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### Sustainable Groundwater Management and Aquifer Recharge in Bayelsa State, Nigeria: A Review of Hydrogeological Characteristics, Threats, and Management Strategies

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#### Abstract

Bayelsa State, situated in the low-lying, hydrologically dynamic core of the Niger Delta, depends almost entirely on groundwater abstracted from the unconfined and semi-confined sands of the Benin Formation for domestic, agricultural, and industrial water supply, because surface water throughout the state is largely contaminated, saline, or otherwise unsuitable for direct use. This paper synthesises the published hydrogeological, hydrochemical, and disaster-risk literature on Bayelsa State to examine the sustainability of current groundwater use and to identify practicable aquifer-recharge and management interventions. Evidence is drawn from borehole hydrochemical surveys, geoelectrical aquifer investigations, coastal saline-intrusion studies, and disaster reports on the catastrophic 2022 flood event that submerged seven of the state's eight Local Government Areas. The review finds that, although the Benin Formation aquifer is generally prolific and recharges readily under the region's high (approximately 2,000-4,000 mm) annual rainfall, groundwater quality is compromised in many

communities by acidity, elevated iron and manganese, and localised saline intrusion driven by unregulated borehole proliferation, tidal influence, and the geological complexity of paleo-channels within the Benin Formation. Escalating flood frequency, attributed to both extreme rainfall and inadequate land-use planning, further threatens aquifer integrity through recharge-zone disturbance and contaminant mobilisation. The paper proposes an integrated management framework combining managed aquifer recharge (MAR) techniques -- rainwater harvesting and infiltration, recharge ponds, coastal injection barriers, and wetland-buffer retention -- with regulatory reform, borehole-spacing controls, and community-based groundwater monitoring. It concludes that sustainable groundwater management in Bayelsa State requires coordinated action across hydrogeological science, disaster risk reduction, and water governance to secure long-term freshwater availability for the state's growing population.

**Keywords:** Groundwater Management, Aquifer Recharge, Benin Formation, Saltwater Intrusion, Niger Delta, Bayelsa State, Managed Aquifer Recharge (MAR), Flood Risk

#### 1. Introduction

Groundwater is the principal source of freshwater for domestic, agricultural, and industrial use across much of the Niger Delta, and nowhere is this dependence more pronounced than in Bayelsa State, where an extensive network of creeks, rivers, and mangrove swamps renders most surface water bodies unsuitable for direct consumption without extensive treatment (Oki & Akana, 2016) [13]. The state's inhabitants, numbering well over two million people spread across riverine and swamp-forest settlements, rely almost exclusively on hand-dug wells and boreholes tapping the Benin Formation, the thick sequence of unconsolidated coastal-plain sands that forms the region's most prolific aquifer system (Etu-Efeotor & Akpokodje, 1990) [4].

This heavy reliance on a single aquifer system, combined with rapid, largely unregulated borehole drilling, rising population pressure, and the compounding effects of climate variability, has raised concerns about the long-term sustainability of groundwater resources in the state. Several hydrochemical studies conducted around Yenagoa, Otuoke, Southern Ijaw, and other communities have documented localised water-quality problems, including acidic pH, elevated iron and manganese concentrations, and, in coastal and estuarine communities, saline intrusion into shallow aquifers (Nwankwoala, 2012;

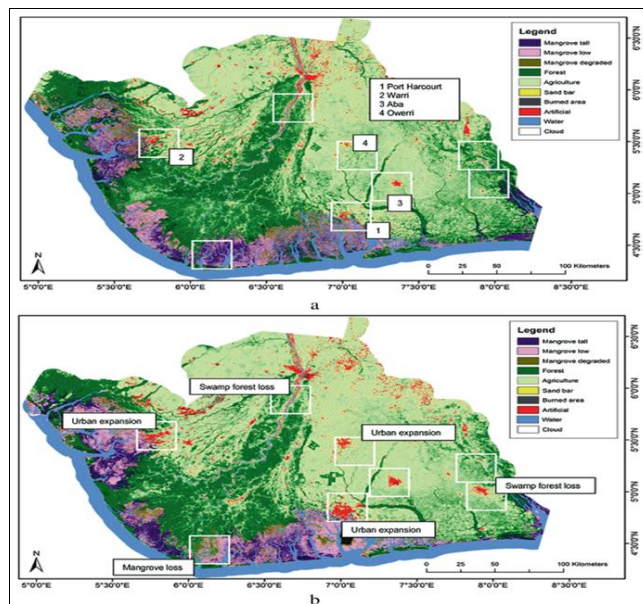
Nwankwoala *et al.*, 2014; Abadom & Nwankwoala, 2018; Nwankwoala *et al.*, 2023) [9, 10, 1, 11]. At the same time, the catastrophic flooding of 2022 -- described by state emergency management authorities as the worst in the state's recorded history -- submerged seven of Bayelsa's eight Local Government Areas, displaced hundreds of thousands of residents, and starkly illustrated the vulnerability of the state's water and sanitation infrastructure to extreme hydrological events (Ominabo, 2022; Guardian, 2023) [14, 6].

Sustainable groundwater management, encompassing both the protection of aquifer quality and the deliberate enhancement of recharge, is therefore not merely a technical hydrogeological concern in Bayelsa State but a matter of disaster risk reduction, public health, and long-term development planning. Managed aquifer recharge (MAR) -- the intentional recharge of aquifers through infiltration basins, recharge wells, bank filtration, and related techniques -- has been successfully applied in water-stressed regions across Africa and elsewhere to buffer against overabstraction, seasonal variability, and saline intrusion (Foster *et al.*, 2012; Tuinhof *et al.*, 2011) [5, 16]. However, MAR and related sustainable-management approaches remain largely unexplored in the specific hydrogeological and socio-institutional context of Bayelsa State.

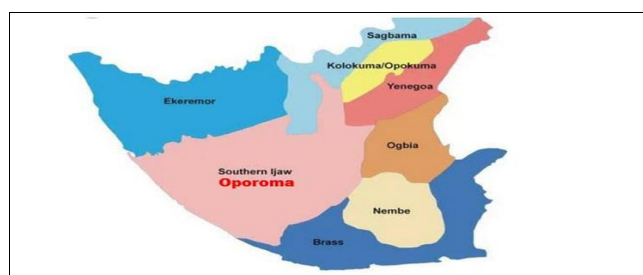
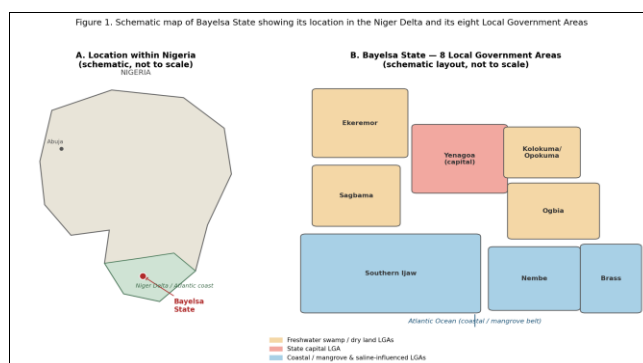
This paper addresses that gap by (i) reviewing the geological and hydrogeological setting of Bayelsa State's aquifer system; (ii) synthesising the documented evidence on groundwater quality, recharge conditions, and threats, including saline intrusion and flood impacts; and (iii) proposing an integrated, context-appropriate framework of sustainable groundwater management and aquifer recharge strategies, supported by policy and institutional recommendations.

## 2. Study Area

Bayelsa State lies in the south-central Niger Delta of Nigeria, bordered by Delta State to the north, Rivers State to the east, and the Atlantic Ocean to the south. The state is administratively divided into eight Local Government Areas (LGAs): Yenagoa (the state capital), Ekeremor, Sagbama, Kolokuma/Opokuma, Southern Ijaw, Ogbia, Nembe, and Brass (Table 1). It occupies a low-lying deltaic plain rarely exceeding a few metres above sea level, characterised by extensive freshwater swamp forest in its northern LGAs and saline mangrove, estuarine, and coastal environments in its southern and coastal LGAs (Fig 1).



Map of Niger Delta Region



**Fig 1:** Schematic map showing Bayelsa State's location within the Niger Delta and its eight Local Government Areas (illustrative, not to scale)

**Table 1:** The eight Local Government Areas of Bayelsa State and their principal water-supply and groundwater management challenges, synthesised from the reviewed literature (Nwankwoala, 2012; Nwankwoala *et al.*, 2023; Nkpoidet *et al.*, 2025) [9, 11, 8]

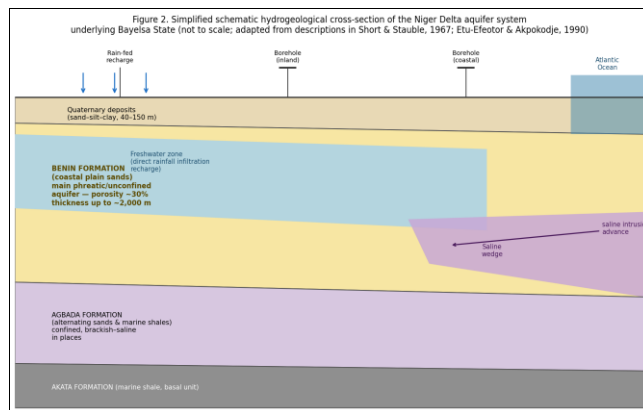
| LGA              | Approximate setting                                    | Predominant water-supply challenge                               |
|------------------|--------------------------------------------------------|------------------------------------------------------------------|
| Yenagoa          | State capital; peri-urban, on relatively higher ground | Rapid urban growth outpacing regulated borehole development      |
| Ekeremor         | Freshwater swamp / riverine                            | Seasonal flooding; limited borehole infrastructure               |
| Sagbama          | Freshwater swamp                                       | Seasonal flooding; shallow well contamination                    |
| Kolokuma/Opokuma | Freshwater swamp, inland                               | Limited hydrogeological data coverage                            |
| Southern Ijaw    | Extensive riverine/creek network                       | Remoteness; flood exposure; surface-water pollution              |
| Ogbia            | Transitional freshwater-brackish                       | Localised saline influence; oil-industry proximity               |
| Nembe            | Coastal/estuarine                                      | Saline intrusion; tidal influence on boreholes                   |
| Brass            | Coastal, Atlantic-facing                               | Highest saline-intrusion risk; limited freshwater lens thickness |

The state's terrain and drainage are dominated by the Nun and Forcados distributaries of the River Niger together with a dense network of tidal creeks, which give the region what has been described as delta-wide hydrological continuity, such that surface-water contamination in one part of the delta is readily transmitted elsewhere (Aweto, 2020) [3]. Because most surface water is either turbid, brackish, or subject to anthropogenic pollution, groundwater from the Benin Formation constitutes, in practice, the only reliably potable water source for the great majority of the state's communities.

### 3. Geology and Hydrogeology

#### 3.1 Regional geological framework

The subsurface geology of the Niger Delta comprises three principal lithostratigraphic units deposited from the early Paleocene onward: the Akata Formation (predominantly marine shale), the Agbada Formation (alternating sands and shales), and the Benin Formation (continental sands and gravels), the last of which forms the youngest and uppermost of the three units and is overlain in turn by variable Quaternary deposits of sand, silt, and clay (Short & Stauble, 1967; Etu-Efeotor & Akpokodje, 1990) [15, 4]. The Benin Formation, often referred to as the Coastal Plain Sands, is the most hydrogeologically important unit in the region: it consists of more than 90 percent massive, porous, coarse sand with occasional clay and lignite interbeds, reaches a reported thickness of up to roughly 2,000 metres, and possesses an average porosity of approximately 30 percent, making it a highly prolific, if geologically heterogeneous, aquifer (Etu-Efeotor & Akpokodje, 1990; Nkpoidet *et al.*, 2025) [4, 8].



**Fig 2:** Simplified schematic hydrogeological cross-section of the Niger Delta aquifer system underlying Bayelsa State, illustrating the Quaternary, Benin, Agbada, and Akata units and the coastal freshwater-saline interface (not to scale; adapted from descriptions in Short & Stauble, 1967 [15], and Etu-Efeotor & Akpokodje, 1990 [4])

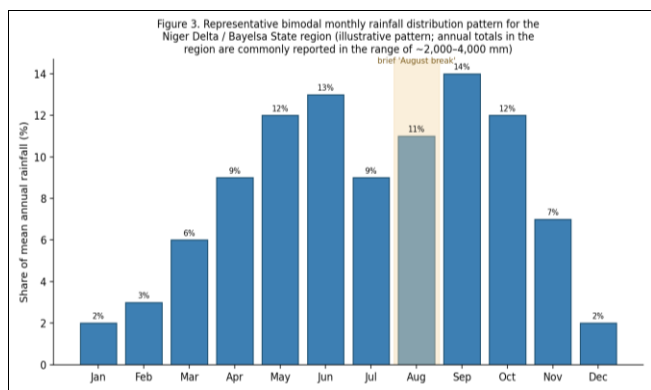
**Table 2:** Lithostratigraphic units of the Niger Delta Basin relevant to groundwater occurrence in Bayelsa State (synthesised from Short & Stauble, 1967 [15]; Etu-Efeotor & Akpokodje, 1990 [4]; Nkpoidet *et al.*, 2025 [8])

| Unit                | Approximate age          | Lithology                                                                          | Hydrogeological role                                                        |
|---------------------|--------------------------|------------------------------------------------------------------------------------|-----------------------------------------------------------------------------|
| Quaternary deposits | Holocene-Recent          | Alternating sand, silt, and clay; clay content increases seaward                   | Shallow, locally confining layer overlying the Benin Formation              |
| Benin Formation     | Miocene-Recent           | >90% massive, porous, coarse sand with thin clay/lignite interbeds; ~2,000 m thick | Principal freshwater aquifer; multi-aquifer system in places; porosity ~30% |
| Agbada Formation    | Eocene-Pliocene          | Alternating sands and marine shales                                                | Deeper, generally confined, and increasingly brackish/saline with depth     |
| Akata Formation     | Paleocene-Recent (basal) | Predominantly marine shale                                                         | Effectively impermeable basal unit; not an exploitable aquifer              |

#### 3.2 Aquifer recharge mechanisms

Recharge to the Benin Formation aquifer in Bayelsa State occurs predominantly through direct infiltration of rainfall across the state's extensive, low-relief, sandy terrain, aided by the formation's high porosity and permeability (Aweto, 2020) [3]. The region's climate is equatorial monsoon in character, with a pronounced wet season running from roughly March through October, a brief mid-season lull often referred to locally as the "August break," and a shorter dry season from November through February (Fig 3). Reported annual rainfall totals for the wider Niger Delta

region commonly fall in the range of approximately 2,000 to 4,000 millimetres, among the highest in Nigeria, which under natural conditions should sustain substantial recharge (Hassan *et al.*, 2020) [7].



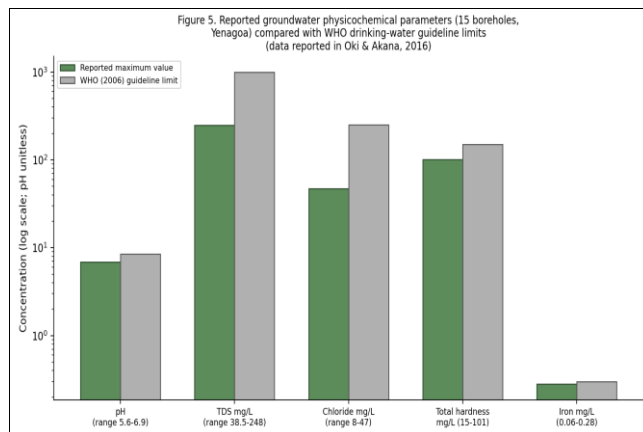
**Fig 3:** Representative bimodal monthly rainfall distribution pattern for the Niger Delta / Bayelsa State region (illustrative pattern consistent with regional climate descriptions in Hassan *et al.*, 2020 [7]; not a specific measured station record)

Despite this high rainfall input, effective recharge is increasingly compromised by rapid, poorly planned urban expansion in and around Yenagoa, which expands impervious surface cover and diverts overland flow away from natural infiltration zones, and by the progressive loss of freshwater swamp forest, which historically functioned as a natural recharge buffer (Nkpoidet *et al.*, 2025) [8].

#### 4. Groundwater Quality: Evidence from the Literature

A substantial body of hydrochemical research has examined groundwater quality across Bayelsa State's communities, generally sampling boreholes and hand-dug wells and comparing physicochemical and heavy-metal parameters against World Health Organization (WHO) drinking-water guidelines. Findings are broadly consistent: groundwater from the Benin Formation is not highly mineralised and most major-ion parameters fall within WHO limits, but recurrent, localised problems include acidic pH, elevated iron and manganese, and -- in coastal and estuarine LGAs -- chloride enrichment associated with saline intrusion (Nwankwoala, 2012; Nwankwoala *et al.*, 2014; Oki & Akana, 2016; Abadom & Nwankwoala, 2018; Nwankwoala *et al.*, 2023) [9, 10, 13, 1, 11].

A representative and frequently cited study of fifteen boreholes across densely populated communities of Yenagoa found pH values ranging from 5.6 to 6.9 (mean 6.30), indicating slightly acidic water attributable to organic-matter content in overlying soils, shale intercalations within the aquifer, and possibly acid rain associated with regional gas flaring; total dissolved solids ranged from 38.5 to 248 mg/L; chloride ranged from 8 to 47 mg/L; and the dominant hydrochemical facies was identified, via Piper trilinear analysis, as a calcium-chloride type water (Oki & Akana, 2016) [13]. Table 3 and Fig 4 summarise these reported parameter ranges against WHO (2006) guideline limits.



**Fig 4:** Reported groundwater physicochemical parameters from fifteen boreholes in Yenagoa compared with WHO (2006) drinking-water guideline limits (data reported in Oki & Akana, 2016) [13]

**Table 3:** Summary of reported groundwater physicochemical parameters for Yenagoa boreholes compared with WHO (2006) guideline limits

| Parameter                     | Reported range (Yenagoa boreholes) | WHO (2006) limit | Remark                                                              |
|-------------------------------|------------------------------------|------------------|---------------------------------------------------------------------|
| pH                            | 5.6 - 6.9 (mean 6.30)              | 6.5 - 8.5        | Slightly acidic; below lower guideline threshold                    |
| Total dissolved solids (mg/L) | 38.5 - 248                         | 1,000            | Well within limit                                                   |
| Chloride (mg/L)               | 8 - 47                             | 250              | Within limit at most sites; localised elevation near coast          |
| Total hardness (mg/L)         | 15 - 101                           | 150              | Within limit                                                        |
| Iron (mg/L)                   | 0.06 - 0.28                        | 0.3              | Generally within limit; other studies report higher localised peaks |
| Magnesium (mg/L)              | 1.76 - 7.5                         | 50               | Within limit                                                        |

Source: Oki & Akana, 2016 [13]

Other studies extend this picture geographically and thematically. Investigations in Otuoke and its environs recorded iron concentrations reaching as high as 10 mg/L in some samples, substantially exceeding WHO guidance, alongside elevated manganese, underscoring the heterogeneity of water quality even within a single LGA (Abadom & Nwankwoala, 2018) [1]. Seasonal comparisons in the Akaba-Atissa communities of Yenagoa LGA likewise report hydrogeological and water-quality variation between wet and dry seasons, reflecting the sensitivity of the shallow aquifer to recharge timing (Aweto, 2020 [3], as cited in related regional hydrogeochemical literature). In Southern Ijaw LGA, seasonal physicochemical profiling of hand-dug wells and boreholes found measurable differences between wet- and dry-season water quality, consistent with a shallow, rainfall-responsive aquifer system that is nonetheless vulnerable to contamination during periods of

reduced flushing (Nwankwoala *et al.*, 2023) <sup>[11]</sup>.

Collectively, these studies indicate that while the Benin Formation aquifer in Bayelsa State is hydraulically prolific and generally yields water broadly suitable for domestic use, quality is neither uniform nor guaranteed, and requires continuous, geographically comprehensive monitoring rather than episodic, community-level sampling.

## 5. Threats to Groundwater Sustainability

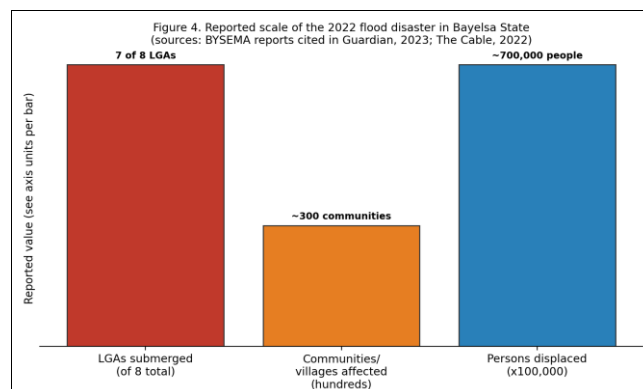
### 5.1 Saline Intrusion

Coastal and estuarine aquifers in the Niger Delta, including those beneath Bayelsa State's southern LGAs, are recognised as being at substantial risk of saline intrusion. A recent regional review estimates that approximately 30 percent of Niger Delta coastal aquifers are already affected by salinisation, driven by a combination of anthropogenic overexploitation, unregulated borehole drilling, and climatic factors such as rising sea level and increased tidal amplitude, compounded by the geological complexity of the Benin Formation, whose paleo-channels, faults, and fractures can provide preferential pathways for saline water to migrate inland (Nkpoidet *et al.*, 2025) <sup>[8]</sup>.

Geophysical and hydrochemical investigations along the wider Niger Delta coastline, including electrical resistivity tomography surveys, have identified thin freshwater lenses -- in places only a few metres thick near the shoreline -- overlying saline zones, with the freshwater-saline interface deepening progressively inland (studies reviewed in Nkpoidet *et al.*, 2025; Udo *et al.*, 2022) <sup>[8, 17]</sup>. Numerical groundwater-flow modelling of the western Niger Delta coastal aquifer suggests that present-day pumping rates are generally insufficient, on their own, to drive significant inland movement of the freshwater-saline interface, but that a combination of reduced recharge and substantially elevated pumping could meaningfully worsen intrusion, underscoring the importance of protecting recharge alongside managing abstraction (Ohwoghere-Asuma *et al.*, 2019) <sup>[12]</sup>.

### 5.2 Flooding and extreme rainfall

In 2022, Nigeria experienced what has been widely described as its worst flooding event in a decade, attributed to a combination of unusually intense and prolonged rainfall, the release of excess water from the Lagdo Dam in neighbouring Cameroon, and inadequate drainage and land-use planning in flood-prone areas (Ominabo, 2022) <sup>[14]</sup>. Bayelsa State was the most severely affected in the country: seven of its eight LGAs were wholly or partially submerged, more than 300 communities and villages were affected, and state emergency management authorities reported that approximately 700,000 to 1.5 million people were displaced or otherwise affected, with the higher displacement figures reported as the crisis extended into 2023 (Ominabo, 2022; Guardian, 2023) <sup>[14, 6]</sup>.



**Sources:** BYSEMA figures as reported in Guardian, 2023 <sup>[6]</sup>, and The Cable, 2022

**Fig 5:** Reported scale of the 2022 flood disaster in Bayelsa State

Beyond the immediate humanitarian toll, such large-scale flooding has direct implications for groundwater sustainability. Prolonged inundation can submerge unprotected wellheads and boreholes, creating pathways for surface contaminants -- including pit-latrines effluent, agrochemical residues, and floodwater-borne pathogens -- to enter the shallow aquifer; it can also disturb natural recharge zones and increase turbidity and organic loading in infiltrating water. Displaced households relying on emergency water sources during and after flood events are, in the interim, cut off from safe groundwater access altogether, compounding public-health risk (Guardian, 2023) <sup>[6]</sup>.

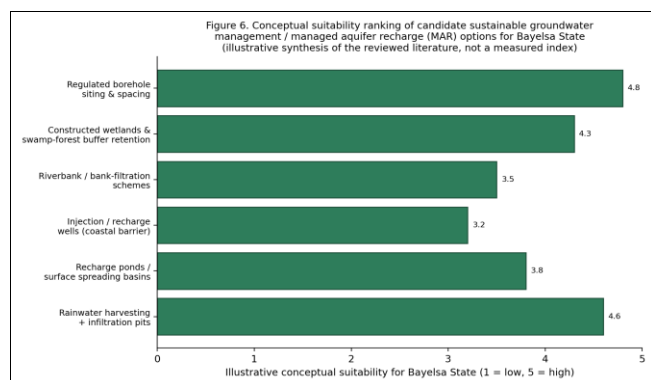
### 5.3 Unregulated abstraction and pollution

A further, cross-cutting threat identified throughout the literature is the largely unregulated proliferation of private and community boreholes across Bayelsa State, often drilled without reference to aquifer-yield assessments, appropriate spacing, or sanitary protection radii around potential contamination sources (Nkpoidet *et al.*, 2025) <sup>[8]</sup>. Combined with weak institutional capacity for groundwater monitoring and enforcement -- a challenge documented broadly across Sub-Saharan Africa -- this unregulated development increases the risk of localised aquifer depletion, cross-contamination between shallow and deeper aquifer horizons, and accelerated saline intrusion in coastal LGAs (Tuinhof *et al.*, 2011; Foster *et al.*, 2012) <sup>[16, 5]</sup>.

## 6. Toward Sustainable Groundwater Management and Aquifer Recharge

Addressing the threats identified above requires an integrated approach that combines deliberate aquifer-recharge enhancement (managed aquifer recharge, or MAR) with stronger groundwater governance. MAR encompasses a family of techniques through which water is intentionally directed into an aquifer, either to augment storage,

counteract saline intrusion, or both; it has been applied with documented success in water-stressed African contexts including South Africa, Namibia, Botswana, and Kenya, albeit with recurring implementation challenges around weak enforcement, limited data, and inadequate cross-sector coordination (Foster *et al.*, 2012<sup>[5]</sup>; CSIR, 2025, as summarised in the reviewed policy literature).



**Fig 6:** Conceptual suitability ranking of candidate sustainable groundwater management and managed aquifer recharge (MAR) options for Bayelsa State, synthesised from the reviewed literature (Foster *et al.*, 2012; Tuinhof *et al.*, 2011; Nkpoidet *et al.*, 2025)<sup>[5, 16, 8]</sup>. This ranking is an illustrative, literature-informed synthesis rather than a measured field index, and is intended to guide prioritisation for site-specific feasibility studies

## 6.1 Recommended technical interventions

**Table 4:** Summary of recommended sustainable groundwater management and aquifer-recharge strategies for Bayelsa State, mapped to their primary target threat

| Strategy                                               | Primary target threat                            | Notes on applicability in Bayelsa State                                      |
|--------------------------------------------------------|--------------------------------------------------|------------------------------------------------------------------------------|
| Rainwater harvesting with infiltration pits/trenches   | Declining recharge in urbanising areas           | Low-cost, community-scale; suited to Yenagoa's expanding impervious surfaces |
| Recharge ponds / surface spreading basins              | Seasonal recharge variability                    | Feasible on higher-ground freshwater-swamp LGAs (Ekeremor, Sagbama)          |
| Coastal injection / recharge-well barriers             | Saline intrusion                                 | Highest priority for Nembe and Brass; requires engineering feasibility study |
| Riverbank filtration schemes                           | Water-quality pre-treatment and recharge support | Applicable along the Nun and Forcados distributaries                         |
| Constructed wetlands / swamp-forest buffer retention   | Loss of natural recharge buffers                 | Complements existing mangrove and freshwater-swamp conservation              |
| Regulated borehole siting, spacing, and depth controls | Unregulated abstraction and cross-contamination  | State-wide policy priority; low capital cost, high governance value          |

## 6.2 Policy and institutional recommendations

Consistent with broader Sub-Saharan African experience, the technical measures above are unlikely to achieve lasting impact without accompanying institutional reform (Tuinhof *et al.*, 2011)<sup>[16]</sup>. This review therefore recommends: (i) establishment of a dedicated state-level groundwater monitoring network, combining periodic water-level and water-quality sampling with community-based reporting; (ii)

mandatory registration, spacing, and construction-standard regulations for new boreholes, with particular emphasis on coastal LGAs at elevated saline-intrusion risk; (iii) integration of aquifer-recharge protection into flood-risk and land-use planning, so that post-2022 reconstruction and future urban expansion in Yenagoa and other growing towns preserve, rather than erode, natural infiltration capacity; (iv) pilot MAR feasibility studies, beginning with coastal injection-barrier trials in Nembe or Brass and recharge-pond trials in the freshwater-swamp LGAs; and (v) stakeholder engagement mechanisms that draw on indigenous community knowledge of seasonal water behaviour alongside modern hydrogeological monitoring, consistent with recommendations made for the wider Niger Delta region (Nkpoidet *et al.*, 2025)<sup>[8]</sup>.

## 7. Conclusion

Bayelsa State's dependence on the Benin Formation aquifer for nearly all potable water supply makes the sustainability of that resource a matter of immediate developmental and humanitarian consequence. The reviewed evidence indicates that the aquifer remains, in hydrogeological terms, prolific and generally rechargeable under the region's abundant rainfall, but that groundwater quality and recharge integrity are increasingly compromised by localised acidity and metal enrichment, coastal saline intrusion linked to both natural hydrogeological complexity and unregulated abstraction, and the disruptive effects of extreme flood events such as that of 2022. A combination of targeted managed aquifer recharge interventions and strengthened groundwater governance -- monitoring, borehole regulation, and recharge-sensitive land-use planning -- offers a realistic pathway toward securing Bayelsa State's groundwater resources for current and future generations. Further site-specific hydrogeological investigation, including aquifer-yield testing and pilot MAR schemes, is recommended as the logical next step building on the desk-based synthesis presented here.

## 8. Methodology Note

This paper is a desk-based, literature-synthesis review. Evidence was compiled from peer-reviewed hydrogeological and hydrochemical studies, institutional and policy reports, and contemporaneous disaster-management reporting on Bayelsa State and the wider Niger Delta, identified through targeted academic and web-based literature searches. Reported figures, parameter ranges, and disaster statistics are attributed to their original sources throughout; conceptual figures explicitly labelled as "illustrative" or "conceptual" (Figures 1, 2, 3, and 6) are original schematic syntheses prepared for this paper to aid interpretation and are not derived from a specific measured dataset. No new field sampling, laboratory analysis, or primary data collection was undertaken for this review.

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