

Quantitative Assessment of Rainwater-Based Aquifer Recharge at Wacot Rice, Northwestern Nigeria: A Scalable Model for Sustainable Water Management

¹Idris-Nda, A., ²Jimada, M.A., ³Ofoegbu, J. O., and ²Hassan, U.A.

¹Department of Geology, Federal University of Technology, Minna, Nigeria.

²Geosolve Engineering Service Ltd, Minna, Nigeria.

³Department of Geology, Nnamdi Azikiwe University, Awka, Nigeria.

Corresponding Author's E-mail: idrisnda@futminna.edu.ng

ABSTRACT

This study presents the design, implementation, and performance evaluation of a managed aquifer recharge (MAR) system at the Wacot Rice facilities in Argungu, Nigeria. Two injector wells were drilled to a depth of 100 meters, with 97.5 meters cased using 250 mm diameter uPVC pipes. Each borehole was gravel-packed with 5 tonnes of well-rounded to sub-angular gravels (2.5–4 mm) and developed using backwashing and air lifting techniques to enhance hydraulic conductivity. Rainwater harvested from a 125 m³ reservoir—operating at 50% effective capacity (62.5 m³)—was filtered through stainless-steel mesh and conglomerate gravel sourced from the Libba formation. The pump system, calibrated to aquifer pressure, discharged water at a rate of 7.5 m³/hour over an 8-hour cycle, yielding a daily recharge volume of 22.5 m³. This translates to an annual recharge capacity of 8,212.5 m³ in a non-leap year and 8,235 m³ in a leap year. Water quality analysis confirmed that the treated rainwater met physical, chemical, and bacteriological standards for aquifer injection. Static water level data indicated a pressure gradient between the WRL and WRAL facilities, guiding injector placement and confirming natural groundwater flow direction. The system demonstrates a scalable and sustainable approach to groundwater management in semi-arid regions, with potential for replication across similar agro-industrial settings.

Keywords: *Managed Aquifer Recharge, Wacot Rice, Argungu, Rainwater harvest, Sokoto Basin*

INTRODUCTION

Water scarcity is a critical challenge in Northern Nigeria, driven by climate variability, population growth, and agricultural expansion. Groundwater, often the only reliable source during dry seasons, is increasingly overexploited. Managed Aquifer Recharge (MAR) offers a promising solution by artificially replenishing aquifers using alternative water sources such as rainwater and treated effluent.

Groundwater is the water that is stored underground in geological units known as aquifers. Groundwater occurrence is a finite consequence of climate and geological factors, while climate is responsible for recharge, geology is responsible for storage and transmission.

The amount of water stored below the ground in most parts of the world exceeds by a significant amount all water that is above the ground and stored in streams, rivers, reservoirs and lakes. This enormous reservoir sustains streamflow during periods without precipitation and constitutes the major source of freshwater for many localities.

Groundwater is considered the preferred source of water to meet domestic, industrial and agricultural requirements, due to its longer residence time in the ground, low level of contamination, wide distribution, and availability within the reach of the end user.

Groundwater recharge is the process where water moves downwards from surface water to groundwater. Recharge is the primary method through which water enters an aquifer. Groundwater recharge also encompasses water moving away from the water table farther into the saturated zone. Recharge occurs both naturally (through the water cycle) and through anthropogenic processes (i.e. artificial groundwater recharge), where rainwater and or reclaimed water is routed to the subsurface. Natural groundwater recharge is affected by many factors with geology, climate change and urbanisation been the dominant factors.

Artificial recharge of groundwater is achieved by putting surface water in basins, wells, furrows, ditches, or other facilities where it infiltrates into the soil and moves downward to recharge aquifers. Artificial recharge is increasingly used for short- or long-term underground storage, where it has several advantages over surface storage, and in water reuse.

Artificial recharge requires permeable surface soils. Where these are not available, trenches or shafts in the unsaturated zone can be used, or water can be directly injected into aquifers through wells or boreholes.

The purpose of artificial recharge of groundwater is to reduce, stop or even reverse declining levels of groundwater to protect underground freshwater in aquifers.

This paper documents the design, implementation, and performance of a MAR system at WACOT Rice

Argungu Limited, one of Africa's largest rice mills. The system integrates rainwater harvesting and wastewater reuse, tailored to local hydrogeological conditions. It serves as a replicable model for industrial-agricultural facilities seeking sustainable water solutions.

BACKGROUND AND CONTEXT

Water Stress in Northern Nigeria

Northern Nigeria lies within the Sahel zone, characterized by arid to semi-arid conditions, erratic rainfall, and high evapotranspiration rates. Groundwater serves as the primary source for domestic, agricultural, and industrial use. However, declining recharge rates and increasing abstraction have led to falling water tables and aquifer stress.

WACOT Rice Argungu Facility

Promoting environmental stewardship and demonstrating its commitment to sustainability, Wacot Rice Argungu Limited has proactively adopted a rainwater harvesting system as part of its broader Environmental, Social, and Governance (ESG) strategy. Located in Argungu, Kebbi State, a semi-arid region in northwestern Nigeria known for its agricultural heritage and seasonal rainfall patterns, the facility requires substantial volumes of water for parboiling, steaming, and cleaning operations. As one of the largest rice mills in Africa, the introduction of a managed aquifer recharge (MAR) system marks a strategic shift toward long-term water security, aligning operational needs with responsible resource management.

The mill is one of the largest rice mills in Africa and sources paddy from various paddy producing states across Nigeria. WACOT Rice also engages in out-grower farming programs with paddy farmers to boost their yields and guarantees off-take of paddy from farmers through buyback arrangements. The rice mill is based on a robust sustainability platform, and the company produces two leading brands of parboiled rice, BIG BULL and PATRIOT.

Located in the semi-arid region of Argungu, the company relies heavily on groundwater resources, which are increasingly under stress due to extensive agricultural use and climate variability. To address these challenges and promote sustainable water management, the implementation of Managed Aquifer Recharge (MAR) using rainfall catchment and treated wastewater presented a viable solution.

Managed Aquifer Recharge involves the purposeful recharge of water to aquifers, enhancing groundwater availability and quality. The dual approach of utilizing both rainfall catchment and treated wastewater can significantly augment the aquifer's recharge capacity, ensuring a reliable water source for agricultural and

industrial activities while maintaining environmental sustainability.

LITERATURE REVIEW

Managed Aquifer Recharge (MAR)

MAR involves the intentional recharge of aquifers using surface water, stormwater, or treated wastewater. It has been successfully implemented in Australia, India, and parts of the Middle East to combat groundwater depletion (Dillon, 2005; Bouwer, 2002). Techniques include infiltration basins, injection wells, and percolation tanks.

Advantages of Groundwater Recharge

Groundwater recharge, particularly through Managed Aquifer Recharge (MAR), offers several advantages including:

1. **Water Supply Augmentation:** Increases the availability of groundwater, providing a reliable source of water for agricultural, industrial, and domestic use. Helps mitigate the effects of drought and seasonal water scarcity.
2. **Improved Water Quality:** Enhances the natural filtration of contaminants as water percolates through soil layers, improving groundwater quality. Reduces the risk of saltwater intrusion in coastal areas by maintaining higher groundwater levels.
3. **Environmental Protection:** Supports the restoration and maintenance of natural ecosystems that depend on groundwater. Reduces surface water runoff, decreasing erosion and the risk of flooding.
4. **Sustainable Water Management:** Helps balance groundwater extraction with recharge, promoting long-term sustainability of water resources. Encourages the use of alternative water sources, such as treated wastewater and captured rainfall, reducing reliance on surface water and over-exploited aquifers.
5. **Economic Benefits:** Provides a cost-effective method for water storage and management compared to constructing new surface reservoirs. Enhances agricultural productivity by ensuring a steady supply of irrigation water.
6. **Climate Change Resilience:** Increases the resilience of water supply systems to climate change impacts, such as altered precipitation patterns and increased frequency of droughts.
7. **Community and Social Benefits:** Improves water security for communities, supporting health, hygiene, and livelihoods. Fosters community involvement and awareness in sustainable water management practices.

Groundwater recharge, therefore, plays a crucial role in ensuring the sustainability, quality, and resilience of

water resources, benefiting both human populations and natural ecosystems.

Rainwater Harvesting

Rainwater harvesting is a low-cost, decentralized method of capturing and storing rainfall for various uses. In semi-arid regions, it enhances water availability and reduces runoff-related erosion (Ariyo et al., 2019). When combined with MAR, it offers dual benefits of water conservation and aquifer recharge.

The method chosen often depends on local climate, soil conditions, land use, and water demand.

1. **Rooftop Rainwater Harvesting:** Rainwater is collected from rooftops via gutters and downpipes and directed into storage tanks or recharge pits. This method is ideal for urban and residential settings; can be adapted for industrial buildings. It is simple, cost-effective, and suitable for potable and non-potable uses.
2. **Surface Runoff Harvesting:** Rainwater flowing over land surfaces (roads, fields) is captured and diverted into reservoirs, ponds, or underground tanks. It is common in rural and agricultural areas, effective for large-scale recharge. The method reduces erosion and flooding; supports irrigation and aquifer replenishment.
3. **Recharge Pits and Trenches:** These are shallow excavations filled with porous materials (gravel, sand) that allow rainwater to percolate into the ground. It is used to recharge groundwater in areas with declining water tables. It enhances aquifer levels; low maintenance; adaptable to various terrains.
4. **Percolation Tanks:** These are large depressions designed to hold rainwater and allow slow infiltration into the soil. It is suitable for community-level recharge in semi-arid regions. It has the potential for long-term aquifer support; can double as water storage for livestock or irrigation.
5. **Check Dams and Nala Bunds:** These are small barriers built across seasonal streams to slow water flow and promote infiltration. They are widely used in watershed management and rural recharge programs. The method is suitable for controlling runoff; increases soil moisture; supports groundwater recharge.
6. **Infiltration Wells and Borehole Recharge:** By this method rainwater is directed into deep wells or boreholes to directly recharge aquifers. This method is highly relevant to industrial setups like WACOT Rice; it is effective in areas with deep water tables. The advantages include targeted recharge; it is scalable and integrates well with pump systems.
7. **Smart Rainwater Harvesting Systems.** This uses sensors, automation, and filtration to optimize collection and usage. It is suitable for urban and

industrial settings with advanced infrastructure. The advantages include efficient water use; real-time monitoring and supports water quality control.

WACOT Rice's use of dual boreholes and low-pressure pumps aligns with the infiltration well/borehole recharge method, enhanced by engineered control of water flow. This positions the system as a hybrid model, combining surface runoff capture with direct aquifer recharge. This makes it a scalable blueprint for other agro-industrial operations.

Wastewater Reuse

Treated wastewater is increasingly recognized as a viable source for aquifer recharge, especially in industrial settings. Studies show that with proper filtration and disinfection, wastewater can meet recharge standards and reduce environmental discharge (Asano et al., 2007).

Wastewater reuse, also known as **water reclamation**, involves treating used water from domestic, industrial, or agricultural sources so it can be safely reused for beneficial purposes. This process transforms what was once considered waste into a valuable resource, reducing pressure on freshwater supplies and supporting environmental resilience.

Methods of Wastewater Treatment for Reuse

1. **Primary Treatment:** Removes large solids and sediments through screening and sedimentation. Prepares water for further biological or chemical treatment.
2. **Secondary Treatment:** Uses biological processes (e.g., activated sludge, biofilters) to break down organic matter. Reduces biochemical oxygen demand (BOD) and suspended solids.
3. **Tertiary/Advanced Treatment:** Includes filtration, disinfection (UV, chlorination), and nutrient removal. Produces high-quality water suitable for irrigation, industrial use, or even potable reuse in advanced systems.

Applications of Recycled Wastewater

As water scarcity intensifies across agricultural and industrial sectors, the reuse of treated wastewater has emerged as a vital strategy for sustainable resource management. By reclaiming water that would otherwise be discarded, industries and communities can reduce environmental impact while ensuring reliable supply for essential operations.

Below are key applications where wastewater reuse plays a transformative role:

1. **Agricultural Irrigation:** Treated wastewater is used to irrigate crops, conserving freshwater for drinking and other critical uses.
2. **Industrial Cooling and Processing:** Recycled water is utilized in cooling systems and for cleaning

equipment in manufacturing and agro-processing facilities.

3. **Groundwater Recharge:** Treated effluent is directed into recharge wells or infiltration basins to replenish depleted aquifers.
4. **Environmental Restoration:** Supports the rehabilitation of wetlands, riparian zones, and degraded ecosystems by maintaining water flow and moisture levels.
5. **Urban Landscaping and Green Spaces:** Used for watering parks, golf courses, roadside vegetation, and other public green areas.
6. **Construction and Dust Control:** Reclaimed water is applied in construction sites for mixing concrete and suppressing dust.
7. **Firefighting and Emergency Use:** Stored treated wastewater can be deployed for firefighting, especially in water-scarce regions.

Benefits of Wastewater Reuse

Wastewater reuse offers a transformative approach to sustainable water management, particularly in regions facing increasing water stress. By reducing dependence on conventional freshwater sources such as rivers, lakes, and aquifers for non-potable applications, it helps conserve vital ecosystems and ensures more equitable water distribution. Moreover, it minimizes the discharge of untreated effluents into natural water bodies, thereby protecting aquatic habitats and improving overall environmental quality. From an economic standpoint, wastewater reuse significantly lowers the costs associated with water extraction, treatment, and long-distance conveyance. It also provides a dependable water source during periods of drought or seasonal scarcity, ensuring uninterrupted operations in agro-processing and industrial facilities. In essence, wastewater reuse not only enhances water security but also reinforces the resilience and sustainability of agricultural and industrial systems.

Relevance to WACOT Rice

If WACOT Rice incorporates wastewater reuse, for example, recycling process water for cooling, cleaning, or irrigation, it would further strengthen its environmental sustainability profile. Combined with rainwater harvesting and aquifer recharge, this creates a closed-loop water management system that minimizes waste, enhance water security, and that will align with global sustainability goals

Hydrogeological Considerations for Aquifer Recharge

Successful MAR requires understanding aquifer properties, including transmissivity, storativity, and pressure dynamics. In Northern Nigeria, aquifers are often semi-confined or artesian, requiring careful calibration of injection systems (Okoli & Atelhe, 2014).

Effective aquifer recharge depends heavily on understanding the subsurface conditions and the behaviour of groundwater systems. Before implementing any recharge intervention, a thorough hydrogeological assessment is required to determine the suitability, sustainability, and potential risks associated with the site.

1. Aquifer Type and Structure

The type and structural configuration of the aquifer are foundational to the success of any recharge initiative. Unconfined aquifers, which are directly exposed to surface infiltration, are typically more receptive to rainwater harvesting systems. In contrast, confined aquifers require more engineered approaches such as pressure-regulated injection. The depth and thickness of the aquifer also influence recharge feasibility, with deeper aquifers demanding more energy-intensive systems and thicker aquifers offering greater storage potential.

2. Hydraulic Properties

The hydraulic behaviour of the aquifer, defined by parameters such as hydraulic conductivity, transmissivity, and storage coefficient, determines how efficiently recharge water can move and be retained underground. High hydraulic conductivity allows water to percolate rapidly through the aquifer material, while transmissivity governs lateral movement across the aquifer. A favourable storage coefficient ensures that the aquifer can hold significant volumes of recharge water without causing saturation or rebound effects.

3. Soil and Lithology

The nature of the surface and subsurface materials plays a critical role in infiltration dynamics. Permeable soils such as sandy loam or gravel facilitate rapid infiltration, making them ideal for surface-based recharge systems. Conversely, clay-rich or compacted soils may hinder percolation and require engineered solutions like recharge wells. The underlying lithology—whether alluvial deposits, fractured bedrock, or karst formations—affects both the rate and direction of groundwater movement and must be carefully mapped to avoid unintended consequences.

4. Groundwater Flow Direction and Gradient

Understanding the natural direction and gradient of groundwater flow is essential for positioning recharge structures effectively. Recharge systems must be aligned with the prevailing flow to ensure that water is distributed evenly and does not migrate toward contaminated zones or areas of low retention. A gentle hydraulic gradient supports uniform infiltration, while steep gradients may

accelerate water movement and reduce residence time within the aquifer.

5. **Water Table Fluctuations**

Seasonal and long-term variations in the water table must be considered to avoid over-saturation or inefficient recharge. During dry seasons, the water table may drop significantly, creating greater capacity for recharge. However, during wet periods, the risk of surface flooding or aquifer rebound increases. Monitoring these fluctuations helps optimize recharge timing and volume.

6. **Risk of Contamination**

Recharge systems must be designed with water quality safeguards to prevent the introduction of contaminants into the aquifer. Rainwater, though relatively clean, may carry surface pollutants, while industrial or domestic wastewater requires thorough treatment before use. Regular water quality monitoring and filtration systems are essential to maintain aquifer integrity and protect downstream users.

7. **Recharge Method Suitability**

The choice of recharge method must be tailored to the site's hydrogeological profile. Infiltration basins are effective in areas with shallow, permeable soils, while injection wells are better

suited for deeper or confined aquifers. Recharge trenches and pits offer a middle ground, especially in semi-arid zones with moderate permeability. The selected method must balance technical feasibility, cost, and long-term sustainability.

Relevance to WACOT Rice

The success of WACOT Rice's aquifer recharge system hinges on its alignment with these hydrogeological principles. The use of dual boreholes suggests a targeted recharge into deeper aquifer zones, likely supported by favourable transmissivity and hydraulic conductivity. The presence of low-pressure pumps indicates controlled flow rates, minimizing the risk of aquifer destabilization or contamination.

METHODOLOGY

The methodology adopted for this study was designed to ensure a technically sound, site-specific, and operationally feasible approach to aquifer recharge through rainwater harvesting. It integrates hydrogeological assessment, infrastructure design, water quality evaluation, and implementation protocols tailored to the Wacot Rice facility. Figure 1 shows the activity flow process that was adopted for the project.

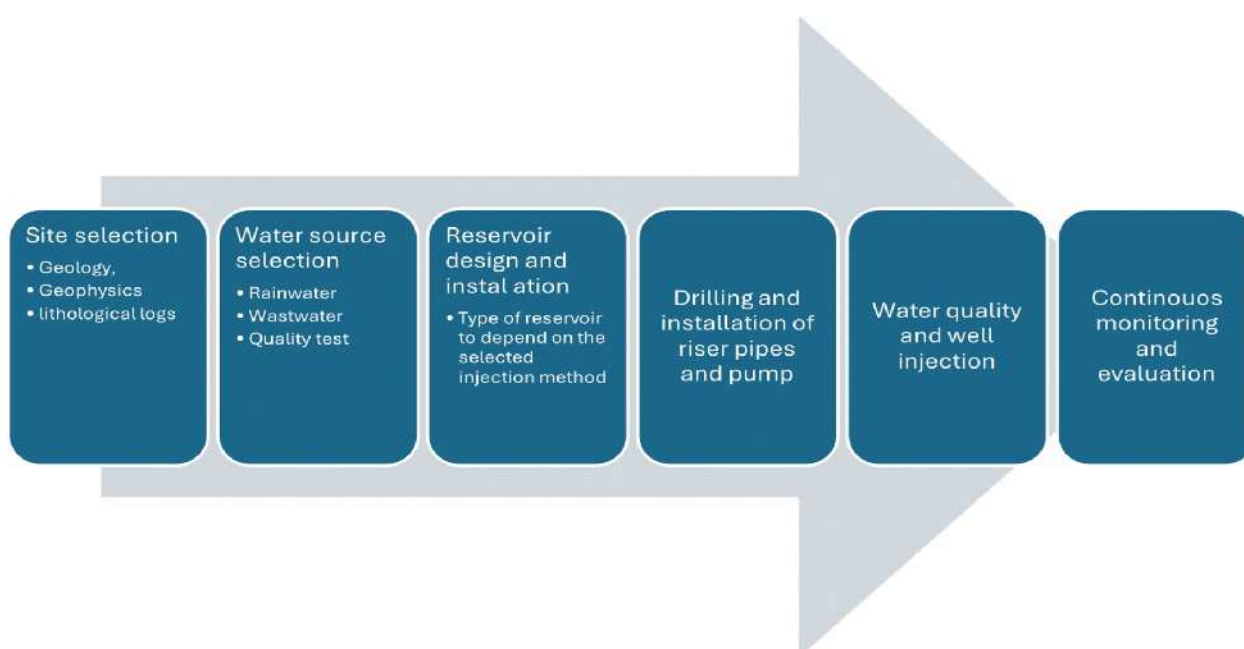


Figure 1: Activity flow process adopted for the project

1. **Site Selection**

i. **Water Level Assessment and Aquifer Pressure Estimation**

Site selection began with a detailed evaluation of static water levels in existing wells across the WACOT Rice facility. This initial step provided insight into the prevailing aquifer pressure and

helped identify zones with sufficient drawdown potential for effective recharge. The data served as a baseline for estimating aquifer responsiveness and recharge feasibility.

ii. **Geophysical Survey Using Vertical Electrical Sounding (VES)**

To characterize the subsurface geology and

delineate aquifer boundaries, a Vertical Electrical Sounding (VES) survey was conducted using a Schlumberger array configuration. The survey extended to a total AB/2 electrode separation of 300 meters, allowing for deep penetration and accurate profiling of subsurface layers. The VES results revealed the depth, thickness, and lateral extent of water-bearing formations, as well as the presence of impermeable zones that could affect recharge dynamics.

iii. Lithological and Wireline Log Analysis

The geophysical data were augmented with lithological logs obtained during drilling operations. These logs provided direct evidence of subsurface stratigraphy, including sediment composition, grain size distribution, and transitions between permeable and impermeable layers. Wireline logs were also employed to assess formation resistivity and porosity, offering further confirmation of aquifer quality and recharge suitability.

iv. Pumping Test Evaluation

Pumping tests were conducted on the existing wells to determine key hydraulic parameters such as transmissivity, storativity, and specific capacity. These tests provided empirical validation of the aquifer's ability to accept and transmit recharge water efficiently. The results helped refine the recharge design and ensured that the system would operate within safe hydraulic limits.

v. Well Design and Construction Oversight

A unique strength of this study lies in the fact that the wells used for both assessment and recharge were designed and constructed by the authors. This allowed for precise control over well specifications, including casing integrity, screen placement, and depth targeting. The direct involvement in well construction ensured that all data collected were reliable and that the recharge system was optimally aligned with site-specific hydrogeological conditions.

2. Water Sources

i. Rainwater and Surface Runoff Capture

The water source for the recharge system was engineered to harness both rooftop rainwater and surface runoff. Rainfall was collected from the expansive roofs of the WACOT Rice facility, providing a clean and elevated catchment surface. Simultaneously, surface runoff from surrounding paved and unpaved areas was directed into a network of drainage channels, which converged at a central collection point designed to maximize water capture during peak rainfall events.

ii. Filtration System

Before entering the reservoir, the harvested water passed through a multi-stage filtration system. The first stage involved a wire mesh screen that intercepted coarse debris such as leaves, sediment, and organic matter. Following this, the water flowed through two graded gravel layers that acted as natural filters, removing finer particulates and improving water clarity. These gravel layers were critical in maintaining the quality of recharge water and preventing clogging of downstream infrastructure.

iii. Gravel Material Provenance

The gravel used in the filtration system was sourced from conglomerates located at the base of the Sokoto–Iullemmeden Basin, specifically where the basin contacts the crystalline basement complex at Libba, along the Kontagora–Sokoto road. This geological origin ensured that the gravel was structurally stable, chemically inert, and hydrologically compatible with the recharge system. The use of locally derived materials also enhanced sustainability and reduced logistical costs.

iv. Reservoir Design and Storage Capacity

Filtered water was stored in a reinforced concrete reservoir with a total capacity of 125 cubic meters. The reservoir was designed to accommodate high-volume rainfall events and provide a buffer for controlled recharge operations. Its structural integrity and placement allowed for gravity-fed distribution into the recharge boreholes, supported by low-pressure pumps and riser pipes that regulated flow rates and minimized energy consumption.

3. Infrastructure Design and Implementation

The infrastructure supporting the aquifer recharge system was meticulously designed to ensure efficient water delivery, structural integrity, and environmental safety. It comprises two primary components: the injector wells and the pump system, both engineered to operate in harmony with the site's hydrogeological conditions and recharge objectives.

1. Injector Wells

Two injector wells were drilled to a depth of 100 meters, strategically targeting the middle and lower aquifer zones identified during the site's hydrogeophysical survey. These depths were selected based on favourable transmissivity and storage coefficients, ensuring that recharge water could be effectively absorbed and distributed within the aquifer system.

Each well was cased and screened using 225 mm diameter uPVC pipes with a wall thickness of 10.8 mm. The casing provided structural

support and protection against collapse, while the screens facilitated controlled infiltration into the aquifer. To enhance filtration and prevent clogging, the annular space around the screens was gravel-packed with carefully graded material. This gravel was selected for its permeability and compatibility with the surrounding lithology, further reducing the risk of sediment intrusion.

To safeguard groundwater quality, the wells were grouted using bentonite-cement slurry, sealing off upper layers and preventing vertical migration of contaminants. This grouting also stabilized the borehole structure and ensured that recharge water was directed exclusively into the intended aquifer zones.

2. Pump System and Flow Control

The recharge system is powered by low-pressure pumps calibrated to match the natural pressure conditions of the aquifer. These pumps were selected to deliver water at a rate that promotes gradual infiltration, avoiding hydraulic shock or over-saturation of the aquifer.

Water is drawn from the 125 m³ concrete reservoir and pumped into the injector wells through riser pipes. To regulate flow and prevent dry pumping, the reservoir is equipped with a float switch system. This automated control mechanism monitors water levels in real time: when the reservoir is full, the pumps are activated to initiate recharge; when the water level drops below a set threshold, the pumps shut off to prevent damage and inefficiency.

In cases where rainfall exceeds reservoir capacity, the float switch redirects excess water into a designated drainage channel. This runoff pathway ensures that surplus water is safely discharged without causing flooding or structural stress to the reservoir. The drainage channel also serves as a secondary infiltration route, allowing some water to percolate naturally into the surrounding soil.

4. Water Quality Assessment

The final stage of the methodology involved a comprehensive evaluation of water quality to ensure that the recharge system met environmental and public health standards. Both raw water (captured directly from rainfall and surface runoff) and treated water (stored in the reservoir after filtration) were subjected to rigorous laboratory analysis.

a. Sampling Protocol

Water samples were collected at two critical points: immediately after initial capture and post-filtration within the reservoir. This dual-point sampling

allowed for comparative analysis and verification of the filtration system's effectiveness.

b. Physical Analysis

Physical parameters such as turbidity, colour, temperature, and total suspended solids (TSS) were measured to assess the clarity and aesthetic quality of the water. These indicators also provided insight into the performance of the gravel filtration layers and the potential for clogging in the injector wells.

c. Chemical Analysis

Chemical testing focused on key indicators including pH, electrical conductivity (EC), total dissolved solids (TDS), and concentrations of major ions such as calcium, magnesium, sodium, chloride, sulphate, and nitrate. These values were compared against WHO and national standards to ensure compatibility with aquifer chemistry and prevent long-term degradation of groundwater quality.

d. Bacteriological Analysis

Microbiological testing was conducted to detect the presence of coliform bacteria, *E. coli*, and other pathogenic organisms. This was critical in confirming that the recharge water posed no biological risk to the aquifer or downstream users. The results informed the need for any additional disinfection steps or pre-treatment protocols.

This final stage validated the integrity of the water source and confirmed the system's readiness for safe aquifer recharge.

RESULTS

Geology

The surveyed area is underlain by rocks belonging to the soft rocks of the Sedimentary basins of Nigeria. Specifically, the area is underlain by rocks of the Sokoto (Iullemmeden) Basin. The Sokoto Basin is located in the north-western part of Nigeria. It comprises principally of a gently undulating plain with an average elevation varying from 250 to 400 m above sea-level. This plain is occasionally interrupted by low mesas. A low escarpment, known as the "Dange Scarp" is the most prominent feature in the basin and it is closely related to the local geology. The sediments of the Sokoto Basin were accumulated during four main phases of deposition. Overlying the Pre-Cambrian Basement complex unconformably, the Illo and Gundumi Formations, made up of grits and clays, constitute the Pre-Maastrichtian "Continental Interclaire" of West Africa. They are overlain unconformably by the Maastrichtian Rima Group, consisting of mudstones and friable sandstones (Taloka and Wurno Formations), separated by the fossiliferous, shelly Dukamaje Formation. The Dange and Gamba Formations (mainly shales) separated by the calcareous Kalambaina

Formation constitute the Paleocene Sokoto Group. The overlying continental Gwandu Formation forms the Post-Paleocene Continental Terminal. These sediments dip gently and thicken gradually towards the northwest, with a maximum thickness of over 1,200 m near the frontier with Niger Republic.

Hydrogeology

The capability of a rock to hold and transmit water in sufficient quantity to be considered economical determines the hydrogeological potential of such a rock. The properties of the rock that determines such a potential include porosity, permeability and degree of jointing in crystalline rock. These in turn determine the transmissivity, storativity and specific yield of the aquifer.

The Gwandu Formation, which is the most promising aquifer in Sokoto basin, lies uncomfortably on the Kalambaina Formation. The sediments are continental in origin and consist of interbedded, partially consolidated sands and clays. The clay beds are mostly thick, massive, white, red, grey black and brown. The sands ranges from fine to coarse in texture. These aquifers remain the sole source of drinking water in most parts of the basin. Gwandu Formation is the most prolific aquifer with an annual recharge exceeding $6.6 \times 10^7 \text{ m}^3$. The artesian aquifer of Gwandu Formation gave free flowing boreholes in about 20% of area of occurrence (14,767sqkm), comprising mainly the Fadama areas and the low land areas extending from Balle (Sokoto State) to Bachaka (Kebbi State). Also, artesian conditions occur in the narrow lowland stretching some 30km southwest of Yeldu (northern Kebbi State). This is the largest proving artesian area in the Sokoto Basin. Also relevant is the generally high heads obtained on the boreholes. The boreholes drilled in some parts of Kebbi State gave positive heads of 7.6m at Argungu, 3m at Birnin Kebbi and 4m at Yeldu. However, it is likely that due to uncontrolled and continuous development of the aquifer, these pressures must have dropped considerably.

Surface geophysical surveys, such as the one conducted here, was targeted at determining the level and depth of the various units that constitute the aquifer in the premises.

Table 1: Static Water Levels in Boreholes at Wacot Rice Facilities

Borehole ID	Facility	Static Water Level (m)
BH 1	Wacot Rice Limited (WRL)	1.8
BH 2	Wacot Rice Limited (WRL)	2.0
BH 3	Wacot Rice Limited (WRL)	1.9
BH 4	Wacot Rice Argungu Ltd (WRAL)	2.5
BH 5	Wacot Rice Argungu Ltd (WRAL)	2.8
BH 6	Wacot Rice Argungu Ltd (WRAL)	2.6

Water Level Assessments

The static water levels recorded across the boreholes at both Wacot Rice Limited (WRL) and Wacot Rice Argungu Limited (WRAL) facilities (Table 1) range from 1.8 m to 2.8 m below ground level. These relatively shallow water rest levels indicate a high water table, which is favourable for aquifer recharge operations. Notably, the boreholes at WRL exhibit slightly shallower water levels (1.8–2.0 m) compared to those at WRAL (2.5–2.8 m), suggesting that aquifer pressure is higher at WRL and lower at WRAL.

This gradient implies a natural direction of groundwater flow from WRL toward WRAL, which is critical for identifying effective recharge points and predicting groundwater flow direction. The data supports the strategic placement of injector wells and informs the calibration of pump systems to align with aquifer dynamics. Additionally, the proximity of the water table to the surface reduces energy requirements for recharge and enhances infiltration efficiency, making both sites hydrogeologically suitable for managed aquifer recharge using harvested rainwater.

Vertical Electrical Sounding

Geophysical surveys indicate a sandy clay layer of about 7m thickness underlying which is a clayey unit that graded into sandy and clayey sandstone up to a depth of 40m which marked the top of the aquifer. The Sandy clay and clayey sandstone serve as aquitards and are capable of storing water but cannot transmit same to boreholes placed in them at quantities to be considered as economical, they can however recharge the underlying aquifer over sufficient periods of time. Below this unit is the sandstone layer which becomes more saturated with depth.

Figures 3 and 4 shows the interpreted VES electric logs for the project sites while figure 5 is the geoelectric section.

Geoelectric Logs

VES 1 WRAL

Layer	Depth (m)	Resistivity (Ohm – m)	Geology
1	1.5	300	Topsoil
2	7	20	Clay
3	20	35	Sandy clay
4	40	50	Clayey sandstone
5	80	80	Sandstone (Water bearing)
6	140	150	Sandstone
7	150	100	Sandstone with admixture of clay
8	180	80	Shale/clay

Drilling and Borehole Development

Two recharge wells were drilled to a total depth of 100 meters, targeting the middle and lower aquifer zones. Casing recovery reached 97.5 meters, using 250 mm diameter uPVC casings and screens with a wall thickness of 18.7 mm. The wells were gravel-packed

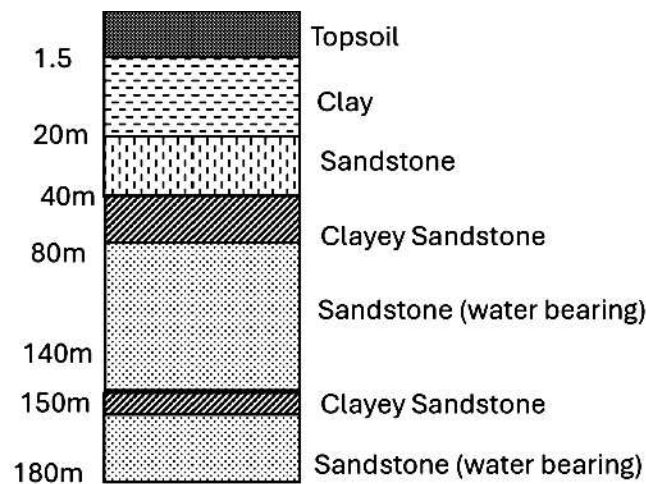


Figure 3: Geoelectric log for the VES conducted at WRAL.

VES 2 WRL

Layer	Depth (m)	Resistivity (Ohm – m)	Geology
1	1.5	450	Topsoil
2	7	240	Sandy Clay
3	20	80	Clay
4	40	180	Clayey sandstone
5	80	400	Sandstone (Water bearing)
6	140	320	Sandstone
7	150	185	Sandstone with admixture of clay
8	180	105	Sandy clay

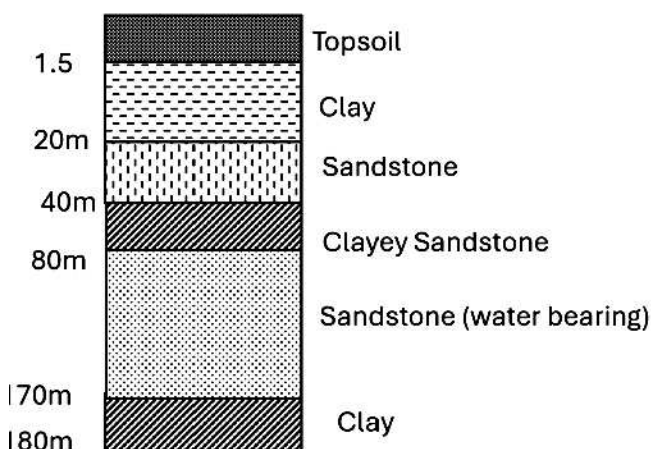


Figure 4: Geoelectric log for the VES conducted at WRAL.

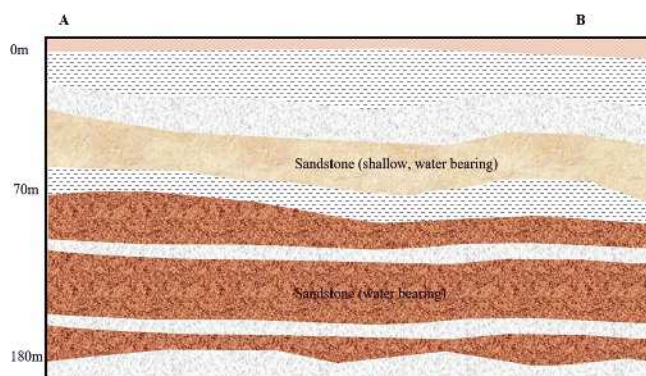


Figure 5: Geoelectric section of the surveyed area showing the expected lithology

with 5 tonnes of well-rounded to sub-angular gravels (2.5–4 mm) per borehole, selected for optimal permeability and placed to the required depth. Figure 6 is the borehole lithological log obtained from samples of the drilled cuttings.

Gravel packing was conducted using a backwashing technique, whereby clean water was pumped through the casing and allowed to exit via the screens. This process facilitated the removal of drilling chemicals, cleaned the gravel, and enabled particle settling based on density and specific capacity, in accordance with Stoke's Law. The annular space above the gravel pack was filled with semi-permeable native materials to seal off poor-quality surface water, while the top 6 meters of each borehole were grouted with cement slurry to prevent contamination from near-surface sources.

Borehole development was achieved through a combination of backwashing and air lifting. Backwashing during gravel packing enhanced hydraulic conductivity around the screen zone. Air lifting was performed using high-pressure jets to clear and stimulate the borehole, allowing for an estimate of potential yield based on discharge rates. The process continued for three hours until the water was clean and sand-free.

Upon completion, each borehole was sealed at the top to prevent intrusion of foreign materials.

Conceptual Designs

Figure 7 illustrates the engineered recharge process, beginning with low-pressure pumping of filtered rainwater from the reservoir into the injection well. The diagram includes a simulated flow response within the aquifer, showing both vertical infiltration into deeper zones and horizontal dispersion along permeable layers. The semi-confined nature of the Argungu aquifer is reflected in the pressure-driven movement of water, which enhances recharge efficiency and supports lateral groundwater migration toward lower-pressure zones.

Figure 8 presents the schematic layout of the rainwater harvesting system. It traces the flow from collector pipes that channel rooftop runoff into a temporary raw water storage unit, where initial sedimentation occurs. From there, water passes through a multi-stage filtration system, including stainless-steel mesh and conglomerate gravel before entering the main reservoir tank for storage and subsequent injection. This design ensures that only clean, particulate-free water reaches the aquifer, aligning with WHO standards for non-chemical water purification.

Water Treatment Process

The water treatment system was designed to ensure that harvested rainwater met the quality standards required

Lithological Log

Depth (m)	Lithology	Penetration Time (minutes)	Log
0-1	Reddish top soil	1	
1-2	Brownish sandy topsoil	1.5	
2-3	Brownish reddish slightly clayey soil	3	
3-4	Brownish reddish slightly clayey soil	3	
4-4.6	Brownish reddish slightly clayey soil	3	
4.6-9.2	Ferruginised sandstone, medium grained	5	
9.2-13.8	Ferruginised coarse grained sandstone with specks of quartz	10	
	Medium to coarse grained ferruginised sandstone	10	
13.8-18.4	Medium to coarse grained ferruginised sandstone	12	
	Shale, ferruginised sandstone, reddish to greyish	18	
	Shale, greyish, non ferruginised	140	
18.4-23	Shale, greyish, non ferruginised, fissile	300	
23-27.6	Mudstone, brownish	120	
27.6-32.2	Mudstone, brownish	145	
32.2-37.8	Mudstone, brownish, slightly greyish	120	
37.8-42.4	Sandstone, medium to fine grained, greyish brown	45	1st Level Aquifer
42.4-47	Sandstone, medium to fine grained, greyish brown	45	
47-51.6	Sandstone, medium to fine grained, greyish brown	45	
51.6-56.2	Sandstone, medium to coarse grained, greyish brown	45	
56.2-60.8	Sandstone, medium to coarse grained, greyish brown	45	
60.8-65.4	Sandstone, medium to coarse grained, greyish brown	45	
65.4-70	Sandstone, medium to coarse grained, greyish brown	45	
70-74.6	Sandstone, medium to coarse grained, greyish brown	45	
74.6-79.2	Sandstone, medium to coarse grained, greyish brown	45	
79.2-83.8	Shale, grey, plastic	350	
83.8-88.4	Shale, grey, plastic highly indurated, with specks of gypsum	360	
88.4-93	Shale, grey, plastic highly indurated, with specks of gypsum	362	
93-97.6	Shale, grey, plastic highly indurated, with coarse sandstone	320	
97.6-102.2	Shale, grey, plastic	285	

Figure 6: Borehole lithological log for the drilled wells

for aquifer recharge. Initial observations revealed that the collected rainwater arriving at the treatment point was heavily contaminated with rice husks and suspended debris. These materials quickly clogged the originally designed filtration system, prompting a redesign of the intake structure.

To address the clogging issue, the stainless-steel wire mesh was reconfigured into a box-type structure. This modification allowed rice husks to be retained at the initial entry point while enabling water to overflow into the treatment chamber. Although this adjustment improved initial filtration, further enhancements along the flow path are recommended to remove finer particulates before water reaches the treatment chamber.

The preliminary treatment section comprises two key components:

- A stainless-steel wire mesh that intercepts coarse debris.
- A **graded gravel bed** made from specially sourced conglomerate material. The gravel's long transport history and depositional environment ensure its stability, permeability, and filtration effectiveness.

Water is forced under hydraulic pressure through this gravel layer, which effectively removes suspended solids and impurities. The filtration process ensures that only clean water reaches the clear water reservoir, ready for injection into the aquifer. Plate 1 displays the gravel used for filtration, as well as the stainless-steel wire mesh box and drainage channel to the reservoir.

Given that the primary water source is rainwater, which

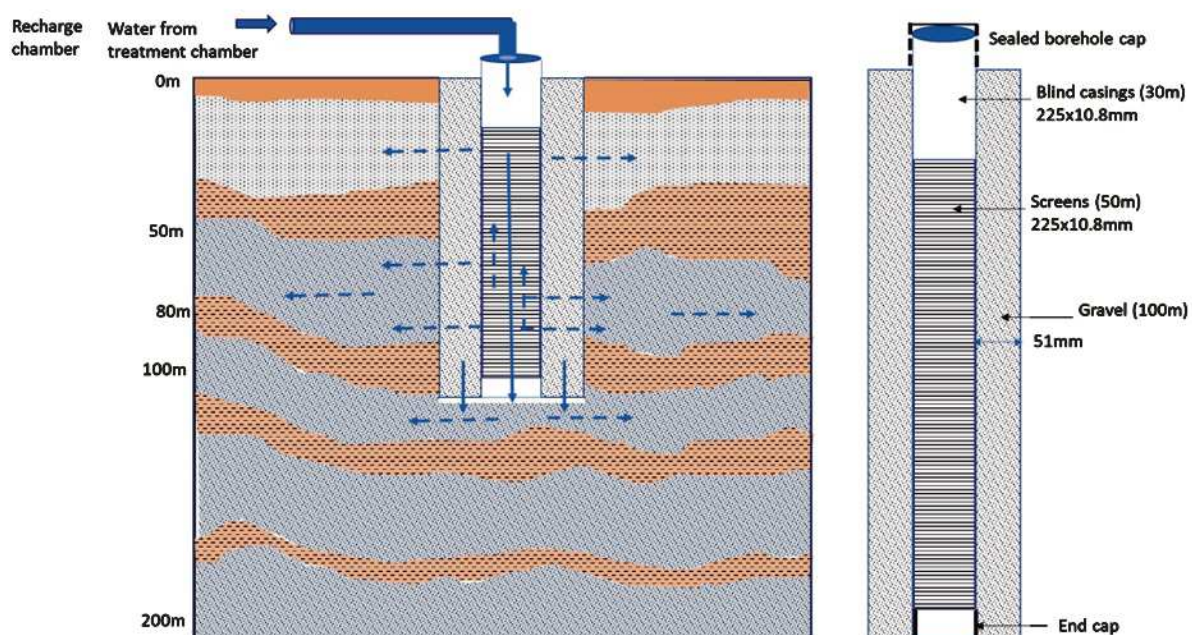


Figure 7: Design concept of the groundwater recharge system using rainwater harvesting

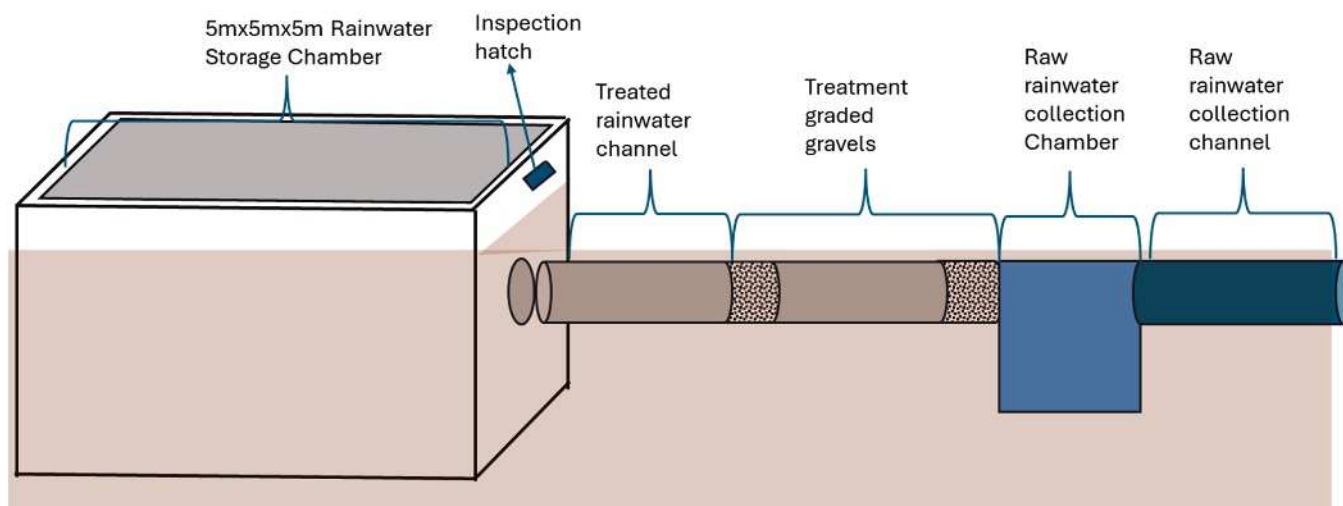


Figure 8: Schematic diagram of the rainfall catchment design (not to scale)

is naturally low in dissolved contaminants, no further chemical or biological treatment was deemed necessary. The combination of mechanical filtration and natural

gravel media provides sufficient purification for safe aquifer recharge.



Plate 1: Gravel material and filtration system

Plates 2 display the drainage channel, reservoir, and inspection window, which provides access to a stainless-steel ladder for chamber maintenance. Plate 3 presents the riser pipes, cover plate seals, and the low-pressure pump used for injection.

Recharge System Installation

The recharge system was installed using riser pipes with a diameter of 50.8 mm extending to a depth of 75 meters

within each injector well. These riser pipes were left open throughout their length to facilitate direct water injection into the targeted aquifer zones.

At the surface, each riser pipe was securely connected to a stainless-steel mounting plate fitted with rubber seals. This configuration served a dual purpose:

- It prevented backflow of water from the top of the system,
- And it sealed the injection pathway, ensuring



Plate 2: Treated rainwater storage reservoir



Plate 3: Riser pipes, well top seal and pressure pump used for the installation

that water was forced downward into the aquifer under pressure supplied by the low-pressure pump system.

This closed-loop design maximized recharge efficiency by eliminating surface leakage and directing all injected water into the subsurface. The pressure-driven flow, regulated by the pump and float switch system, allowed for controlled infiltration aligned with the aquifer's natural absorption capacity.

Water Level Float Switch

A water level float switch is a control device used to monitor and regulate water levels within a storage tank. It operates by means of a buoyant float that rises and falls with the water level, triggering an internal switch mechanism when predefined thresholds are reached.

Functional Applications

- **Automated Pump Control:** Activates the pump when the water level is low and deactivates it when the tank is full, ensuring

efficient recharge operations.

- **Overflow Prevention:** Prevents excess water from entering the tank once maximum capacity is reached, protecting infrastructure and minimizing waste.
- **Drainage Control:** Opens valves to discharge water when necessary, maintaining optimal operating conditions.

For this project, a horizontal float switch was installed in the 125 m³ reservoir to manage water flow into the aquifer. The switch automatically halts pump operation when water levels fall below the minimum threshold and resumes pumping when the reservoir is full. In overflow conditions, the system redirects excess water into a designated drainage channel, ensuring safe discharge and preventing structural stress on the reservoir.

Design Calculations

Storage Capacity

The recharge system utilizes a reinforced concrete reservoir with the following dimensions:

- **Length:** 5 meters
- **Width:** 5 meters
- **Depth:** 5 meters

This yields a **total volume of 125 m³**. However, to account for operational constraints and sediment accumulation, only **50% of the total volume** is considered usable for rainwater storage:

- **Effective Rainwater Storage Volume** = 125 m³ × 0.5 = **62.5 m³**

Discharge Rate

The installed low-pressure pump has a calibrated discharge rate of:

- **7.5 m³/hour**

To fully discharge the effective storage volume of 62.5 m³:

- **Total Discharge Time** = 62.5 m³ ÷ 7.5 m³/hour = **8 hours**

Storage Replenishment Rate

The rate at which rainwater replenishes the reservoir is primarily influenced by rainfall intensity and duration. Observations at the site indicate that a single heavy rainfall event can refill the reservoir within 1 to 2 hours of continuous precipitation. This rapid replenishment supports daily recharge cycles during the rainy season.

Aquifer Recharge Rate

Aquifer recharge is defined as the volume of water introduced into the subsurface per unit time. Based on the pump's discharge capacity and operational cycle:

- **Recharge Cycles per Day** = 24 hours ÷ 8 hours = **3 cycles/day**
- **Recharge Volume per Day** = 7.5 m³/hour × 8 hours = **22.5 m³/day**

Annual recharge estimates:

- **Non-leap year:** 22.5 m³/day × 365 days = **8,212.5 m³/year**
- **Leap year:** 22.5 m³/day × 366 days = **8,235 m³/year**

Aquifer Pressure Considerations

The Argungu aquifer has been classified as semi-confined, exhibiting pressures above atmospheric levels. This elevated pressure plays a critical role in determining recharge feasibility. To achieve effective infiltration, the pump must deliver water at a pressure slightly higher than the aquifer pressure, thereby reversing the natural hydraulic gradient and enabling downward flow into the aquifer.

Careful calibration of pump pressure ensures:

- Overcoming aquifer resistance
- Preventing backflow
- Enhancing recharge efficiency
- Maintaining groundwater balance

Pump Selection Advisory

Given the aquifer's pressure dynamics and the system's calibrated performance, it is not advisable to replace the current pump with a higher-capacity unit. Doing so may disrupt the controlled recharge process, increase energy consumption, and risk damaging the aquifer structure. The existing pump setup is optimized for both hydraulic compatibility and sustainable groundwater management.

DISCUSSION

The implementation of a managed aquifer recharge (MAR) system at the Wacot Rice facilities demonstrates a practical and sustainable approach to groundwater management in semi-arid regions. The integration of rainwater harvesting, filtration, and controlled injection into the Argungu aquifer reflects a holistic understanding of site-specific hydrogeological conditions.

Static water level measurements revealed a pressure gradient between the older WRL facility and the newer WRAL site, indicating natural groundwater flow from WRL to WRAL. This insight guided the strategic placement of injector wells and informed pump calibration to match aquifer pressure, ensuring efficient recharge without over pressurisation.

The gravel-packed wells, developed through backwashing and air lifting, exhibited high hydraulic conductivity and clean discharge, confirming their readiness for recharge operations. The use of locally sourced conglomerate gravel and semi-permeable sealing materials enhanced system compatibility with native geology while minimizing environmental impact.

Water quality analysis confirmed that the harvested rainwater, once filtered through stainless-steel mesh and gravel beds, met physical, chemical, and bacteriological standards for aquifer injection. The float switch system provided automated control over pump operation and overflow management, ensuring operational safety and efficiency.

Design calculations showed that the system can recharge approximately 22.5 m³/day, translating to over 8,200 m³ annually. This volume is significant for maintaining groundwater levels and supporting agricultural and industrial water demands in the region.

CONCLUSION

This study successfully demonstrates the feasibility and effectiveness of a rainwater-based aquifer recharge system tailored to the hydrogeological context of the Wacot Rice facilities in Argungu. The integration of engineering design, water quality assurance, and pressure-calibrated injection has resulted in a robust system capable of enhancing groundwater sustainability.

Key outcomes include:

- Efficient recharge of a semi-confined aquifer under pressure
- Use of locally sourced materials for filtration and sealing
- Automated control of water levels and pump operation
- Environmentally sound water treatment using natural filtration

The project serves as a model for similar interventions in other parts of northern Nigeria and beyond, where groundwater stress and seasonal rainfall patterns demand innovative recharge solutions. Continued monitoring and adaptive management will be essential to optimize performance and ensure long-term aquifer health.

RECOMMENDATIONS AND SCALABILITY POTENTIAL

The success of the MAR system at Wacot Rice demonstrates its viability as a scalable solution for sustainable groundwater management in semi-arid regions of Nigeria. To replicate and expand this model, the following recommendations are proposed:

1. **Regional Replication:** Similar agro-industrial zones across northern Nigeria, particularly those with seasonal rainfall and declining groundwater tables can adopt this system with minimal adaptation. Areas within the Sokoto Basin, Bida Basin, Chad Basin, and parts of the Middle Belt are ideal candidates.
2. **Addressing Aquifer Stress:** Many aquifers in

Nigeria are under increasing stress due to overexploitation from irrigation, industrial use, and unregulated borehole drilling. Recharge interventions like the one demonstrated in this study can:

- i. **Restore groundwater balance** by offsetting extraction volumes with controlled recharge.
 - ii. **Delay or reverse aquifer depletion**, especially in areas where natural recharge is insufficient.
 - iii. **Reduce land subsidence and water quality degradation**, which are common consequences of overdrawn aquifers.
- MAR systems should be prioritized in regions where groundwater levels have dropped significantly over the past decade, and where rainfall patterns still offer viable recharge opportunities.

3. **Policy Integration:** Government agencies such as the Nigerian Hydrological Services Agency (NIHSA) and River Basin Development Authorities should incorporate MAR into national water resource strategies, especially for climate resilience and irrigation support.
4. **Community-Level Deployment:** Scaled-down versions of this system can be implemented in rural communities using ferrocement tanks, solar-powered low-pressure pumps, and locally sourced filtration media.
5. **Monitoring and Data Sharing:** Establishing a centralized database for recharge volumes, aquifer response, and water quality will support long-term performance tracking and inform future designs.
6. **Capacity Building:** Training programs for engineers, hydrologists, and technicians should be developed to support widespread adoption and maintenance of MAR systems.

By adopting these recommendations, Nigeria can move toward a more resilient and decentralized groundwater management framework, reducing dependence on overexploited aquifers and enhancing water security for agriculture and domestic use.

ACKNOWLEDGEMENT

The author extends sincere appreciation to the management of Wacot Rice Ltd. for their invaluable support throughout the course of this study. Their commitment to innovation and sustainable water management provided the enabling environment for the successful design and implementation of the aquifer recharge system. Gratitude is also expressed to the technical and operations teams whose collaboration during fieldwork and system deployment was instrumental to the outcomes presented in this paper.

REFERENCES

- Ariyo, S., Adebayo, A., & Olorunfemi, M. (2019). Groundwater exploitation and sustainability in Northern Nigeria. *Journal of Environmental Hydrology*, 27(3), 45–58.
- Asano, T., Burton, F. L., Leverenz, H. L., Tsuchihashi, R., & Tchobanoglous, G. (2007). *Water Reuse: Issues, Technologies, and Applications*. McGraw-Hill.
- Bear, J. (1979). *Hydraulics of Groundwater*. McGraw-Hill.
- Bouwer, H. (2002). Artificial recharge of groundwater: hydrogeology and engineering. *Hydrogeology Journal*, 10(1), 121–142.
- Dillon, P. (2005). Future management of aquifer recharge. *Hydrogeology Journal*, 13(1), 313–316.
- FAO. (2022). *Lake Chad Basin Water Resources Assessment*. Food and Agriculture Organization of the United Nations.
- Freeze, R.A. & Cherry, J.A. (1979). *Groundwater*. Prentice-Hall.
- Mercy Corps. (2017). *Water and Conflict in Northern Nigeria*. Mercy Corps Nigeria.
- National Water Resources Institute (NWRI). (2023). *Guidelines for Managed Aquifer Recharge in Nigeria*.
- Nigerian Meteorological Agency (NiMet). (2024). *Annual Rainfall Report for Kebbi State*.
- Okoli, A. C., & Atelhe, G. A. (2014). Nomads and nation-building in Nigeria: Issues and challenges. *African Journal of Political Science and International Relations*, 8(3), 56–65.
- Todd, D.K. & Mays, L.W. (2005). *Groundwater Hydrology*. 3rd Edition. Wiley.
- WACOT Rice Ltd. (2025). *Internal Borehole Drilling and groundwater recharge using rainfall harvest Reports*.
- WHO. (2017). *Guidelines for Drinking-Water Quality*, 4th Edition. World Health Organization.