacity.

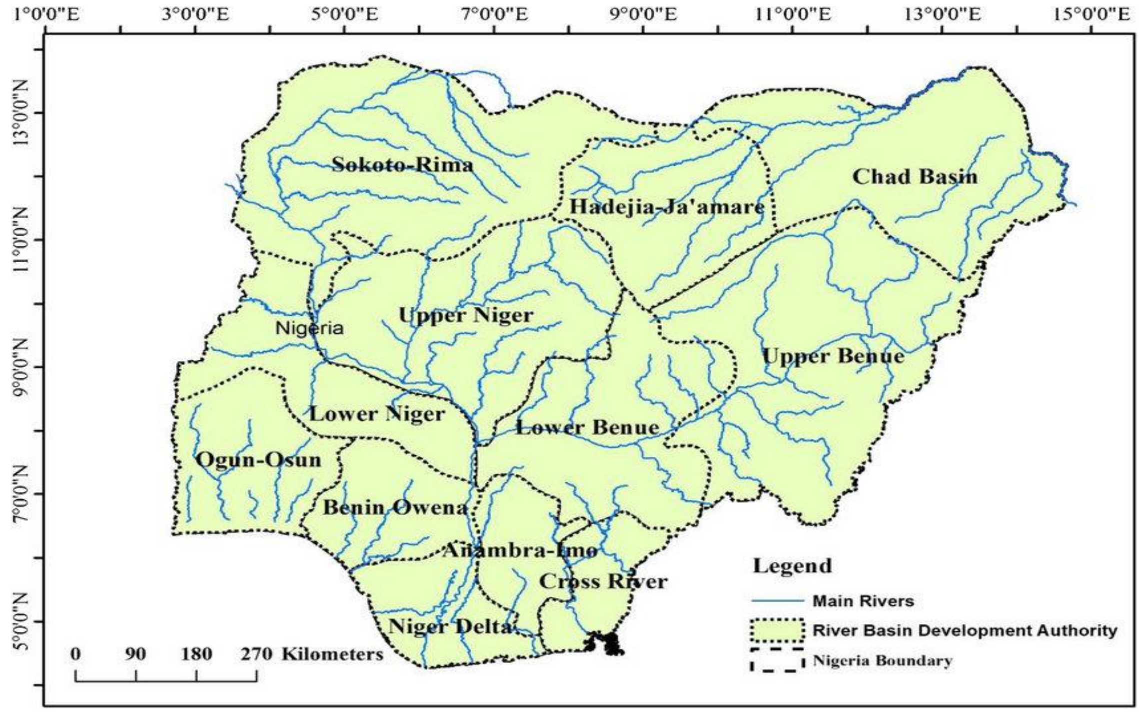

Fig. 9: Main Rivers and River Basin Development Authority Areas in Nigeria

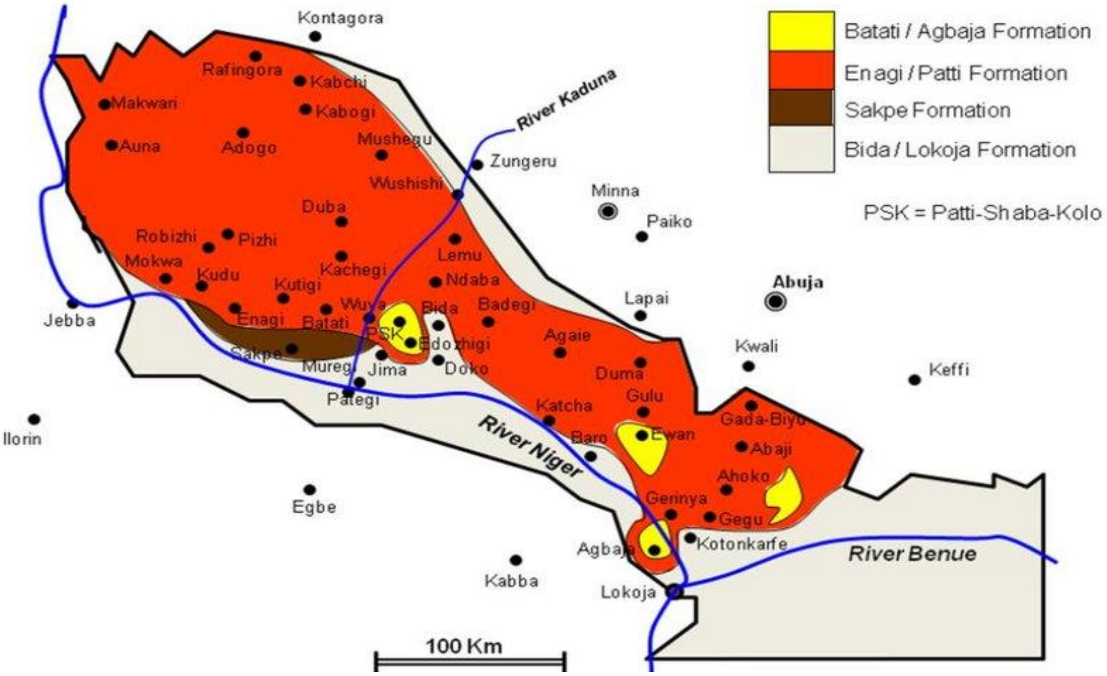

Fig. 10: Diagram showing River Niger and Benue with numerous tributaries

3.3 Aquifers across the River Basins in Nigerian states

Hydrogeological characteristics of Nigerian state has shown 27 major aquifers with much more minor ones across all states and River Basins. The Alluvium is the largest aquifer system covering over 26% of the country's area, followed by Basalt (14.12%), Banded Gneissic Complex (12.09%), Sandstone (23.21%), Shale (7.11%), Gneiss (4.08%), Schist (3.33%), Granite (3.18%), Charnockite (3.41%), Limestone (2.54%), Quartzite (1.48%), Laterite (2.29%) systems. The distribution of the principal aquifer systems over Nigeria and across its 12 river basin development areas is expected to contribute greatly to the development and exploitation of such groundwater to mitigate the climate change pandemic and strengthen food security in the nation. The Alluvium aquifers cover a major portion of the states thus the river basins with the major sources of recharge of these aquifers being the river Niger, river Benue (Fig. 10) and their numerous tributaries.

3.4. Chad River Basin

The Bima Sandstone which is the main aquifer of the area is the lateral equivalent of the regional Nubian Sandstone which is the target aquifer unit in Niger, Chad, Sudan, Libya and Algeria. It is the deeper part of the aquifer series in the Nigerian sector of the basin and rests unconformably on the basement producing groundwater of about 0.9-3.4 l/sec in most places. The thickness ranges from 300 m to 2,000 m and the depth between 2,700 and 4,600 m. The Plio-Pleistocene Chad Formation and the younger overlying Quaternary sediments are the main source of groundwater in the Nigerian sector of the Chad Basin. The stratigraphy consists of sediments accumulations dated from Paleozoic (dominantly arenaceous), Lower Cretaceous (Continental Intercalaire arenaceous), Middle Cretaceous (marine limestones), Continental Hamadien (equivalent of the Continental Intercalaire),

Upper Cretaceous (continental sandstones), Continental Terminal (lacustrine and deltaic types of sediments dated Mio-Pliocene) lying unconformably on the Upper Cretaceous and the basement complex. The Chad Basin in the Nigerian sector shows a depositional sequence from top to bottom: Quaternary, Early Pliocene, Continental Terminal, Gombe Sandstone, Fika Shale, and Gongila, Yolde and Bima Sandstones Formations (Maduabuchi et al. 2004). The transmissivity ranges from 0.6 to 8.3 liters/sec and the aquifer which recharges from rainfall and run-off of river Niger is mainly used for domestic water supply (hand dug wells and shallow boreholes), vegetable growing and livestock watering.

3.5. Hadeja-Jama'are River Basin

The Hadeja-Jama'are River System (H-JRS) is part of the larger basin known as Komadugu Yobe River Basin. It is situated in the semi-arid northern part of Nigeria. The two major rivers of the H-JRS (Hadejia and Jama'are) meet in the Hadejia-Nguru Wetlands (HNWs) to form the Yobe. The Hadejia take its source from the Kano highlands while the Jama'are takes its source from the Jos plateau. Apart from Tiga and Challawa gorge dams, other large-scale water resources management and irrigation projects are the Kano River Irrigation Project (KRIP), Hadejia Valley Irrigation Project (HVIP) and the Hadejia Nguru Wetlands (HNW) Conservation Project, which is the most extensive flood-plain area in the basin. In addition to the ecological richness of the wetlands, the HNW also serve as groundwater recharge zones largely untapped. The mean annual rainfall ranges from about 1100 mm in the upstream basement complex area, to about 400 mm in the middle part of the basin and less than 300 mm near Lake Chad.

In the Hadeja-Jama'are river basin area irrigation project, the utilization of the project is just 50% while the Zobe dam in Dutsin-Ma, Katsina which was constructed 40 years ago, currently has few irrigation activities as the scheme is not formally developed, The area cultivated is not commensurate with the amount of water in the dam. For instance, at the end of the 1999/2000 irrigation season, out of the 100,300 ha developed only 35,000 ha were irrigated giving a pathetic 65% capacity not utilized. This is a clear indicator of the need of harnessing the groundwater potential to supplement the surface water source for irrigation of cultivated farmlands. Consequence of these cases highlighted by previous workers include the danger of poor irrigation, poor management and institutional performance. More than 29% of the farmers of Tomas Irrigation Project (TIP) expressed unhappiness with the water allocation method currently used and about 55% of water users hold the opinion that irrigation scheme management, operation and maintenance is an exclusive responsibility of the government notably the River Basins not theirs. In addition to poor water management, infrastructural decay and stakeholders' conflict are identified major problem affecting the scheme. A study (Abdullateef et al 2021) titled: Assessment of groundwater recharge potential in a typical geological transition zone in Bauchi, NE-Nigeria made it clear the importance of groundwater to humanity. The fact was affirmed in another study (Bayero 2019) in his Masters unpublished thesis. The socio-economic challenges of irrigation farming along River Yobe (Mohammeed and Ali 2021) has shown there is need for groundwater to supplement surface water production.

In the Hadeja-Jama'are river irrigation project, the utilization of groundwater to supplement the surface dam water is inevitable because of its large irrigable potential that can produce large amount of food for the country. Moreso, climate smart irrigation system can be adopted as a resilient measure that will encourage dry season farming in Nigeria. The country is in dire need of food security due to the ever increasing population and its now obvious that rain-fed agricultural technique is no longer sustainable for the country. More than 29% of the farmers of Tomas Irrigation Project (TIP) also expressed unhappiness with the water allocation method currently used and about 55% of water users hold the opinion that irrigation scheme management, operation and maintenance is an exclusive responsibility of the government. In addition to poor water management, infrastructural decay and stakeholders' conflict are other major problems affecting the scheme. The majority of irrigation schemes in northern Nigeria are characterized by environmental degradation such as salinity. Both quantity and quality aspects of water are important as these jointly affect the success of irrigation schemes and environmental sustainability (Mohammed and Ibrahim 2015). Thus, in the process to establish any socio-economic projects such as irrigation schemes, there is a need to ensure long-term maintenance of valued environmental resources in an evolving human influence. Notable aquifers for groundwater production in the area include Aluvium sand, weathered granite, sandstone with some Charnockite with water production capacity as high as 3.1 liters/sec.

3.6 Sokoto River Basin

The Sokoto-Rima river Basin of northwestern Nigeria lies in the sub-Saharan Sudan belt of west Africa and in a zone of savannah-type vegetation. Rainfall is averaging about 30 inches annually in much of the river basin and occurs chiefly in a wet season which lasts from May to October. A prolonged dry season extending from October to April is dominated by dusty harmattan winds from the northeast. April and May are the hottest months, when temperature occasionally reach 105°C. Flow in streams of the Sokoto Basin is mostly overland runoff. Only in a few reaches, fed by ground-water discharge from the sedimentary rocks are perennial streams. In the River Zamfara basin, groundwater discharge contributes almost 1 inch of the average 3.33 inches of total annual runoff. In the vicinity of Sokoto, the River Rima flows throughout the year sustained by spring discharge from perched ground water in the limestone of the Kalambaina Formation. On the crystalline terrain where most of the streams rise, total annual runoff may exceed 5 inches, very little of which is ground-water discharge. The sedimentary rocks of the basin range in age from Cretaceous to Tertiary and are composed mostly of interbedded sand, clay, and some limestone; the beds dip gently toward the northwest. Alluvium of Quaternary age underlies the lowlands of the River Sokoto (now Sokoto) and its principal tributaries with an average groundwater production capacities that ranges from 0.9-1.3liters/seconds. These rocks contain three important artesian aquifers in addition to regional unconfined ground-water bodies in all the principal outcrop areas and a perched water body in the outcrop of the Kalambaina Formation which can be tapped for groundwater production. Identification of linear features was done using filters in the area (Abdulsalam et al 2011).

Artesian aquifers occur at depth in the Gundumi Formation, the Rima Group, and the Gwandu Formation and are separated from one another by clay beds in the lower part of the Rima Group and the Dange Formation. In outcrop, clay in the Dange Formation also supports the perched water of the Kalambaina Formation. The Gundumi Formation, resting on the basement complex, is composed of varicolored clay, sand, gravel and attains a thickness of 800 to 1,000 feet in its downdip extensions. Most of the formation is thin bedded and clayey and therefore does not yield large quantities of water to boreholes; the average yield is 2,700 gph (gallons per hour). (All gallons are imperial gallons) Nevertheless, the upper part of the formation is sandy and more permeable and forms a regional artesian aquifer from which yields of as much as 6,600 gph are obtained from single boreholes. Clay in the lower part of the Rima Group confines the Gundumi aquifer downdip, so that at Rabah and Sokoto, for example, in the River Sokoto fadama (valley floor), artesian flow is found in boreholes screened in the Gundumi areas with production as much as 2.1liters/seconds.

Aquifer tests indicate low transmissivities, ranging from 300 to 5,000 gpd per ft (gallons per day per foot) in the lower part of the Gundumi Formation; but in the upper sandy zone the transmissivities are much higher, reaching 66,000 gallon per day per. In the western part of the Sokoto Basin, more productive aquifers with higher heads usually lie above the Gundumi aquifer so that it is not attractive for development, except in the River Sokoto fadama where artesian flow is possible. Also, at the Bakolori irrigation dam in Zamfara State, under the Sokoto Rima Water Project, the area cultivated is not commensurate with the amount of water in the dam. Aquifers that can support the exploitation of underground water include Limestone, sand, shale and Quartzite with production capacity as high as 2.1 liters/seconds.

3.7. Upper Niger River Basin

The Mid-Niger Basin otherwise known as the Bida Basin or the Nupe Basin is a NW-SE trending intracratonic sedimentary basin extending from Kontagora in Niger State of Nigeria to areas slightly beyond to areas like Kwara North and Lokoja in the south (Ibrahim et al 2025). It is delimited in the northeast and southwest by the basement complex while it merges with Anambra and Sokoto basins in sedimentary fill comprising post orogenic molasse facies and a few thin unfolded marine sediments with abundant groundwater production capacity that ranges from 0.9-1.7 liters/seconds. The basin is a gently down-warped trough whose genesis may be closely connected with the Santonian orogenic movements of southeastern Nigeria and the Benue valley.

The Bida Sandstone is divisible into two members, namely the Doko Member and the Jika Member. The Doko Member is the basal unit and consists mainly of very poorly sorted pebbly arkoses, sub-arkoses and quartzose sandstones with water yield of approximately 0.8 liters/sec. These are thought to have been deposited in a braided alluvial fan setting. The Jima Member is dominated by cross-stratified quartzose sandstones, siltstones and claystones. Trace fossils comprising mainly Ophiomorpha burrows have been observed. Lithologic units (Lokoja formation of southern Bida basin) range from conglomerates, coarse to fine grained sandstones, siltstones and claystones in the Lokoja area. Subangular to subrounded cobbles, pebbles and granule sized quartz grains in the units are frequently distributed in a clay matrix. Both grain supported and matrix supported conglomerates form recognizable beds at the base of distinct cycles at outcrop. The sandstone units are frequently cross-stratified, generally poorly sorted and composed mainly of quartz plus feldspar and are texturally and mineralogically immature, thus, supports groundwater production as they constitute good aquiferous potential in the area with groundwater production capacity of about 1.9 to 2.3 liters/sec. The major aquifers contained in this River basin area are Sandstone, claystone, siltstone and Gneise with several minor fractures that constitute other aquifers.

Table 7: 12 River Basin Development Areas and distinct aquiferous properties in Nigeria (Ibrahim et al 2025).

S/N	River Basins Authority	Coverage areas	Total Land Area (Km^2)	Aquifer rock types	Production capacity (L/secs)
1	Anambra-Imo River Basin	Anambra, Imo, Enugu, Kogi N, Abia and Ebonyi.	26,460	Black shales, limestone, siltsones, regressive sandstones @ alluvial sand	2.3-5.1
2	Niger Delta River Basin	Rivers, Bayelsa and parts of Delta.	21,765	Gravel, alluvium and unconsolidated sand	1.6 to 4.1
3	Benin-Owena River Basin	Edo, Delta North, Ondo and Ekiti.	46,300	Sandstone, shale, Quartzite, Alluvium, basalt and Banded Gneissic Complex	1.1-3.6
4	Ogun-Osun River Basin	Lagos, Oyo, Ogun and Osun	58,237	Limestone, sandstone, shale, Basalt and Banded Gneissic Complex.	0.7 to 3.1
5	Chad Basin Development Authority	Borno, Yobe and Adamawa part	152,156	Sandstone, Aluvium, granite and Schists	0.9-3.4
6	Hadejia-Jama'are River Basin Development Authority	Kano, Jigawa and Bauchi	89,230	Aluvium, weathered granite, Bauchite, sandstone.	0.6-3.1
7	Cross River Basin Development Authority	Cross-River and Akwa-Ibom	29,570	Alluvium, Phylites, Schists, Gneisses and Amphibolites	0.9 to 3.6
8	Lower Benue River Basin Development Authority	Benue, Plateau and Nasarawa	71,970	Gneiss, Schist, Granite, Charnockite and Limestone.	0.98 to 3.51
9	Lower Niger River Basin Development Authority	Kwara and Part of Kogi	48,908	Gneisses, migmatities, metasediments i.e schists, quartzites	0.9 to 4.1
10	Upper Niger River Basin Development	Niger, Kaduna and FCT	123,470	Sandstone, claystone, siltstone and Gneise	1.9-2.3

	Authority				
11	Sokoto Rima River Basin Development Authority	Katsina, Zamfara, Sokoto and Kebbi	126,104	Sand, Limestone, Shale and Quartzite. Banded gneiss complex	0.8-2.1
12	Upper Benue River Basin Development Authority	Adamwa, Taraba, Gombe and Bauchii	127,908	Alluvium, Bauchite, pegmatite, Basalt, Granite, sandstone @ Banded Gneissic Complex	0.8 to 4.1

3.8. Ogun-Oshun River Basin

The Dahomey River Basin is a combination of inland/coastal/offshore basin that stretches from southeastern Ghana through Togo and the Republic of Benin to southwestern Nigeria, as it is commonly referred to as Ogun-Oshun river basin with its vast water collection point of the area. It is separated from the Niger Delta by a subsurface basement high referred to as the Okitipupa Ridge. Its offshore extent is poorly defined till date. Sediment deposition follows an east-west trend. In the Republic of Benin, the geology is fairly well known. Groundwater production in this Nigerian river basin varies greatly from areas and among adjoining states of south-western Nigeria. Production capacities ranges from 0.7 to 3.1 liters per second.

Sedimentation in the northern zone which is located inland and close to the basin periphery began during the Maastrichtian when a thin sequence (<200 m) of unconsolidated sands, grits, silts, clays and shales were deposited. This sequence rests on the basement; the transitional facies is marked by a basal conglomerate or white to grey sandy and kaolinitic clays derived as degradation products from the surrounding Precambrian rocks. In the southern zone, which is coastal and offshore, the oldest sediments consist mainly of loose sand, grits, sandstones and clay with shale interbeds which progressively grade into shale. They are late Albian and possibly Neocomian in age. It consist of an extensive deposit of limestone, sandstone, shale, Basalt and Banded Gneissic Complex that serve as the aquiferous rocks in that basin area.

3.9. Lower Benue River Basin

The Benue river valley is believed to have been formed as a result of the failure of the Benue arm to continue opening at the beginning of the Cretaceous when Gondwana land started breaking up (Benkhelil, 1989). The valley was therefore filled up with both continental and marine sediments which have all experienced extensive brittle and ductile deformational events giving rise to extensive folding, faulting and jointing along the entire length of the valley with groundwater potential reaching about 3.89 liters/sec. The river is a typical plain river with low slope, a wide flow variation and a sandy bed over pre-existing sandstone through its entire length. Its width is variable and its narrowest bed is in Yola, near the border of Cameroun Republic with a width of approximately 780m to 1,000m in Lokoja. From the morphological point of view Wuroboki to Makurdi, may be classified as a meandering river, with many islands, some of which are the results of previous changes in the course of the river.

The Benue trough is an elongate sedimentary basin, over 800km long and 100–120 km wide. It has a general NE-SW trend and extends from the Niger Delta Basin to the southern margin of Lake Chad Basin. In its upper part, the basin bifurcates into a N–S trending arm (Gongola arm) and an E–W trending arm (Yola arm). The sedimentary infilling contains marine and continental deposits (Albian- Maestrichtian age). The Benue River Basin between the International border with Cameroon and Lokoja is classified as hydrological area III and IV in the Nigerian drainage system classification, covering 98.0 x 103 sq km at the International border of Cameroun and drainage area of 338.2x103 sq km at Lokoja and gross surface water potential of $108.10x10^{9}m^{3}$/year (Adebola et al 2018). The groundwater production aquiferous potential include Gneiss, Schist, Granite, Charnockite and Limestone. Groundwater production is high and ranges between 0.98 to 3.51 liters/second.

3.10. Anambra-Imo River Basin

The extent and distribution of groundwater within the basin area is primarily controlled by lithology and other secondary factors, including topography and nearness to the source of recharge (Nfor et al. 2007). The geology of the aquifer at Awka and Nise, both in Awka South LGA of Anambra State, is the Ebenebe Sandstone which is the lower member of the Imo Formation. However, it has been noted that the Imo Formation constitutes a poor aquifer due to its sedimentological characteristics. Within most basin areas, sustainable water production is only carried out by drilling beyond the over 150 m thick pile of shale in the Imo Formation into the underlying aquiferous Ajali Sandstone (Nfor et al. 2007), especially at Ifite, Amansea, Ezeozu, and some other places. The major problem with drilling more than about 30 m at Ifite-Awka after encountering the water table (underlying aquiferous Ajali Sandstone), is the high probability (about 98%) of having iron content in the water, which on exposure to fresh air, leads to changes in the colour of the water to reddish-brown, hence unfit for human consumption. This portrays the overriding influence of lithology on groundwater distribution in the basin area. At Nimo, the core source of water for the area is the Nanka Formation. The Nanka Formation dips gently away from the water divide that runs from the north to the south of Anambra State, where the study area is located.

However, previous work (Nfor et al. 2007) identified that the groundwater flows southwesterly and easterly away from the water divide. Nanka Formation is considered to be highly prolific in water production, having four aquifer horizons, and recognized as: shallow, upper, lower, and deep aquifers; and the most exploited are the upper and lower aquifers, the most prolific of them being the deep aquifer with an average of 5 L/s. The marine Cenomanian - Turonian Nkalagu Formation (black shales, limestones and siltsones) and the interfingering regressive sandstones of the Agala and Agbani Formations rest on the Asu River Group. Mid-Santonian deformation in the Benue Trough displaced the major depositional axis westward which led to the formation of the Anambra Basin. Post-deformational sedimentation in the Lower Benue Trough, therefore, constitutes the Anambra Basin. The Enugu and the Nkporo Shales represent the brackish marsh and fossiliferous pro-delta facies of the Late Campanian-Early Maastrichtian depositional cycle (Ofomah, 1997). Deposition of the sediments of the Nkporo/Enugu For- mations reflects a funnel-shaped shallow marine setting that graded into channeled low-energy marshes. The coal-bearing Mamu Formation and the Ajali Sandstone accumulated during this epoch of overall regression of the Nkporo cycle. The Mamu Formation occurs as a narrow strip trending north-south from the Calabar Flank, swinging west around the Ankpa plateau and terminating at Idah near the River Niger.

The Ajali Sandstone marks the height of the regression at a time when the coastline was still concave. The converging littoral drift cells governed the sedimentation and are reflected in the tidal sand waves which are characteristic for the Ajali Sandstone. The best exposure of the Nkporo Shale is at the village of Leru (Lopauku), 72 km south of Enugu on the Enugu – Portharcourt express road, while that of Enugu Shale is at Enugu, near the Onitsha-Road Flyover. The Mamu Formation is best exposed at the Miliken Hills in Enugu, with well-preserved sections along the road cuts from the King Petrol Station up the Miliken Hills and at the left bank of River Ekulu near the bridge to Onyeama mine. The aquiferous formations within Anambra State include the Alluvial Plain Sands, the Ogwashi-Asaba Formation and the Ameki/Nanka Sands. These formations were encountered in different towns with Anambra State.

3.11. Niger-Delta River Basin:

The geology of the Niger Delta has been studied by several geoscientists. There is a general agreement amongst these that the Niger Delta is underlain by three principal formations, namely: Akata, Agbada and Benin Formations. The Akata Formation, which is predominantly shale and clay and the Agbada Formation which is generally fluviatile and fluviomarine are primarily of interest to the hydrocarbon industry as it constitute the reservoir areas and traps for hydrocarbon production. The depositional pattern which accompanied sedimentation during the formation of the delta, gave rise to structural traps (growth faults and roll-over anticlines) in the Agbada Formation, which facilitated the accumulation of petroleum in the reservoirs of the Niger Delta. The Agbada Formation while suitable for petroleum accumulation is considered too deep to be of interest for groundwater abstraction. Together, Akata and Agbada formations provide hydrocarbon source rock and reservoir and account for nearly all the hydrocarbon discoveries in the Niger Delta Nigeria.

The Benin Formation on the other hand which occurs at shallower horizons consists of continental deposit of sand and gravel and is therefore of greater significance to the groundwater and civil construction sectors. It is now well known that the Benin Formation (Miocene to Recent) posses' excellent water yielding properties even at great depths. Well cuttings from the logs of oil wells spread across the Niger delta, reveal that the Benin Formation is laterally extensive and extends to depths of 2000 m in some places. The granular composition of Benin Formation presents it as a veritable construction aggregate, besides serving as competent layer to support most piled foundations within depths of civil engineering significance. However, due to the continuing evolution of the delta, the three major formations have now been overlain by various types of Quaternary and Cenozoic deposits. The Cenozoic succession of recent Niger Delta consists of a continental Upper Deltaic plains made up continental alluvial plains, braided streams and meander beds. The sediments here are largely unconsolidated sands, feldspar, limonite coated sand grains silt and clay deposited in fresh water beach swamps. Deposition of the aquifer materials is thought to have occurred in alluvial fan, fluvial channel, tidal channel, intertidal flat, beach and related microenvironments. Water production varies and ranges between 1.6 to 4.1 liters/secs.

3.12. Benin-Owena River Basin:

The Benin Region is underlain by sedimentary formation of the South Sedimentary Basin. The geology is generally marked by top reddish earth, composed of ferruginized or literalized clay sand. Previous workers first used the term Benin sand to describe the reddish earth underlain by sandy clays and ferruginized sandstone that mark the Paleo-Coastal Environment of Paleocene-Pleistocene Age (Christopher, 2006). These sediments spread across the southern fringes of the Anambra Basin and marking the upper facies off-flaps of the Niger Delta which used the name Coastal plain sands to describe the formation of red earth underlain by sands and clays that mark an ancient coastal plain environment now exposed in Calabar, Owerri, Onitsha and the Benin Region with the age deducted to be Oligocene-Pleistocene. However, workers have reinstated the name Benin formation to identify the reddish-brown-yellow generally white sands often with clayey and pebbly horizons with type-locality around Benin. This is also referenced at Calabar and other parts of South Eastern Nigeria. The formation was further established by well logging of Etete 1, well drilled on-shore east of River Niger by Shell Nigeria. Petroleum Development Company (SPDC). The formation is about 1830 m thick at the seashore but thins landwards. The sedimentary suits of the Benin Formation dip 2° - 8° south with capacity to hold and release large amount of groundwater to wells.

Geologically, the Benin-Owena area comprises of 1) the Benin formation; 2) alluvium; 3) drift/top soil and 4) Azagba-Ogwashi (Asuba-Ogwashi) formation with large potential for groundwater production. A study carried out in Ekiti (Adeoye et al 2025) and titled Application of Integrated Geophysical Methods for Groundwater Exploration in Iworoko-Ekiti, Southwestern Nigeria, revealed abundant groundwater that can be produced to support agricultural yield and combat climate change for food security. The basin area is thus prolific in groundwater production with the capacity to produce between 1.1 to 3.6 liters/second. Common rock types that constitute excellent aquifers in the area include sandstone, shale, Quartzite, Alluvium, basalt and Banded Gneissic Complex.

3.13. Upper Benue river basin

The Benue River basin which originated from the Mandara mountains in Cameroun is the major tributary of the Niger River (it empties its water into the Niger at Lokoja where a confluence is formed). The major tributaries of the Benue River in Nigeria are Rivers Katsina-Ala, Donga, Taraba, Gongola and Pai (Nwabineli et al 2012). Though most studies have concentrated on the geomorphological characteristics, while several other studies have focused on the flooding implication less focus has been on the ground water potential of this significant region.

Although groundwater plays a large role in supporting social and economic development in the study area, the water resource-base is far from being adequately understood. There is a lack of systematic data and information on groundwater across Sub-Saharan Africa, with studies occurring on an ad-hoc basis without strategic oversight or coordination. The Upper Benue River Basin (UBRB) in Nigeria lies in the semi-arid regions of the country which represent areas of significant water shortage amidst growing demand and diverse uses. The basin also suffers from occasional drought over the years. In most situations, groundwater monitoring in the basin is limited or non-existent. Furthermore, despite the huge number of wells drilled each year, groundwater monitoring systems for obtaining, compiling, and analyzing information have failed in various sub regions in several nations leading to losses on the huge amount of money invested to drill such wells and boreholes since it failed to yield the relevant information for research, policy and socio-economic development (Abdullateef et al 2021) and (Abdulallahi 2018). It is against this background that this study examines the dynamics of groundwater resources of the Upper Benue River Basin in Nigeria. Morphometric analysis and prioritization of upper Benue River watershed was conducted (Odiji et al 2021) to enumerate the great benefits of the river.

The Upper Benue River Basin, which crosses seven states of the Nigerian Federation (Adamawa, Gombe, Bauchi and Taraba State), is situated between latitudes 6°29′N and 11°46′N and longitude 8°55′E and 13°30′E. The basin spans 480 kilometers from West to East and 532 kilometers from north to south. The basin spans 154,328.9 km^2 of land. Upper Benue River Basin is bounded to the north by Lake Chad basin, to the east and south by Republic of Cameroon, and to the west by Lower Benue and Upper Niger basins. The results imply that areas of high ground water potential have the least coverage while areas with low and poor ground water potential had the highest areal coverage. The result reveals that the water table depth is lowest at the southern part, while the northern part of the basin have high depth or lower water table heights (Adebayo, 1997). Thus, access to ground water resources is relatively better in the southern part of the basin than in the northern part. The basin area is highly prolific in underground water production with the capacity to produce between 0.8 to 4.1 liters/second. Common rock types that constitute good aquifers in the area to facilitate groundwater withdrawal include Alluvium, shale, Quartzite, shale, basalt and sandstone.

3.14. Cross river Basin

The metamorphic rock units in this area are: phylites, schists, gneisses, and amphibolites. These rocks are intruded by pegmatites, granites, granodiorites, diorites, tonalites, Monzonites, and dolerites. Associated with the rocks are charnokites which occur as enclaves in gneisses and granodiorites These rocks record three phase of tectonothermal events which have affected the Nigerian basement with the most resent being the Pan-African Orogeny dating about 600±150 Ma ago. The main results of the deformation include fractures, faults, folds, and dykes trending N-S, NE-SW, and NW-SE directions. Similar trends characterized major lineaments revealed by remote sensing and aeromagnetic interpretation. The basin area is drained mainly by Imo River, KwaIboe River and Cross River together with their tributaries. The area is mostly flat lying sandy coastal area. The main landforms are mangrove swamps and floodplains with recent alluvial accumulations, beach ridges and mangrove mudflats (Theophilus et al 2013). The average annual rainfall is about 3000 mm and the area experiences humid tropical climate. The minimum and maximum temperature in the area ranges from 26 to 28°C.

The area experiences two seasons: wet season (April–October) and dry season (November–March). Groundwater in Akwa Ibom axis occurs in three major systems (George et al.2013): (1) the upper aquifer system; (2) the middle aquifer system and (3) the lower aquifer system. The upper aquifer consists of clayey sand to sand with varying proportions of gravel that reaches 30 m in thickness and fully saturated with groundwater. The aquifer is recharged by percolation of rainfall and direct infiltration of river water. Discharge from the aquifer takes place through withdrawals from wells, boreholes, ponds, percolation into the underlying middle and lower aquifer systems and evaporation in places where the water table is close to the ground surface. The rock types that constitute the aquifers of the area include the coastal plain sands, beach ridge complex and alluvium of Quaternary Period. The basin area is good in underground water production with the capacity to produce between 0.9 to 3.6 liters/second.

3.15. Lower Niger River Basin

The basin area covers Kwara state and part of Kogi and its geology falls within the Basement Complex of Southwestern part of Nigeria covering notable areas of the two states and its rock is composed of Precambrian to Lower Paleozoic in age. This Precambrian Crystalline Basement Complex consists of gneisses and migmatities; metasediments i.e schists, quartzites and metavolcanics and Pan-African (older) granite and late-stage minor pegmatitic and aplitic intrusive. According to previous workers, the areas are mostly situated on the undifferentiated Precambrian Basement Complex rocks of granitic and metamorphic origin. These rocks represent the deeper, fractured aquifer which is partly overlain by a shallow, porous aquifer within the lateritic soil cover. The rock units form part of the regional Southwestern highlands of Nigeria running NW-SE parallel to the River Niger. The subsurface comprises the weathered, slightly weathered and fresh (fractured or unfractured) crystalline basement rocks. The oldest rocks in the area comprise gneiss complex whose principal member is biotite-hornblende gneiss with intercalated amphibolites. This underlies, over half of the city. Other rock types are the older granite mainly porphiritic granite, gneiss and granite-gneiss and quartz schist. Ilorin is underlain by crystalline rocks mainly gneisses and migmatite with pegmatite veins. Rock types within the study areas include;migmatite- gneiss, banded gneiss, granite gneiss, augen gneiss, quatzitesgranites. The Physico-chemical properties of groundwater result (Akudo et al 2025) finally established the purity of such that can be used for irrigation purpose.

Previous workers (Abdulbariu et al 2024) in their published article titled Application of Vertical Electrical Sounding for the determination of water bearing zones in Lokoja area made it abundantly clear that the groundwater potential of Lokoja area with aquifer resistivity thickness is about 40 meters. More importantly, other workers (Ibrahim et al 2024a) in manuscripts titled climate change variability and impacts on aquifers Performance and Groundwater production at Akerebiata area has revealed the impact of climate change on groundwater production in Kwara state. Another study (Ibrahim et al 2024b) also elucidates the comparative analysis of selected Geologic terrains for groundwater production. Factors like Geology, Vegetation, topography and climate are obvious indicators affecting the production of groundwater in kwara state but still far better than rainfall for irrigation of farmlands. This finding was corroborated (Olatunji et al 2020) in an article titled Preliminary Integrated Assessement of Hydrogeological Conditions a Case Study of Parts of Ilorin Crystalline Rocks Southwestern Nigeria. The main aquiferous rock types mapped out in this basin area included quartzite, alluvium, sandstone, Gneisses, migmatities, metasediments i.e schists. The basin area is known for water production that ranges between 0.98 to 3.51 liters/seconds.

4. CONCLUSION

The study concludes that climate change has made the planet earth more unhabitable and vulnerable for man with abnormal increase in the earths temperature traced to more burning of fossil fuel and other activities of man. This has aggravated the food insecurity of the nation with attendant variability of the weather episode most especially unpredictability of rainfall pattern. In essence, the study has shown that groundwater is a viable mitigative option to supplement the surface water sources to enhance food security in the nation. Water production capacity ranges between 0.98 to 5.1 liters/second in these aquifers across the River basins and Nigerian states With an expansive network of floodplain areas in Nigeria, Artesian wells can be developed with more groundwater potential that will be much more useful and impactful for agricultural farming in Nigeria. Moreso, drip irrigation can also serve to hasten the rate of percolation of water into the root system of crops in good infiltration time to support the nourishment and establish the highly needed food security in the country. Policy makers will also need look inward for a more cost effective approach to promote this by encouraging and supporting the drilling of shallow and deep wells at little or no cost for enhanced agricultural productivity in Nigeria.

4.1. Recommendations

1. If increase in food production is a must in Nigeria and as evidenced and suggested by World bank captured in the SPIN ie Sustainable Power and Irrigation for Nigeria project, then, groundwater production will have to be harnessed, incorporated in the scheme to supplement the surface dam water to promote its safety.
2. Water Users Association (WUA) is a welcome innovative move across the country, but are better managed across the 12 River Basins with groundwater source in areas with comparative advantage. This number of WUA will increase astronomically if groundwater source is thus incorporated into the scheme.
3. The 4 components of SPIN are quite laudable, feasible for food, energy and water security in Nigeria with commitment from all stakeholders. However, the first thing to be done to make the project durable is to have appropriate record of all intending water users and other details in black and white and then providing the best irrigable water source (surface dam, deep or shallow wells) with comparative advantage to their respective farm locations.
4. Environmental and social impact assessment should focus on water resources and use, air quality, terrestrial ecology, biodiversity, natural resources, land use, human and socio-economic context, public and land resources from the disposal of waste water etc. This is very crucial to provide adaptative and mitigative measures to all negative impacts that will come up.
5. Stakeholders will need set up Project Management Unit staffed with competent multi-disciplinary experts from all River basin (as contained in world bank report) areas.
6. Appropriate record of all shallow and deep wells (location, coordinates, depth, SWL, Yield etc) must be taken for appropriate and timely rehabilitation, if need be, to serve the farmers and nation more efficiently. This record will have to be digitized and available online for transparency and accountability. Today, no organization has the record of all water wells.
7. With all the above steps taken, Nigeria as a nation is on the path of eradicating hunger, with food sufficiency, just as dry season farming will bounce back with renewed vigour to claim the country back from climate change pandemic.

Acknowledgement

The authors sincerely thank friends and well wishers for the encouragement during the most tedious part of this work. Special thanks to support staffs and Industrial Training Geoscience students of 2024 and 2025 sets at Lower Niger River Basin Development Authority, Ilorin, Kwara State for the support and unquantifiable assistance in compiling articles and useful data. More importantly, my wife Mrs. Damilola Bilqees for the patience during some critical aspects of the work. Insightful contributions from senior colleagues across the 12 River basins are well appreciated, especially from the listed co-authors. Finally, the authors appreciate all stakeholders of SPIN project (including the World bank) in Nigeria with great capacity to encourage the much more needed dry season farming, as the turning point, to combat and mitigate the changing climate ravaging the global community.

Informed consent

Not applicable.

Ethical approval

Not applicable.

Conflicts of interests

The authors declare that there are no conflicts of interests.

Funding

This study has not received any external funding.

Data and materials availability

All data associated with this study are present in the paper.

REFERENCES AND NOTES

1. Abdulbario I, Aroke L. Omoneke A, Muawiya B, Aminu Pam D, Dung A, Sodiq M, Salisu B, Ajogwu C, Odinaka Bertha O, Akagbue S, Ibrahim OI, Application of Vertical Electrical Sounding (VES) for the determination of water bearing zones in Karaworo, Lokoja, Kogi State. Journal of Geography, Environment and Earth Science International. 2024; 27(11): 47-73
2. Abdullahi B, Field evidence of occurrence of groundwater in Gombe formation around Barambu and Gedawo, Northeastern Nigeria. Advanced Journal of Environmental science and Technology. 2018;9 (1):001-008
3. Abdullateef L, Tijani MN, Nuru NA, John S, Mustapha A. Assessment of groundwater recharge potential in a typical geological transition zone in Bauchi, NE-Nigeria using remote sensing/GIS and MCDA. Heliyon. 2021; 7(4): doi: 10.1016/j.heliyon.2021.e06762.
4. Abdulsalam, NN, Nasir, MA, Likason KO. Identification of Linear Features Using Continuation Filters over Koton Karfi Area from Aeromagnetic Data. World Rural Observation. 2011; (3): 1-8
5. Adebayo AA, The Influence of Relief on Rainfall Distribution in Upper Benue River Basin Development Authority (UBRBDA) Nigeria. National Geography of India. 1997; 43(1); 1-7.
6. Adebola AO, Ibrahim AH, Wigeti WH, Yaro NA. Drainage basin morphology and terrain analysis of the Lower Benue River Basin, Nigeria. Science World Journal. 2018; 13(1): 18-22.
7. Adeoye AS, Ajayi CA, Ibrahim OI. Application of Integrated Geophysical Methods for Groundwater Exploration in Iworoko-Ekiti, Southwestern Nigeria. Faculty of Natural and Applied Sciences Journal of Applied and Physical Sciences. 2025; 22 (2):28-38.
8. Akudo EO, Ibrahim O, Muhammed NM, Musa KO, Ahmed II JB, Aigbadon GO. Physico-chemical characteristics and water quality indices to assess the suitability of Groundwater Reservoir in some communities of Kogi state, Nigeria. Journal Sci. Environ. Manage. 2025; 29(1):35-41.
9. Amanambu AC. Obarein OA. Mossa J. Li L, Ayeni SS, Balogun O, Oyebamiji A, Ochege, FU. Groundwater system and climate change: Present status and future considerations. Journal of Hydrology. 2020;589:8-25. doi: 10.1016/j.jhydrol.2020.125163.
10. Bayero MT. Assessing the sustainability of drainage system in irrigated agricultural land: A case study of Kano River irrigation scheme in Nigeria defended," [Master Thesis], Pan-African University Institute for Water and Energy Sciences. 2019;1–133.
11. Benkhelil J, The origin and evolution of the Cretaceous Benue Trough, Nigeria. Journal of African Earth Science. 1989; 8z251-282
12. Christopher N, Akujieze GE, Oteze C. Groundwater quality of Benin City urban aquifer of the Pleistocene-Oligocene Benin Formation, Nigeria. Klobex Academic Publishers. 2006; 7 (2): 69-85 http://www.klobex.org
13. Cobbing J. Groundwater and the discourse of shortage in Sub-Saharan Africa. Hydrogeology Journal. 2020; 28:1143–1154. doi: 10.1007/s10040-020-02147-5.
14. Dada SS. Proterozoic evolution of Nigeria: The basement complex of Nigeria and its mineral resources (A Tribute to Prof. M. A. O. Rahaman). Akin Jinad & Co. Ibadan, 2006; 29-44
15. Dashora Y, Dillon P, Maheshwari B, Soni, P, Dashora R, Davande S, Purohit RC, Mittal H K. A simple method using farmers'measurements applied to estimate check dam recharge in Rajasthan, India. Sustainable Water Resources Management. 2018; 4(2): 301–316. doi: 10.1007/s40899-017-0185-5.
16. Dillon P, Stuyfzand P, Grischek T, Lluria M, Pyne RDG, Jain RC, Bear J, Schwarz J, Wang W, Fernandez E, Stefan C, Pettenati M, Van der Gun, J. Sprenger, C. Massmann G, Scanlon BR, Xanke J, Jokela P, Zheng Y, Rossetto R, Shamrukh M, Pavelic P, Murray E, Ross A, Bonilla Valverde, JP, Palma Nava A, Ansems N, Posavec K, Ha K, Martin R, Sapiano M. Sixty years of global progress in managed aquifer recharge.

Hydrogeology Journal. 2019; 27: 1–30. doi: 10.1007/s10040-018-1841-z.

17. George N, Jimmy 1, Akpan A, Otu A. Asuquo G. Preliminary Geophysical Investigation to Delineate the Groundwater Conductive Zones in the Coastal Region of Akwa Ibom State, Southern Nigeria, around the Gulf of Guinea. International Journal of Geosciences. 2013;4: 108-115
18. Ibrahim OI, Adekunle RR, Ibrahim KO, Ibrahim BB, Abdulbario I. Comparative Analysis of Aquifer Properties in Selected Geologic Terrain in Nigeria. The Progress Multidisciplinary studies. 2024b; 5(2)12-23.
19. Ibrahim OI, Akudo EO, Ibrahim BD, Ali AY, Adekunle AO. Geotechnical and chemical insights for sugarcane plantation irrigation: An environmental assessment of Bulk Water Supply area, Nigeria. Discovery Nature. 2025; 2: e3dn1043. 1-20
20. Ibrahim OI, Lawal MS, Andesikuteb YA, Orire Ismaila OA. Kehinde K. Climate Change Variability and Impacts on Aquifers Performance and Groundwater Production at Akerebiata area. The Progress Multidisciplinary studies. 2024a; 5 (1): 37-51.
21. Lapworth DJ, Nkhuwa DCW, Okotto-Okotto J, Pedley S, Stuart ME, Tijani MN, Wright J. Urban groundwater quality in sub-Saharan Africa: current status and implications for water security and public health. Hydrogeology Journal. 2017; 25(4): 1093-1116.
22. Maduabuchi C, Faye S, Maloszewski P. Isotope evidence of paleorecharge and paleocli-mate in the deep confined aquifers of the Chad Basin, NE Nigeria. Sci Total Environ. 2004; 370: 467-479
23. Magesh NS, Chandrasekar N. Soundranayagam JP. Delineation of groundwater potential zones in Theni district, Tamil Nadu, using remote sensing, GIS and MIF techniques. Journal of Geosciences Frontiers. 2021;189-196.
24. Mohammed AA, Ibrahim DHA. Variabilty of irrigation water quality in Kano River Irrigation Project, JORİND, 2015;13(2): 1–7.
25. Mohammed U, Ali, MS. Socio-economic challenges of irrigation farming along River Yobe (A case study of Yobe State), IOSR Journal of Environmental Science, Toxicology and Food Technology. 2021; 15(4):1–7.
26. Nfor BN, Olobaniyi SB, Ogala JE. Extent and Distribution of Groundwater Resources in Parts of Anambra State, Southeastern, Nigeria. Journal of Appl. Sci. Environ. 2007; 11 (2): 215 - 221
27. Nwabineli COC, Ogedi HI, Nwokoye O. Aquifer Characteristic of the Lafia Sub Basin of The Middle Benue River Basin, Nasarawa State, Nigeria. The International Journal of Engineering and Science (IJES). 2012; 1 (2):155-157.
28. Odiji CA, Aderoju OM, Eta JB, Shehu I, Mai-Bukar A, Onuoha H. Morphometric analysis and prioritization of upper Benue River watershed, Northern Nigeria. Applied Water Science, 2021; 11(2): 1-28.
29. Ofomah JC, Ezeigbo HI. Hydrogeological Evaluation of the Anambra River Basin, Southeastern Nigeria. Water Resources Journal of Nigeria Association of Hydrogeologists. 1997; 8(1and 2):18-26.
30. Olatunji JA, Olasehinde DA, Olasehinde PI, Awojobi MO, Akinrinmade OA, Obaro RI. Preliminary Integrated Assesesement of Hydrogeological Conditions a Case Study of Parts of Ilorin Crystalline Rocks Southwestern Nigeria. IOSR Journal of Applied Geology and Geophysics. 2020; 8(5):01-06.
31. Scanlon BR, Reedy RC, Faunt CC, Pool D, Uhlman K. Enhancing drought resilience with conjunctive use and managed aquifer recharge in California and Arizona. Environmental Research Letters. 2006;11(3):1–15. doi: 10.1088/1748-9326/11/3/035013.
32. Shah T, Bhatt S, Shah RK, Talati, J. Groundwater governance through electricity supply management: Assessing an innovative intervention in Gujarat, Western India. Agricultural Water Management. 2008;(11): 1233–1242. doi: 10.1016/j.agwat.2008.04.006.
33. Shanono NJ, Bello N, Muntaqa I, Usman T. Stakeholders conflict and infrastructural decay ın Nigerian irrigation schemes: A review of Nigerian Journal of Engineering Science and Technology Research. 2020; 6(1):78–90.
34. Shanono NJ, Nuraddeen MN, Nura YU. Appraising the current state of irrigation schemes in northern Nigeria using sustainability pillars. Environmental Research and Technology. Environ Res Tec. 2022; 5 (4): 305–314, doi: 10.35208/ert.1097795
35. Sultana S, Ahmed KM, Mahtab-Ul-Alam SM, Hasan M, Tuinhof A, Ghosh SK, Rahman MS. Ravenscroft P, Zheng Y. Lowcost aquifer storage and recovery: Implications for improving drinking water access for rural communities in coastal Bangladesh. Journal of Hydrologic Engineering. 2015;20(3)1943doi: 10.1061/(ASCE)HE.1943-5584.0001100.
36. Theophilus O, Arong S, Avwenagha E, Oghenero. Evaluation of ground water resource in Akamkpa area, Cross river state, Nigeria. Advances in Applied Science Research; 2013: 4(5):10-24.
37. Villholth KG. Groundwater irrigation for smallholders in Sub-Saharan Africa – a synthesis of current knowledge to guide sustainable outcomes. Water International; 2013: 38 (4): 369–391. doi: 10.1080/02508060.821644.