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Geoelectric Delineation of Aquifer Units in Bayelsa State, Nigeria: A Review of Case Studies and Groundwater – Management Implication

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Abstract
Groundwater is Bayelsa State's principal dependable water source, but development is complicated by heterogeneous Niger Delta sediments, shallow water tables, flooding, contamination and possible saline influence. This structured narrative review synthesises geoelectric aquifer studies published from 2010 to 2026 and evaluates their management implications. Publications were identified, screened and compared by survey design, curve type, layer sequence, aquifer resistivity, depth, thickness, hydraulic properties, protective capacity, vulnerability and validation. Evidence is concentrated in Yenagoa, Ogbia, Otuoke, Opolo-Epie and Elebele and consistently indicates multilayer aquifers of fine- to coarse-grained sand separated locally by discontinuous clay, silty-clay and sandy-clay units. Schlumberger vertical electrical sounding has delineated productive horizons, guided drilling depth, assessed overburden protection and extended sparse pumping-test information. Reported parameters vary because of genuine facies changes and differences in electrode spread, sounding density, inversion, classification thresholds and calibration. Resistivity alone cannot uniquely distinguish clay, freshwater sand, saline groundwater or contamination; borehole logs, pumping tests, hydrochemistry and microbiological analyses remain essential. The review recommends locally calibrated interpretation, integrated VES-ERT investigations, systematic monitoring and abstraction control, a unified state groundwater database, wider coastal coverage and regional aquifer correlation to support sustainable development and protection.

Keywords: *aquifer delineation; Bayelsa State; electrical resistivity; groundwater management; hydrogeophysics; Niger Delta; vertical electrical sounding*

Introduction

Groundwater is the principal dependable source of water for households, public institutions, commercial activities and industries in much of Bayelsa State. Although the state is traversed by rivers, creeks and seasonally inundated wetlands, the widespread presence of surface water does not necessarily translate into safe or continuously usable supplies. Surface sources are commonly affected by high turbidity, suspended and organic matter, microbial contamination, flood-borne pollutants and, in estuarine and coastal settings, possible brackish or saline influence. Weak or intermittent municipal supply has consequently encouraged the proliferation of privately drilled boreholes and shallow wells, particularly in Yenagoa and its rapidly urbanising environs (Abam & Nwankwoala, 2020; Agbalagba *et al.*, 2011; Okiongbo & Akpofure, 2012). This dependence makes reliable delineation of aquifer units fundamental to public water security, because unsuccessful drilling, inappropriate screen placement or completion in a vulnerable shallow horizon can increase costs and expose users to poor-quality groundwater.

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The hydrogeological setting of Bayelsa State is controlled by the young, unconsolidated sediments of the Niger Delta. The freshwater-bearing domain is associated mainly with the Benin Formation and younger alluvial, fluvial, swamp and coastal deposits, which comprise laterally and vertically variable successions of fine- to coarse-grained sand, gravel, silt, clay and locally organic-rich materials. These sediments form a complex multilayered aquifer system in which productive sand bodies may be unconfined, semi-confined or locally separated by discontinuous clay lenses and aquitards. The frequency and thickness of clay interbeds generally increase towards parts of the coastal delta, while shallow water tables, high rainfall, flooding and hydraulic interaction with rivers and creeks create rapid recharge pathways as well as potential routes for contaminant migration (Abam & Nwankwoala, 2020; Hassan *et al.*, 2019). Consequently, aquifer depth, thickness, continuity, hydraulic productivity and natural protection may change markedly over short distances, making subsurface investigation necessary before borehole construction.

Electrical resistivity methods have become prominent in groundwater exploration in Bayelsa State because they are non-invasive, comparatively economical and capable of providing depth-related information over wider areas than isolated boreholes. Vertical electrical sounding (VES), particularly with the Schlumberger array, has been used to infer the number of subsurface layers, their resistivities and thicknesses, aquifer depths and the geometry of water-bearing sand units. Published studies have also derived Dar–Zarrouk parameters—especially longitudinal conductance and transverse resistance—to evaluate aquifer protective capacity and obtain first-order estimates of transmissivity. For example, geoelectric investigations in Yenagoa identified multiple layers and aquiferous horizons with wide resistivity and depth ranges, reflecting the heterogeneity of the deltaic deposits (Okiongbo & Akpofure, 2012). Geoelectric–hydraulic correlations reported for parts of Bayelsa State further indicated that resistivity-derived parameters can provide useful preliminary estimates of transmissivity where pumping-test information is sparse, although such relationships require local calibration (Oborie & Udom, 2014; Okiongbo & Odubo, 2012).

The published case studies collectively demonstrate both the value and the interpretational complexity of the method. Oborie *et al.* (2013), using Schlumberger VES supported by borehole lithologs, delineated shallow and deeper aquifer units in Yenagoa and Ogbia and showed that thin discontinuous clay beds locally subdivide otherwise extensive sandy aquifers. Okiongbo and Akpofure (2016) integrated VES, borehole information, pumping tests and hydrochemistry to characterise the shallow alluvial aquifer in Yenagoa, illustrating the advantage of combining electrical and independent hydrogeological evidence. Similarly, Oborie and Nwankwoala (2012) examined relationships between geoelectric and groundwater parameters in Ogbia, while Okiongbo and Odubo (2012) reported a strong correspondence between transmissivity estimated from pumping tests and from geoelectric parameters. These studies indicate that VES can support the identification of productive aquifer units, the estimation of drilling targets and the appraisal of aquifer vulnerability, but they also reveal that the reliability of conclusions depends on survey depth, station density, model interpretation and the availability of validation data.

A central difficulty is that electrical resistivity is not a unique indicator of lithology or water quality. Low resistivity may reflect clay-rich strata, saline or brackish pore water, elevated dissolved solids or contaminant-affected groundwater, whereas relatively high resistivity may represent freshwater-bearing clean sand, partially saturated sand or coarse dry material. The same nominal resistivity range may therefore receive different lithological interpretations in different locations. Hydrochemical studies in Yenagoa have reported spatial variations in acidity, electrical conductivity, dissolved ions and iron, demonstrating that delineation of a conductive layer alone cannot establish whether it is an aquitard, a mineralised aquifer or a contaminated water-bearing unit (Agbalagba *et al.*, 2011; Nwankwoala *et al.*, 2014; Okiongbo & Douglas, 2015). This ambiguity explains why borehole logs, pumping tests and water chemistry are essential for constraining geoelectric models and for separating aquifer occurrence from groundwater potability. The review framework is summarised in Figure 1.

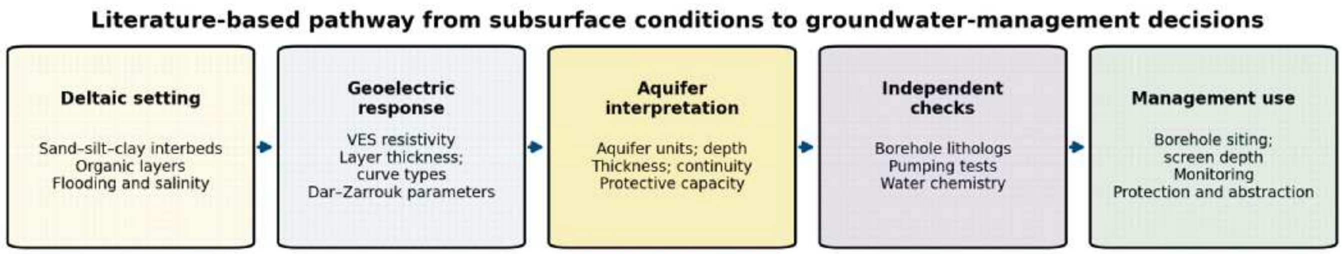

Fig. 1: Conceptual framework for reviewing geoelectric aquifer delineation and groundwater-management implications in Bayelsa State.
Source: Author's synthesis based on the reviewed literature.

Despite the substantial contribution of these publications, the available evidence remains fragmented. Most investigations are site-specific and concentrated in Yenagoa, Ogbia and a limited number of adjoining communities; they differ in electrode spacing, number of sounding stations, inversion procedures, reporting formats and the criteria used to assign lithology, aquifer potential and protective-capacity classes. Reported aquifer resistivities, depths and thicknesses are therefore not always directly comparable, and some papers provide limited discussion of model non-uniqueness, equivalence, suppression or uncertainty. In addition, management implications are often stated for individual study sites without being synthesised into a broader framework for borehole regulation, groundwater monitoring and aquifer protection. Regional work on the Niger Delta similarly emphasises that groundwater development is constrained less by an absence of aquifer material than by incomplete hydrogeological information, pollution pressures, weak coordination and limited long-term monitoring (Abam & Nwankwoala, 2020; Hassan *et al.*, 2019).

A review of the published case studies is therefore necessary to consolidate the evidence, compare survey and interpretation approaches, assess the consistency of aquifer classifications and distinguish recurring hydrogeological patterns from location-specific conclusions. Such a synthesis can clarify which parts of Bayelsa State have received adequate geoelectric attention, the curve types and layer sequences most frequently reported, the ranges of aquifer resistivity, depth and thickness, and the degree to which geoelectric interpretations have been checked against borehole, hydraulic or hydrochemical data. It can also identify geographical gaps, inconsistent resistivity–lithology assignments, insufficiently validated empirical relationships and areas where vulnerability assessments remain uncertain. Importantly, comparative review can translate technical findings into practical guidance for borehole siting, target depth and screen placement; identification of weakly protected shallow aquifers; prioritisation of water-quality surveillance; and regulation of abstraction in productive aquifer zones.

Accordingly, this review aims to synthesise and critically evaluate published applications of geoelectric methods in the delineation and characterisation of aquifer units in Bayelsa State and to examine their implications for groundwater development, protection and sustainable management. It identifies relevant published studies, evaluates their electrode configurations and interpretation procedures, compares reported geoelectric sequences and curve types, and synthesises aquifer resistivity, depth, thickness, continuity, hydraulic potential, protective capacity and vulnerability. It further examines how the reported interpretations were validated, compares findings from Yenagoa with those from Ogbia and other investigated locations, and highlights methodological and geographical gaps requiring future attention. The scope is restricted to peer-reviewed articles, reviews and related scholarly case studies involving VES or associated electrical resistivity techniques in Bayelsa State, with selected Niger Delta publications used only for regional context. No new resistivity acquisition, borehole drilling, pumping testing, hydrochemical sampling, inversion of unpublished data or field-derived aquifer mapping is undertaken; all conclusions and management implications are derived from the published evidence.

Methodology

This study adopted a structured narrative review design with transparent, reproducible procedures for identifying, selecting, appraising and synthesising published case studies. A structured narrative approach was considered appropriate because the eligible studies were methodologically heterogeneous, reported different combinations of vertical electrical sounding (VES), Dar–Zarrouk parameters, borehole information, pumping tests and hydrochemical evidence, and did not provide sufficiently uniform data for formal meta-analysis. The review nevertheless incorporated the key reporting principles of systematic evidence synthesis, including an explicit search strategy, predefined eligibility criteria, standardised data extraction and critical appraisal (Grant & Booth, 2009; Page *et al.*, 2021; Snyder, 2019). It was restricted to published evidence and involved no new geoelectric field survey, borehole drilling, pumping test, water sampling, inversion of unpublished resistivity data or statistical reanalysis of raw field measurements.

Relevant publications were identified for the period 2010 to 2026 through searches of Google Scholar, Scopus, Web of Science, Crossref, African Journals Online, SpringerLink, ScienceDirect, institutional repositories and individual journal websites. The reference lists of retrieved articles and review papers were also examined to locate additional case studies. Searches combined geographical, methodological and hydrogeological terms using Boolean operators where supported. Core combinations included "geoelectric aquifer Bayelsa State," "vertical electrical sounding Yenagoa groundwater," "aquifer protective capacity Yenagoa," "geoelectric transmissivity Bayelsa," "hydrogeophysical characterisation Yenagoa," "groundwater vulnerability Bayelsa State," "electrical resistivity aquifer Niger Delta," and "Dar–Zarrouk parameters Bayelsa groundwater." Variants of place names, including Yenagoa, Ogbia, Amassoma, Tombia, Nembe, Sagbama and Southern Ijaw, were paired with the terms aquifer, resistivity, VES, hydrogeophysics, transmissivity, protective capacity and vulnerability. The preliminary corpus included the previously identified Bayelsa and supporting Niger Delta publications, with emphasis on the directly relevant studies of Okiongbo and Akpofure (2012, 2016), Okiongbo and Odubo (2012), and Hassan *et al.* (2019).

Records were screened first by title and abstract and subsequently by full-text assessment. Studies were included when they examined a location in Bayelsa

State, applied a geoelectric or electrical resistivity method, and reported interpretable information on subsurface layers or aquifer units. Eligible papers were required to provide at least one comparable aquifer attribute, such as resistivity, depth, thickness, lithological interpretation, hydraulic-property estimate, longitudinal conductance, transverse resistance, protective capacity or vulnerability class, together with sufficient bibliographic and methodological information for evaluation. Regional Niger Delta studies were retained only when they described comparable coastal aquifers, contributed a method directly relevant to the Bayelsa case studies, or helped interpret the wider hydrostratigraphic and groundwater-management setting. Publications were excluded when they lacked electrical resistivity information, focused exclusively on surface-water quality, reported no identifiable aquifer parameter, duplicated an earlier dataset without additional interpretation, were geographically unrelated to Bayelsa or a comparable Niger Delta environment, or provided insufficient methodological detail for meaningful comparison. The screening and synthesis workflow is shown in Figure 2.

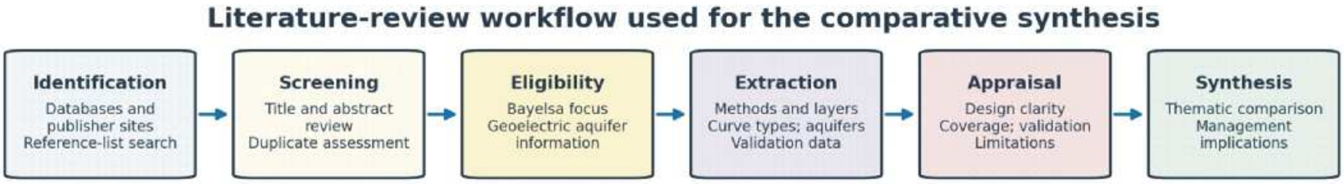

Fig. 2: Literature-review workflow for the identification, appraisal and synthesis of published geoelectric case studies.
Source: Authors' conceptualisation, informed by Page *et al*. (2021) and Snyder (2019).

A standardised extraction matrix was used to record, for each eligible publication, the author and year, study location and purpose, geoelectric method, electrode configuration, number and distribution of sounding stations, maximum electrode spacing, instrument and interpretation software, reported curve types, number of geoelectric layers, aquifer resistivity, depth, thickness and inferred lithology. The matrix also captured hydraulic-conductivity or transmissivity estimates, longitudinal conductance, transverse resistance, protective-capacity or vulnerability rating, the type of independent validation used, principal findings, acknowledged limitations and stated groundwater-management implications. Where a paper reported more than one aquifer unit or study locality, the information was extracted separately to preserve the original spatial and hydrostratigraphic distinctions. Units and terminology were harmonised for comparison, but published values and classifications were retained without recalculation or reinterpretation of the original field curves.

Methodological quality was appraised using criteria tailored to geoelectric aquifer studies. These included clarity of the survey objective and design; adequacy and reporting of electrode configuration and maximum spread; number, spacing and geographical distribution of sounding stations; transparency of manual or computer-assisted interpretation; reporting of model fit or inversion error; and recognition of equivalence, suppression and non-uniqueness. Additional weight was given to studies that constrained resistivity interpretations with borehole lithological logs, well-screen information, pumping-test results, groundwater electrical conductivity or hydrochemical evidence. The appraisal also considered whether aquifer and protective-capacity classes were based on clearly stated thresholds, whether empirical geoelectric–hydraulic relationships were locally calibrated, and whether limitations associated with clay, salinity, contamination and lateral facies variation were acknowledged. Quality appraisal was used to qualify the confidence assigned to individual findings rather than to calculate a numerical score or automatically exclude otherwise relevant Bayelsa case studies.

The eligible publications were synthesised through descriptive comparison and thematic grouping. Studies were organised by location, survey technique and analytical purpose, including aquifer delineation, hydraulic-property estimation, protective-capacity assessment, vulnerability mapping and integrated hydrogeophysical–hydrochemical characterisation. Reported curve types, layer sequences and aquifer parameters were tabulated, while resistivity, depth and thickness ranges were compared across Yenagoa, Ogbia and other investigated locations. Areas of agreement were identified where independent publications reported similar aquifer architecture, geoelectric behaviour or management concerns; areas of disagreement were examined in relation to differences in survey depth, station density, inversion method, lithological assumptions and validation evidence. Because the source studies varied substantially in design and reporting, no pooled effect estimate, new inversion, inferential statistical analysis or numerical recalibration of published empirical equations was undertaken.

The final critical synthesis linked the published evidence to groundwater-management decisions. Particular attention was given to the reliability of proposed drilling targets, selection of screen intervals, identification of thin or weakly protected shallow aquifers, interpretation of high- and low-transmissivity zones, and the need for hydrochemical verification where low resistivity could represent clay, saline water or contamination. Findings from Bayelsa State were interpreted within the regional coastal-aquifer framework described by Hassan *et al.* (2019) and the broader hydrogeological synthesis of Abam and Nwankwoala (2020). The approach was therefore designed to distinguish conclusions that are consistently supported across the literature from site-specific interpretations, expose geographical and methodological gaps, and develop evidence-based priorities for borehole regulation, aquifer protection, groundwater-quality monitoring and future hydrogeophysical research.

Geological and Hydrogeological Setting of Bayelsa State

Bayelsa State occupies a central, low-lying part of the Niger Delta in southern Nigeria and is characterised by an intricate network of distributary rivers, tidal creeks, swamps and estuarine channels. Yenagoa, the state capital and the most intensively investigated locality, lies within a predominantly alluvial and floodplain environment; other published case-study locations include Ogbia and communities distributed across the freshwater and coastal-swamp belts. The terrain is generally flat, poorly drained and locally waterlogged, while extensive wetlands, seasonal inundation and river crossings can constrain access and the spatial distribution of geophysical survey stations. These geographical conditions also explain the strong dependence on groundwater for domestic, institutional and commercial supply, despite the visual abundance of surface water, because many surface-water bodies are affected by suspended sediment, organic loading, microbial contamination, flood-borne wastes and, toward the coast and tidal reaches, possible brackish-water influence (Agbalagba *et al.*, 2011; Okiongbo & Akpofure, 2012; Okiongbo & Douglas, 2015). Figure 3 locates Bayelsa State and the principal case-study communities.

The climate is humid tropical, with high rainfall, a prolonged wet season and frequent flooding. Recharge to the shallow aquifer system is therefore largely associated with direct rainfall infiltration through permeable sandy horizons, supplemented locally by hydraulic interaction with rivers, creeks and floodwater. The very shallow water table reported across parts of the Niger Delta promotes rapid recharge but also creates short contaminant travel paths where the protective cover is thin or sandy. In tidal and estuarine settings, seasonal changes in river stage and tidal head may alter local gradients, enhance mixing and influence the distribution of fresh and saline groundwater. Thus, rainfall, flooding and surface-water connectivity operate both as recharge mechanisms and as pathways through which dissolved wastes, nutrients, microorganisms and petroleum-related contaminants may reach shallow groundwater (Abam & Nwankwoala, 2020; Hassan *et al.*, 2019; Ohwoghere-Asuma *et al.*, 2020).

Regionally, the Niger Delta sedimentary succession is commonly described in terms of the Akata, Agbada and Benin Formations. The Akata Formation constitutes the deep, marine, shale-dominated basal unit; the overlying Agbada Formation comprises interbedded sandstone and shale deposited mainly in paralic to delta-front environments; and the upper Benin Formation consists predominantly of continental to fluvial, unconsolidated sands with subordinate clay and silt. The groundwater systems examined by shallow geoelectric and borehole studies in Bayelsa State occur principally within the Benin Formation and younger alluvial, floodplain and swamp deposits. These near-surface sediments are highly heterogeneous, reflecting channel migration and repeated deposition of sand, silt, clay and organic-rich materials. Consequently, lithological boundaries may be laterally discontinuous, and similar depths may contain markedly different proportions of clay and sand between nearby communities or even between adjacent sounding stations (Abam & Nwankwoala, 2020; Hassan *et al.*, 2019; Oborie *et al.*, 2013). Figure 4 illustrates the resulting geological and hydrostratigraphic setting.

Published borehole and geoelectric evidence indicates a multilayer hydrostratigraphy rather than a single uniform aquifer. Shallow unconfined aquifers commonly occur in fine- to medium-grained sands beneath thin surficial deposits, whereas intermediate and deeper sand bodies may be semi-confined or locally

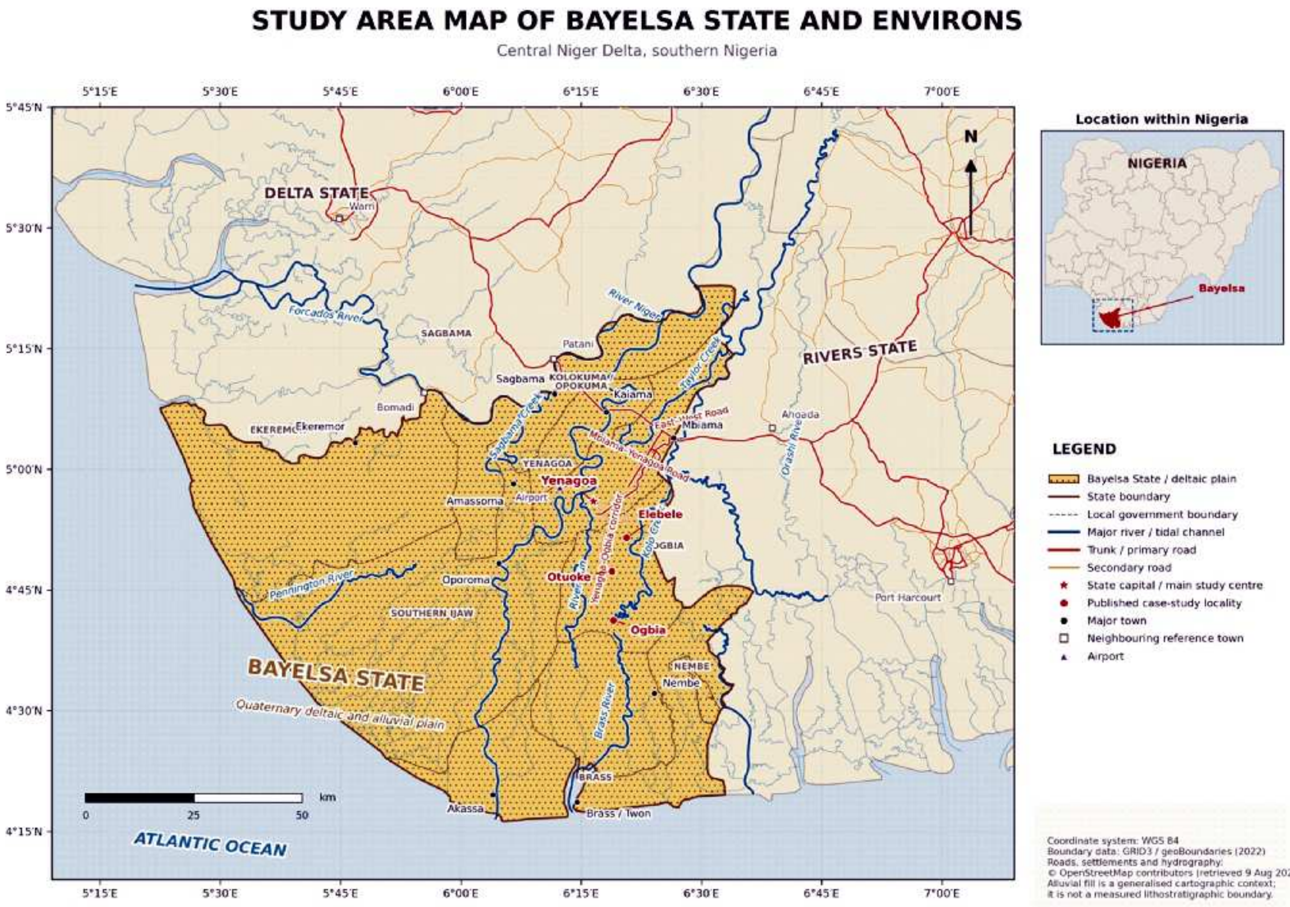

Fig. 3: Location of Bayelsa State and principal geoelectric case-study localities within its riverine-estuarine setting.

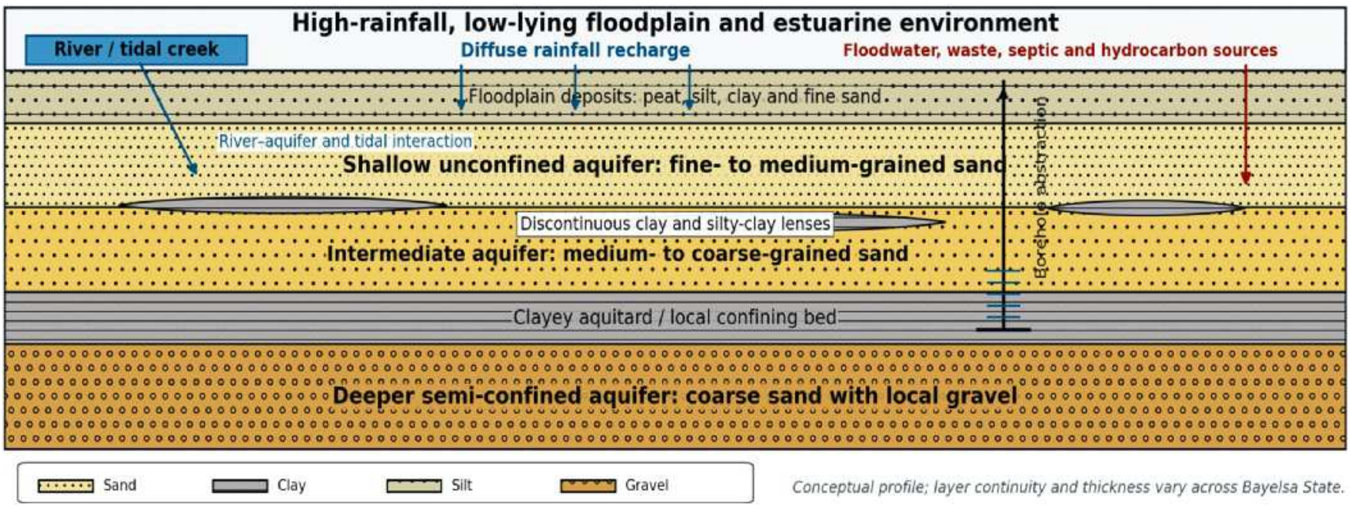

Fig. 4. Conceptual geological and hydrostratigraphic setting of Bayelsa State based on the published literature.
Source: Authors' conceptualisation from Abam & Nwankwoala (2020), Hassan et al. (2019), and Oborie et al., (2013).

confined by discontinuous clay and silty-clay lenses. The thickness, depth and continuity of these units vary spatially, and the same clay lenses that provide local protection may terminate abruptly or become sandy over short distances. In Yenagoa and its environs, vertical electrical sounding, borehole logs, pumping tests and hydrochemical information have delineated freshwater-bearing sands within a sequence of near-surface clay, silty sand and deeper alluvial sand units (Oborie *et al.*, 2013; Okiongbo & Akpofure, 2012, 2016). Geoelectric–hydraulic studies further show that thick sandy horizons can possess high transmissivity, although the transfer of local empirical relationships beyond their calibration areas requires caution (Okiongbo & Odubo, 2012).

The hydrogeological setting creates important water-quality and management challenges. Published studies from Yenagoa report spatial variability in iron and other dissolved constituents, with groundwater composition influenced by mineral weathering, redox conditions, recharge-water quality and local anthropogenic inputs (Agbalagba *et al.*, 2011; Okiongbo & Douglas, 2015). Iron and manganese enrichment can impair acceptability and treatment performance, while elevated electrical conductivity and total dissolved solids may reflect natural mineralisation, mixing with brackish water or contamination. Nitrate and microbial pollution are plausible where shallow wells or boreholes are poorly sealed and located near septic systems, waste dumps or flood-prone areas. Petroleum exploration, illegal refining, spills and associated waste disposal add further risk in parts of the Niger Delta, while coastal abstraction may intensify saline intrusion where pumping disturbs the freshwater–saline-water balance (Abam & Nwankwoala, 2020; Hassan *et al.*, 2019; Ohwoghere-Asuma *et al.*, 2020).

These conditions have direct implications for the interpretation and management of Bayelsa aquifers. Low resistivity may indicate clay, but it may also result from saline or contaminated pore water; conversely, a resistive sandy layer may be productive but cannot be assumed to contain potable water without hydrochemical confirmation. Reliable groundwater development therefore requires the integration of geoelectric models with borehole lithology, screen-depth information, pumping-test results and water-quality data. The shallow water table, discontinuous protective clay cover, seasonal flooding, poor sanitary completion of some boreholes and largely unregulated abstraction reinforce the need for wellhead protection, appropriate setback distances, periodic water-level and quality monitoring, and aquifer-specific drilling and screen-placement decisions. The published setting consequently provides the physical basis for critically comparing the reviewed geoelectric case studies and translating their findings into sustainable groundwater-management guidance for Bayelsa State.

Conceptual Basis of Geoelectric Aquifer Investigation

Electrical-resistivity investigation is based on the contrast in the capacity of earth materials to conduct electric current. In a conventional four-electrode measurement, current is introduced through two current electrodes and the resulting potential difference is measured between two potential electrodes. The measured quantity is converted to apparent resistivity, which represents the bulk electrical response of the volume sampled by the electrode array rather than the true resistivity of a single layer. The standard relationship is

$$\boldsymbol{\rho_a = K(\Delta V/I)} \qquad (1)$$

where ρ_a is apparent resistivity, K is the array-dependent geometric factor, ΔV is the measured potential difference and I is the injected current. In porous deltaic sediments, the response is controlled jointly by mineral composition, grain size, porosity, degree of saturation, clay content and pore-water conductivity. Clay and organic-rich deposits are commonly conductive because of surface conduction and retained ionic water; freshwater-bearing sand may be more resistive, whereas saline or contaminated sand can also be strongly conductive. Consequently, resistivity is a hydrogeophysical indicator rather than a unique lithological identifier, and published Bayelsa interpretations require local geological and hydrochemical control (Ohwoghere-Asuma *et al.*, 2020; Okiongbo *et al.*, 2011).

Vertical electrical sounding (VES) investigates vertical changes in electrical properties by progressively increasing electrode spacing about a sounding centre. Wider spacing increases the effective depth of investigation, and inversion of the apparent-resistivity curve provides an equivalent one-dimensional model of true layer resistivity, thickness and depth to geoelectric boundaries. The published Bayelsa studies have used these parameters to infer overburden thickness, lithological succession, depth to the top of aquifers, saturated thickness and the geometry of shallow and deeper groundwater-bearing sands. Schlumberger VES is dominant because the potential electrodes are moved less frequently than the current electrodes, permitting relatively efficient depth sounding with good signal strength. Yenagoa case studies used Schlumberger arrays together with one-dimensional inversion, borehole logs and, in stronger designs, pumping-test and hydrochemical data (Oborie *et al.*, (2013; Okiongbo

& Mebine, 2015). The Wenner configuration offers simple geometry and generally strong signal response, while dipole–dipole measurements and two-dimensional electrical resistivity imaging are more sensitive to lateral changes and may better represent discontinuous clay lenses, channel sands and contaminant plumes; however, these arrays are less prominent in the reviewed Bayelsa literature. The geoelectric investigation process is summarised in Figure 5.

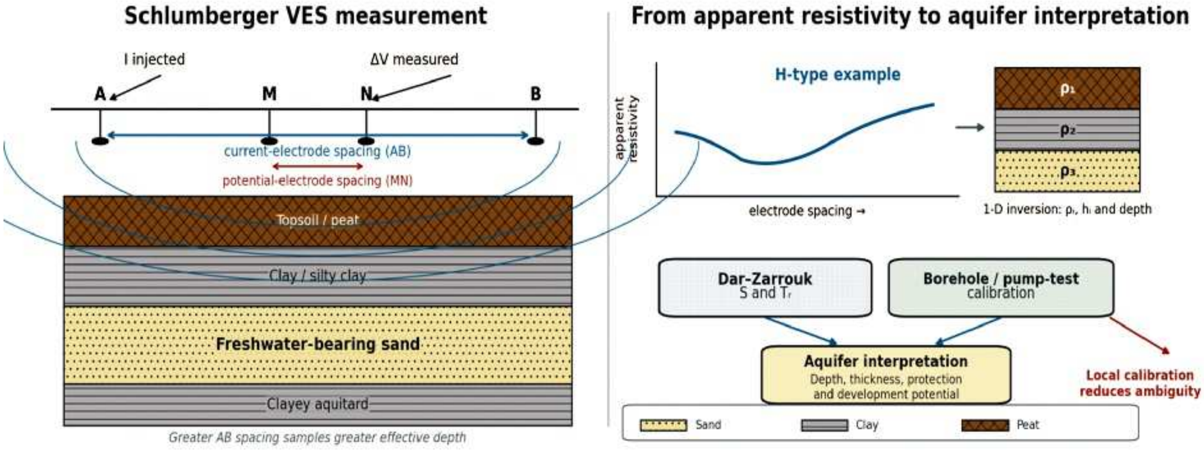

Fig. 5: Conceptual basis of geoelectric aquifer investigation.

The shape of a VES curve expresses the relative order of layer resistivities. For three-layer models, A-, H-, K- and Q-types respectively follow $\rho_3 < \rho_3 < \rho_3$, $\rho_3 > \rho_3 < \rho_3$, $\rho_3 < \rho_3 > \rho_3$ and $\rho_3 > \rho_3 > \rho_3$. Multilayer forms such as HA, KH, HK and KQ combine these elementary patterns and are common in sedimentary environments containing alternating conductive clay and resistive sand. Hydrogeologically, an H-type response may indicate a conductive clay or silty-clay layer between more resistive units, whereas a K-type response may reflect a comparatively resistive sand body bounded by more conductive materials. Complex curves can therefore suggest multiple aquifer and aquitard units, but the same curve family may have different lithological meanings where salinity, iron-rich pore water or clay content changes. The Bayelsa literature accordingly shows that curve-type interpretation is most reliable when checked against borehole lithology, screened intervals, groundwater electrical conductivity or hydrochemical results (Okiongbo & Akpofure, 2012, 2016; Okiongbo & Mebine, 2015).

Resistivity–lithology relationships in Bayelsa are therefore treated as overlapping, site-dependent ranges. Published interpretations commonly associate very low to low resistivity with clay, silty clay, peat, organic-rich deposits or saline water; intermediate values with sandy clay, clayey sand, fine sand or mineralised groundwater; and higher values with cleaner, freshwater-bearing medium- to coarse-grained sand. These associations are not universal. The 2012 Yenagoa vulnerability study reported a wide resistivity range for aquiferous horizons, while the integrated hydrogeophysical study later delineated freshwater aquifers using resistivity together with borehole, pumping-test and hydrochemical evidence (Okiongbo & Akpofure, 2012, 2016). This variability explains why a fixed threshold transferred from one community to another can misclassify conductive freshwater sand as clay, or saline sand as an aquitard. Interpretation should instead consider layer position, thickness, curve context, nearby logs and pore-water quality.For a horizontally layered earth, true layer resistivity and thickness can be combined into Dar–Zarrouk parameters. Longitudinal conductance and transverse resistance are expressed as

$$S = \Sigma(h_i/\rho_i) \quad (2)$$

$$T_r = \Sigma(h_i\rho_i) \quad (3)$$

where h_i and ρ_i are the thickness and resistivity of the ith layer. In the reviewed studies, overburden longitudinal conductance was used as an indicator of aquifer protective capacity because thick, conductive clay-rich cover yields greater conductance and may retard contaminant migration. Low conductance commonly signifies thin or sandy cover and greater vulnerability, although protection also depends on fractures, land use, water-table depth and contaminant loading. Transverse resistance integrates aquifer thickness and resistivity and has been used as a proxy for groundwater potential or transmissivity where lithology and groundwater resistivity are sufficiently uniform. Okiongbo and Odubo (2012) and Okiongbo and Mebine (2015) demonstrated the value of Dar–Zarrouk parameters for extending hydraulic information beyond the limited distribution of pumping-test wells, while Okiongbo *et al.* (2011) and Okiongbo and Akpofure (2012) applied conductance-based reasoning to protective-capacity and vulnerability assessment.

The link between electrical and hydraulic properties arises because porosity, pore connectivity, tortuosity, saturation and grain fabric influence both current flow and groundwater movement. Aquifer transmissivity is conventionally the product of hydraulic conductivity and saturated thickness, whereas geoelectric estimation relates these hydraulic quantities to aquifer resistivity, formation factor and Dar–Zarrouk parameters. Published Yenagoa applications derived local diagnostic relationships by pairing VES parameters with borehole or pumping-test values, then estimating hydraulic conductivity and transmissivity at sounding locations without direct tests (Okiongbo & Mebine, 2015; Okiongbo & Odubo, 2012). Such relationships are empirical and may change with clay fraction, pore-water salinity and depositional texture. Their management value lies in regionalising sparse hydraulic data and identifying comparatively favourable aquifer zones, but they should be regarded as calibrated estimates rather than substitutes for properly designed pumping tests. The most defensible conceptual approach for Bayelsa is therefore an integrated sequence: VES or resistivity imaging delineates geoelectric units; borehole logs constrain lithology and layer equivalence; pumping tests calibrate hydraulic relationships; hydrochemistry distinguishes freshwater, saline and contaminated conductive zones; and the combined evidence supports decisions on drilling depth, screen placement, aquifer protection and sustainable abstraction (Mgbolu *et al.*, 2019; Ohwoghere-Asuma *et al.*, 2020; Okiongbo & Akpofure, 2016).

Results and Discussion

Review of Published Geoelectric Case Studies in Bayelsa State

Published geoelectric evidence is concentrated in Yenagoa and the Ogbia axis but now includes Opolo-Epie, Otuoke and Elebele. The studies consistently depict sand-dominated alluvium interrupted by clay and silty-clay lenses and show that resistivity interpretation becomes more reliable when constrained by boreholes, pumping tests, hydraulic heads and chemistry.

Okiongbo *et al.* (2011) used 11 Schlumberger VES stations in Yenagoa to delineate five layers and identify likely fourth- and fifth-layer aquifers. Aquifer-top depth varied from about 6 to 52 m. Longitudinal conductance indicated weak protection around INC and Opolo and moderate-to-good protection elsewhere; conductive near-surface layers also implied corrosion risk. The study linked groundwater vulnerability with engineering planning and showed that weakly protected zones require stricter waste, sanitation and infrastructure controls.

Okiongbo and Odubo (2012) paired 19 VES stations with four pumping-test boreholes. Pumping-test transmissivity ranged from 1,634 to 5,292 m²/day and conductance-derived estimates from 721 to 8,991 m²/day, with $R^2 = 0.92$ in the calibration set. The results support reconnaissance ranking of productive Coastal Plain sands, but the small calibration set limits transferability; production-well design still requires pumping and recovery tests.

Okiongbo and Akpofure (2012) delineated topsoil, conductive wet clay, a thick sand aquifer and a deeper unresolved unit in Yenagoa. Longitudinal conductance produced poor-to-good protective classes, and adjacent boreholes did not necessarily show equivalent water quality, indicating lenticular and discontinuous sand bodies. The study demonstrates that a nearby successful well cannot guarantee the same aquifer thickness, protection or quality at another site.

In Ogbia, Oborie and Nwankwoala (2012) combined Schlumberger VES with wet- and dry-season chemistry. Aquifer resistivity was about 43-416 Ωm; high transverse resistance suggested appreciable potential, while low-to-moderate conductance indicated variable protection. Seasonal relations between formation resistivity and groundwater conductivity, together with fresh-to-slightly-brackish chemistry, show why local water quality must constrain interpretation.Oborie *et al.* (2013) interpreted 32 soundings to AB = 800 m and correlated them with 12 borehole logs. The first aquifer averaged 7.6 m depth in Yenagoa and 8.0 m in Ogbia, with thicknesses of 23-59 and 12-53 m and resistivities of 74-562 and 165-530 Ωm. Deeper units occurred near 45.5 m in Yenagoa and 68.5 m in Ogbia; an approximately 10 m clay bed locally created semi-confined conditions in Ogbia. The comparison supports site-specific lithological correlation before screen selection. Figure 6 synthesises the principal early case studies and their implications.

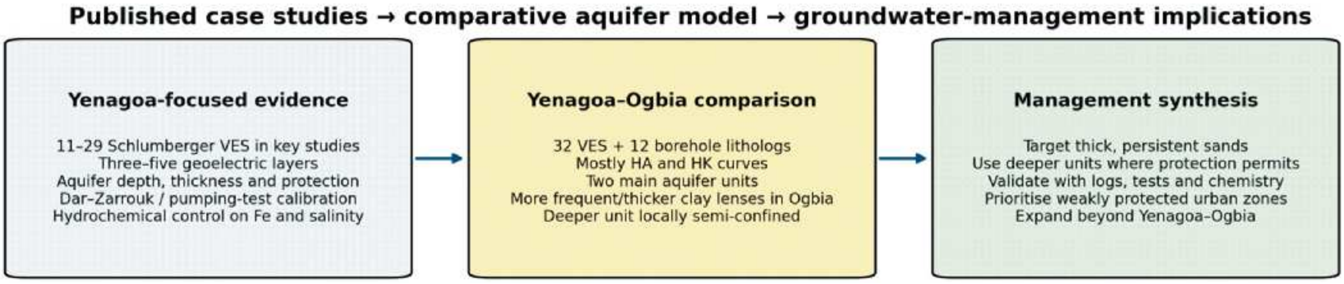

Fig. 6: Conceptual synthesis of the principal published Bayelsa case studies. The diagram summarises literature-derived evidence and management implications; it is not a new field map or geophysical result.

Okiongbo and Mebine (2015) combined 14 VES datasets with borehole information and calibrated geoelectric-hydraulic relations at three reference wells. Aquifer resistivity and thickness were 136.1-828.6 Ωm and 8.3-97.6 m; inferred hydraulic conductivity and transmissivity confirmed productive unconsolidated sand. The small calibration set and sensitivity to clay and salinity nevertheless restrict extrapolation.The most integrated Yenagoa investigation used 29 VES stations with boreholes, pumping tests and chemistry (Okiongbo & Akpofure, 2016). Freshwater-aquifer resistivity and thickness were 134-664 Ωm and 6.7-41.4 m; transmissivity was 189-2,609 m^2/day and hydraulic conductivity 28-118 m/day. The observed association between near-surface lithology and iron illustrates that aquifer quantity and quality must be evaluated together.

These early studies agree that aquifers are mainly unconsolidated sand, clay lenses create strong heterogeneity, shallow units are variably protected, and deeper units can be thicker and locally semi-confined. Differences in numerical ranges reflect both real facies variation and unequal survey depth, inversion, season and validation. Their results are useful locally but should not be extrapolated to the whole state without new control.Subsequent studies broadened the evidence from hydraulic estimation toward spatial vulnerability, groundwater flow, GIS mapping and borehole-constrained community surveys.

Oborie and Udom (2014) combined geoelectrical sounding with pumping tests to estimate transmissivity beyond tested wells. The approach demonstrates the spatial value of locally calibrated VES parameters, but also confirms that regressions developed in clean sand may perform poorly where clay, grain size or salinity changes. Geoelectric estimates should therefore guide reconnaissance, while pumping tests govern pump selection and abstraction.Oborie and Oki (2017) integrated 12 Ogbia VES stations with hydraulic heads. The main aquifer had resistivity of about 165-522 Ωm, thickness of 32.8-52.4 m and an average top depth of 6.8 m. Protection ranged from poor/weak to good, and regional flow was generally north-to-south. Vulnerability and flow direction together show that contaminants may move from upgradient communities into otherwise moderately protected areas.

Akana *et al.* (2016) showed that Yenagoa's shallow aquifer vulnerability varies with overburden, water-table depth, urban waste and flooding. Their results distinguish intrinsic vulnerability from actual pollution risk and support sanitary seals, flood-proof wellheads, adequate setbacks and periodic chemical and microbiological testing rather than reliance on drilling depth alone.At Opolo, Ovuru and Eteh (2021) delineated prospective aquifers from resistivity, thickness and curve geometry, while Eteh *et al.* (2021) combined VES-derived conductance with GIS to map protection. The point data reveal marked local heterogeneity; interpolated boundaries are best used to prioritise verification and monitoring, not as fixed aquifer limits. The wider case-study evidence and management relevance are summarised in Figure 7.

Adejumo *et al.* (2021) used 17 Otuoke soundings with an ABEM SAS 1000, WinResist and IPI2Win. A, K, KH and HK curves defined three to four layers and aquifer targets generally between 20 and 90 m. The wide depth range and mixed curves demonstrate changing geometry; lithological logs, pumping tests and water-quality analysis remain necessary before commissioning.A second Otuoke study correlated five VES models with borehole logs and confirmed sandy clay, dry sand, clay and saturated fine- to coarse-grained sand (Adejumo, Ottih, *et al.*, 2021). Agreement strengthened local interpretation but did not prove lateral continuity, underscoring the need for additional soundings or ERT where confining layers and saline boundaries must be traced.Oki and Didei (2024) modelled 10 VES stations at Federal University Otuoke. Three sites had poor, one moderate and the remainder

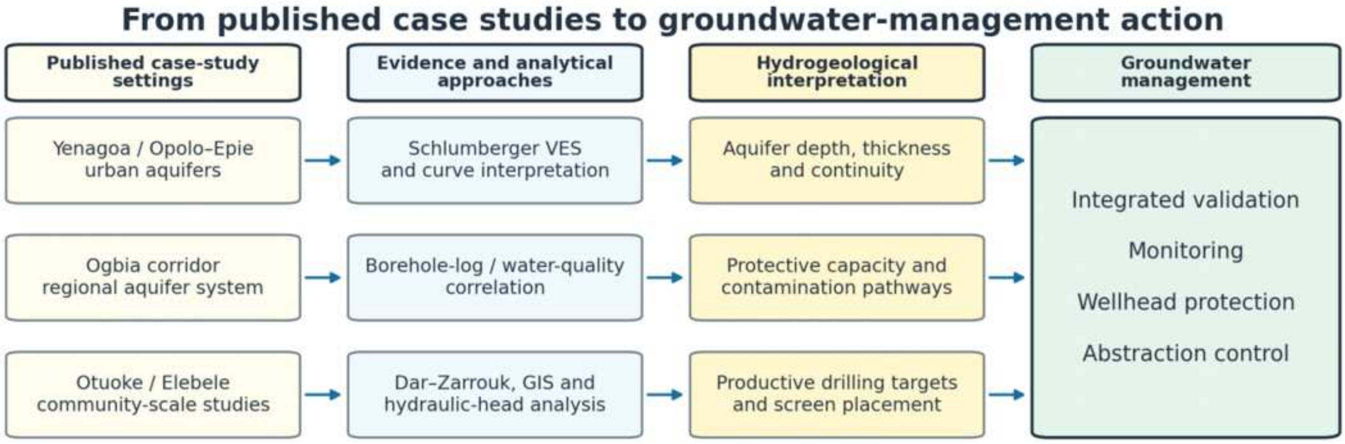

Fig. 7: Literature-based synthesis of reviewed geoelectric case studies in Bayelsa State and their groundwater-management relevance.

generally good overburden conductance. These contrasts support risk-based campus groundwater management that combines protection mapping with sanitary inspection, abstraction records and testing for microorganisms, nitrate, chloride, iron and manganese.

At Opolo-Epie, three VES profiles and a borehole log identified fine-to-coarse sands and clay, including a promising coarse-sand interval at about 33.3-42.4 m (Egai *et al.*, 2024). Disagreement over some deeper clay intervals illustrates one-dimensional suppression and equivalence; pumping tests, chemistry and complementary imaging are therefore required.Five Elebele VES datasets resolved four to five layers, with aquifer prospects near 10, 24.2 and 36.8 m and local clay confinement (Egai, Paaru, & Ofor, 2024). The small dataset limits extrapolation but confirms that aquifer depth and confinement vary over short distances; community programmes should not adopt a uniform drilling depth.

Overall, the case studies establish a multilayer system in which shallow aquifers are readily recharged but vulnerable, deeper sands are often thicker yet only locally confined, and resistivity ranges overlap across lithologies and water qualities. The strongest interpretations combine VES with multiple logs, seasonal chemistry, pumping tests or hydraulic heads. Conductance classes are useful screening indicators, but actual risk also depends on source loading, preferential flow, borehole integrity, flooding and regional groundwater movement.

Hydrochemical Constraints on Geoelectric Interpretation

Hydrochemical evidence is indispensable to a review of geoelectric aquifer delineation because electrical resistivity responds to both the solid framework and the conductivity of the pore water. In the unconsolidated, clay-interbedded and locally estuarine setting of Bayelsa State, a conductive layer may represent clay or organic-rich sediment, but it may also represent freshwater sand affected by dissolved ions, brackish-water encroachment or contamination. Conversely, a relatively resistive unit may be a clean freshwater-bearing sand, a dry or incompletely saturated sand, or a coarse sediment with weak ionic conduction. The hydrochemical case studies reviewed here are therefore considered only where they validate, refine or place limits on geoelectric interpretation. Their principal contribution is to distinguish hydraulic occurrence from water quality: a layer may be a productive aquifer in geoelectric and pumping-test terms yet remain unsuitable for drinking without treatment.

Agbalagba *et al.* (2011) analysed water from eight commercial boreholes in Yenagoa and reported spatial variation in pH, electrical conductivity, biochemical oxygen demand, calcium, iron and trace-metal occurrence. Their ionic-ratio analysis indicated that ion exchange and silicate weathering were important controls on groundwater chemistry. The study also reported generally elevated iron and isolated lead detections, and interpreted the first aquifer as more exposed to contamination and saline influence than deeper aquifer units. These findings are directly relevant to geoelectric interpretation: low resistivity within a shallow sand cannot automatically be assigned to clay, while apparent aquifer continuity does not demonstrate chemical acceptability. The recommendation to preferentially investigate deeper units, rather than indiscriminately exploiting the shallowest saturated layer, supports the use of VES-derived depth and thickness information together with aquifer-specific chemical testing and sanitary borehole completion.

The hydrogeochemical assessment by Okiongbo and Douglas (2013) similarly showed that aquifer characterisation requires more than the recognition of a sand layer. Their evaluation of groundwater quality across Yenagoa and its environs used major-ion chemistry and graphical interpretation to identify spatial variation in water composition and suitability. Okiongbo and Akpofure (2014) extended this approach by combining major-ion data, multivariate statistics and conventional hydrochemical plots. The dominant water types included Ca-Cl, Ca-HCO_3 and Na-HCO_3 facies, while ionic relationships indicated silicate weathering and reverse ion exchange as major controls on groundwater evolution. These facies provide a chemical basis for qualifying geoelectric units: Ca-HCO_3 or Na-HCO_3 water with low dissolved-ion content is more consistent with recently recharged freshwater in permeable sand, whereas elevated chloride, sodium and electrical conductivity may indicate longer residence, mixing, saline influence or anthropogenic loading. The interpretation must remain site specific because natural ion exchange can alter Na and Ca without necessarily indicating seawater intrusion.

Nwankwoala *et al.* (2014) applied descriptive statistics and correlation analysis to groundwater in Yenagoa. The waters were generally soft, slightly acidic and low in total dissolved solids, but iron varied considerably and locally reached concentrations of management concern. This distinction is important for hydrogeophysical review: low TDS and modest conductivity can support the interpretation of freshwater-bearing sand even when iron is elevated. Iron enrichment may arise from reductive dissolution, mineral weathering or well-completion conditions and can produce aesthetic and treatment problems without implying that the aquifer is saline. Correlation analysis can identify groups of variables with a common source or process, but correlation alone does not establish causation; its strongest use is in combination with lithological, redox and spatial evidence.

The most developed multivariate treatment among the listed Yenagoa studies was presented by Okiongbo and Douglas (2015), who analysed 51 borehole samples using graphical methods and principal component analysis. Three components explained 78.38% of the total variance and were interpreted as reflecting silicate weathering, reverse ion exchange and oxidation reactions, with only limited anthropogenic influence. This result demonstrates how multivariate methods can reduce a large chemical dataset to process-related associations and thereby strengthen interpretation of resistivity contrasts. Principal component analysis and correlation analysis were more consistently used than cluster analysis in the core Bayelsa literature. The limited application of cluster analysis is itself a methodological gap, because grouping chemically similar wells could help test whether geoelectrically correlated aquifer units also display coherent water types across space. Figure 8 shows how hydrochemistry resolves non-unique resistivity interpretations.

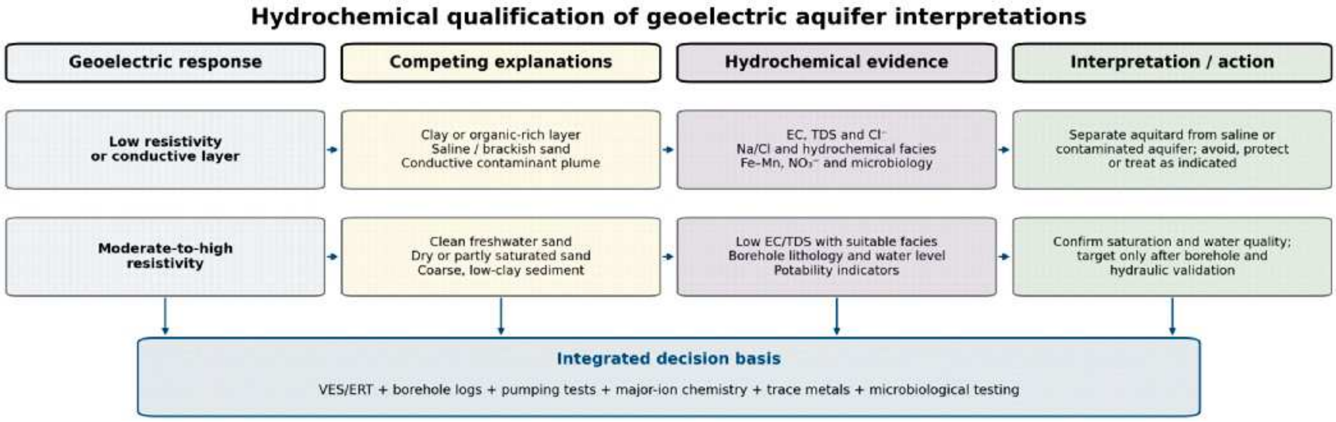

Fig. 8: Conceptual use of hydrochemistry to resolve non-unique geoelectric aquifer interpretations. The diagram is an original synthesis of the reviewed literature and does not represent new field data.

Taken together, the Yenagoa studies provide a practical interpretive sequence. Where VES or electrical resistivity imaging identifies a low-resistivity unit, borehole lithology should first determine whether the interval is clay-rich or sandy. If it is sandy, groundwater electrical conductivity, TDS, chloride and the Na-Cl relationship help evaluate saline or contaminant influence. Piper or related facies diagrams then place the sample within its broader hydrochemical evolution, while iron and manganese data indicate redox-sensitive mineralisation that may affect potability even in otherwise fresh water. Nitrate and microbiological indicators are required to assess sanitary contamination because dilute microbial pollution may not create a resolvable resistivity anomaly. For moderate- or high-resistivity sands, hydrochemistry verifies that the unit is saturated with fresh water rather than merely dry, coarse material. Thus, the geoelectric and chemical datasets answer different but complementary questions: geoelectric methods define geometry and continuity, whereas hydrochemistry defines water type, origin, evolution and suitability.

Regional studies from the Niger Delta and other southern Nigerian coastal aquifers reinforce this interpretation. Nganje *et al.* (2017) showed that groundwater chemistry in the Niger Delta region reflects geological controls and water-rock interaction, while Owoyemi *et al.* (2019) demonstrated strong spatial variation in groundwater quality and geochemical evolution across Delta State. Aladejana *et al.* (2020) further showed that shallow coastal aquifers with permeable overburden can experience water-quality changes associated with flooding, saline influence and redox processes. These regional results are relevant to Bayelsa because its shallow water tables, frequent flooding, tidal creeks and discontinuous clay lenses create multiple pathways by which pore-water chemistry may alter the measured resistivity of aquifer units. However, regional chemical ranges should not be transferred uncritically to Bayelsa; local geology, season, depth and pumping history must be considered.

The principal limitation of resistivity-only interpretation is therefore non-uniqueness. Low resistivity can signify clay, peat, saline water, high dissolved solids or a contaminant plume, while high resistivity can signify either freshwater-bearing sand or unsaturated coarse sediment. Geoelectric delineation also does not establish potability, because acidity, iron, manganese, nitrate, trace metals and microorganisms may remain unacceptable in an aquifer that appears favourable in thickness and resistivity. The reviewed evidence supports an integrated management protocol in which geoelectric surveys guide borehole location and screen depth; borehole logs confirm lithology; pumping tests establish productivity; and hydrochemical and microbiological analyses determine whether each screened aquifer can be safely used. Repeated wet- and dry-season sampling is particularly important in shallow and weakly protected aquifers. In management terms, this integration reduces the risk of mistaking conductive freshwater sand for clay, targeting saline or contaminated layers, or commissioning productive boreholes whose water requires unrecognised treatment. Hydrochemical studies should consequently be treated not as separate water-quality exercises, but as essential validation and decision-support components of geoelectric aquifer investigation in Bayelsa State.

Regional Comparison with Other Niger Delta Studies

Regional comparison is necessary because the aquifers beneath Bayelsa State are part of the laterally extensive but internally heterogeneous Benin Formation groundwater system that underlies much of the Niger Delta. Published syntheses describe this system as a complex succession of unconsolidated sand and gravel aquifers separated by discontinuous clay and shale lenses, with hydraulic conditions varying from shallow unconfined units to deeper semi-confined and confined aquifers. The broad architecture is therefore shared across Bayelsa, Delta and Rivers States, but the thickness, continuity, hydraulic performance and water quality of individual units change with depositional setting and distance from the coast. Abam and Nwankwoala (2020) noted that coarser, more laterally extensive sands tend to dominate the inland and upper-delta sectors, whereas clay intercalations become more frequent toward the transition and coastal zones. Hassan *et al.* (2019) similarly showed that regional groundwater management requires a hydrostratigraphic framework rather than the assumption of one uniform aquifer, because borehole logs and hydraulic data reveal vertically stacked aquifers with contrasting resilience to contamination and abstraction.

The Bayelsa case studies fit this regional model. Shallow freshwater-bearing sands are widespread and commonly productive, but their protection depends on the thickness and continuity of overlying clayey materials. Deeper sands may provide larger saturated thicknesses and greater buffering from surface contamination, yet confinement is local rather than regional because the clay separators are discontinuous. This pattern is comparable to the shallow coastal aquifers reviewed by Hassan *et al.* (2019), in which transmissivity and hydraulic conductivity vary markedly over short distances as channel sands grade laterally into silty or clay-rich deposits. The implication is that productive boreholes may occur close to low-yield or poorly protected sites even within the same settlement. Bayelsa should therefore not adopt a uniform drilling depth or yield expectation; geoelectric interpretation must be coupled with lithological logs and pumping tests to identify the locally continuous part of an aquifer and to distinguish transmissive sand from conductive clay or mineralised groundwater.

The Ndokwa investigations in Delta State provide an instructive inland comparison. Mgbolu *et al.* (2019) integrated vertical electrical sounding, aquifer hydraulic characterisation and vulnerability assessment to classify groundwater-potential zones and evaluate the protective function of the overburden. The study demonstrates the management advantage of treating aquifer potential and vulnerability as related but separate attributes: thick or resistive sand may offer favourable yield, while a thin or permeable vadose zone may still permit rapid contaminant migration. Relative to the more estuarine parts of Bayelsa, Ndokwa commonly represents a more continental depositional setting, with thicker sandy units and less direct exposure to tidal salinity. Nevertheless, the occurrence of weak protective cover in some locations shows that inland position alone does not guarantee aquifer security. The lesson for Bayelsa is that groundwater-potential mapping should always be accompanied by protective-capacity or vulnerability evaluation, especially where high-yield shallow aquifers are developed near waste-disposal sites, septic systems, fuel-storage facilities or flood-prone ground. The inland-to-coastal comparison is illustrated in Figure 9.

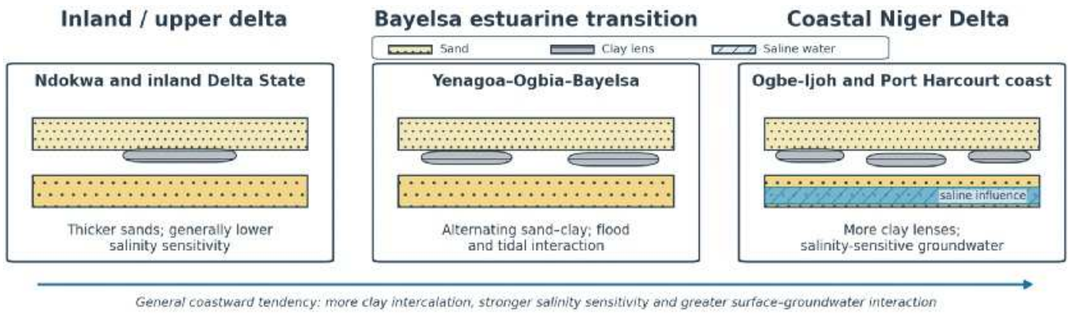

Fig. 9: Literature-based conceptual comparison of aquifer architecture and groundwater pressures from inland to coastal sectors of the Niger Delta. The diagram is a synthesis rather than a measured regional cross-section.

Western Delta State studies also show why electrical and hydrochemical evidence must be interpreted together. In Ogbe-Ijoh, Ohwoghere-Asuma *et al.* (2020) combined resistivity investigation with groundwater-quality evaluation in a low-lying coastal environment. The work showed that conductive subsurface zones cannot automatically be labelled as clay because groundwater mineralisation and contamination may also reduce bulk resistivity. Water-quality constraints, including acidity, further demonstrated that a geophysically delineated aquifer may not be suitable for drinking without treatment. Owoyemi *et al.* (2019), using spatial and hydrogeochemical analysis across Delta State, likewise identified pronounced geographical variation in groundwater evolution and suitability. These findings parallel Bayelsa, where tidal creeks, variable recharge, organic-rich sediments and anthropogenic inputs can produce similar electrical responses through different processes. Consequently, the transfer of fixed resistivity thresholds between Yenagoa, Ogbia, Ogbe-Ijoh and other deltaic communities should be avoided unless supported by pore-water conductivity, chloride, total dissolved solids and borehole-lithology data.

The Osubi vulnerability study provides a further comparison between site-specific geoelectric interpretation and regional risk assessment. Chinemelu and Adeoye (2022) applied the DRASTIC-GIS framework and classified 7% of Osubi as very highly vulnerable, 18% as highly vulnerable, 60% as moderately vulnerable and 15% as having low vulnerability. The most vulnerable sectors were associated with waste dumps and residential sanitation systems. Although DRASTIC does not replace geoelectric sounding, it incorporates depth to groundwater, recharge, aquifer and soil media, topography, vadose-zone characteristics and hydraulic conductivity, thereby placing resistivity-derived aquifer information within a broader contaminant-pathway model. The Bayelsa literature would benefit from comparable integration. Longitudinal conductance can indicate the filtering potential of the overburden, but urban floodwater, abandoned wells, poorly sealed annuli and shallow septic systems may bypass that natural protection. A combined geoelectric-GIS framework is therefore more appropriate for prioritising wellhead protection and groundwater-quality monitoring in rapidly expanding parts of Yenagoa.

Rivers State and Port Harcourt studies reinforce the regional importance of hydrochemistry and abstraction management. Eyankware *et al.* (2021) characterised groundwater in a coastal Niger Delta aquifer and reported that high electrical conductivity corresponded with poorer groundwater quality, reflecting the influence of dissolved ions and possible salinisation processes. The study also illustrates that management must consider corrosion and scaling, not only aquifer yield. Regional hydraulic assessments synthesised by Hassan *et al.* (2019) and Abam and Nwankwoala (2020) indicate that the Benin Formation can sustain prolific boreholes, but large yields and high permeability also create efficient pathways for contaminant transport and increase the risk of drawdown-induced movement of mineralised water where pumping is concentrated. For Bayelsa, the Port Harcourt comparison supports regulated borehole spacing, routine water-level observation and periodic electrical-conductivity and chloride monitoring around high-capacity public, industrial and commercial abstractions.

Supporting studies from the wider Niger Delta and adjoining southern Nigerian sedimentary basins help to qualify the Bayelsa interpretation. Nganje *et al.* (2017) demonstrated that major-ion chemistry and hydrochemical processes vary with lithology, residence time and anthropogenic influence across the Cross River Basin and Niger Delta region. In the Eastern Dahomey Basin, Aladejana *et al.* (2020) showed that shallow coastal groundwater quality is sensitive to seasonal recharge, flooding, redox conditions and climate-related changes; their findings are relevant to Bayelsa because both settings contain shallow unconsolidated aquifers exposed to saline influence and intense rainfall. These regional studies show that recharge is not uniformly beneficial. Rainfall replenishes aquifers, but in densely settled or flooded terrain it can also mobilise nitrate, microbial contaminants, hydrocarbons and dissolved metals through permeable sands or poorly completed wells. The management objective should therefore be to protect recharge quality while maintaining infiltration, rather than simply maximising recharge.

Recent integrated work further confirms the value of linking geoelectric and hydrochemical evidence. Ben-Owope and Agbasi (2025) combined geo-electrical and hydrochemical characterisation of unconfined Niger Delta aquifers and related the results to sustainable groundwater use and the achievement of water-related development goals. This approach addresses a recurrent weakness in earlier investigations: geoelectric data are effective for defining layer geometry and apparent protective capacity, whereas hydrochemistry is required to determine whether the identified groundwater is fresh, saline, naturally metal-rich or anthropogenically contaminated. When combined with pumping tests, the three evidence streams provide complementary answers—where the aquifer occurs, how much water it may transmit and whether the water is suitable for the intended use. This integrated sequence is particularly important in Bayelsa because low resistivity may represent clay, saline water, high iron-bearing groundwater or hydrocarbon-affected pore fluids, while high resistivity may reflect either freshwater-bearing sand or unsaturated coarse material.

Across the Niger Delta, the principal similarities are therefore the dominance of unconsolidated sandy aquifers, vertical and lateral interbedding with clay, shallow groundwater levels, high rainfall recharge, spatially variable protective capacity and vulnerability to both surface-derived contamination and saline influence. Bayelsa is distinguished less by a unique aquifer lithology than by the intensity with which these regional controls interact. Its extensive river and creek network, very low relief, frequent flooding and estuarine setting strengthen surface-water-groundwater connectivity and make shallow aquifers responsive to tidal and seasonal hydraulic changes. Urban expansion in Yenagoa increases abstraction and contaminant loading, while hydrocarbon production, pipelines and associated facilities add potential sources of petroleum-related pollution. In communities with limited sanitation and drainage infrastructure, floodwater and wastewater may reach boreholes through permeable near-surface sediments or defective wellheads even where the deeper aquifer has moderate natural protection. Table 1 summarises the regional aquifer contrasts and management priorities.

The regional comparison supports a differentiated management strategy for Bayelsa State. Inland and relatively well-drained zones may prioritise confirmation of aquifer continuity, yield and borehole interference, whereas estuarine and coastal zones require stronger salinity surveillance, conservative abstraction and hydrochemical validation. In all settings, VES or two-dimensional resistivity imaging should guide drilling but should not be used alone to certify water quality. Borehole logs should confirm lithology and screen placement; pumping and recovery tests should establish transmissivity and sustainable discharge; and chemical and microbiological testing should determine fitness for domestic, institutional or

Table 1: Regional comparison of aquifer characteristics and management priorities reported in the reviewed literature.

Regional setting	Aquifer architecture	Principal concern	Management emphasis
Ndokwa/inland Delta	Thicker sand units with variable overburden	High potential can coincide with weak protection	Joint potential–vulnerability assessment
Osubi/Ogbe-Ijoh	Shallow sands with clay and conductive pore water	Waste sources, acidity and resistivity ambiguity	DRASTIC-GIS plus hydrochemical validation
Bayelsa estuarine belt	Multilayer sands separated by discontinuous clay	Flooding, tidal interaction and poorly sealed wells	Site-specific VES, pumping tests and wellhead protection
Port Harcourt/coast	Highly permeable coastal sands with clay lenses	Salinity, corrosion and concentrated abstraction	EC/chloride monitoring and abstraction control

industrial use. A state-wide groundwater information system should integrate geoelectric models, lithological logs, screened intervals, static and dynamic water levels, pumping-test results, seasonal hydrochemistry and contaminant-source inventories. Such integration would allow the many site-specific Bayelsa investigations to be correlated with regional Niger Delta patterns and converted into enforceable guidance for wellhead protection, borehole spacing, abstraction control, flood-resilient construction and long-term aquifer monitoring.

Comparative Synthesis of Published Findings

The publications considered in this review span 2011–2025, but the directly relevant Bayelsa geoelectric evidence is concentrated mainly between 2011 and 2016 and geographically clustered in Yenagoa and Ogbia. Later publications increasingly provide regional Niger Delta comparisons, vulnerability frameworks and integrated hydrochemical interpretation rather than equivalent state-wide coverage. This temporal and spatial distribution is important: the existing literature is sufficiently mature to establish recurring hydrogeological patterns, but it remains too uneven to represent all parts of Bayelsa State with equal confidence. Yenagoa, Ogbia and adjoining central Bayelsa communities have received repeated attention, whereas Brass, Nembe, Southern Ijaw, Sagbama and many riverine or estuarine settlements remain under-represented. Consequently, the published evidence should be treated as a strong synthesis of investigated localities rather than a complete geoelectric atlas of the state (Oborie *et al.*, 2013; Okiongbo & Akpofure, 2012, 2016).

Survey design was dominated by one-dimensional vertical electrical sounding using the Schlumberger configuration. Key Yenagoa and Bayelsa investigations used 19 soundings with maximum current-electrode separations of approximately 300–400 m, whereas the Yenagoa–Ogbia comparison used 32 soundings and a maximum AB of 800 m, supported by 12 borehole lithological logs (Oborie *et al.*, 2013; Okiongbo & Akpofure, 2012; Okiongbo & Odubo, 2012). The deeper spread used by Oborie *et al.* (2013) enabled a clearer distinction between shallow and deeper aquifer units, while shorter spreads were adequate for shallow aquifer characterisation and vulnerability analysis. Survey density, sounding orientation and access constraints varied considerably because of buildings, vegetation, wetlands and narrow road corridors. Computer-assisted one-dimensional inversion was widely adopted, using packages such as Interpex IX1D and related iterative programs, although inversion errors, equivalence tests and uncertainty bounds were not consistently reported. The methodological trend across the literature therefore moves from VES-only interpretation towards integration with borehole logs, pumping tests, groundwater electrical conductivity and hydrochemistry, with two-dimensional resistivity imaging appearing more often in regional studies than in the earlier Bayelsa publications (Hassan *et al.*, 2019; Mgbolu *et al.*, 2019; Ohwoghere-Asuma *et al.*, 2020).

Three- to five-layer earth models recur across the published Bayelsa investigations. Four-layer models were reported around parts of Yenagoa, while the broader Yenagoa–Ogbia study identified three, four and five layers depending on sounding depth and local sedimentary variability (Oborie *et al.*, 2013; Okiongbo & Akpofure, 2012). The more complex models generally reflect repeated alternation of fine- to coarse-grained sands with thin clay, silty clay or clayey-sand lenses rather than fundamentally different regional stratigraphy. Ogbia commonly displayed greater variability and more frequent or thicker clay intercalations than Yenagoa, producing locally semi-confined deeper aquifers. Thus, differences in layer number should not be interpreted solely as geological contradiction; they also arise from maximum electrode spread, data density, inversion assumptions, suppression of thin beds and the depth interval investigated. The consistent regional message is a multilayer groundwater system within the unconsolidated Benin Formation and younger deltaic deposits, with aquifer boundaries locally interrupted rather than laterally uniform (Abam & Nwankwoala, 2020; Oborie *et al.*, 2013).

Published curve-type distributions support this interpretation. HA and HK curves were the most prominent forms in the Yenagoa–Ogbia investigation, with HA more common in Yenagoa and HK more prominent in Ogbia; KH, AA and more complex combinations also occurred (Oborie *et al.*, 2013). Other Yenagoa studies described four-layer sequences equivalent to H- or K-bearing composite curves, showing that resistivity first decreases into conductive near-surface or clay-rich material and then increases into sandy aquifer units (Okiongbo & Akpofure, 2012).

The literature does not, however, provide a standardised state-wide frequency table because sample sizes, naming conventions and the number of resolved layers differ among studies. Curve types are therefore most useful as qualitative indicators of vertical lithological succession: H components commonly reflect conductive material between more resistive layers, K components indicate a relatively resistive intermediate bed, and A or AA trends are associated with progressively increasing resistivity. Their hydrogeological significance must be confirmed from layer thickness, borehole lithology and water chemistry rather than curve shape alone. Figure 10 consolidates the comparative evidence from the reviewed studies.

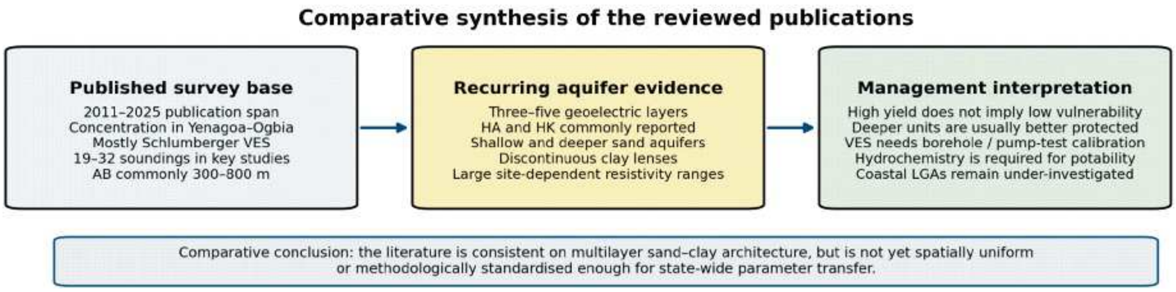

Fig. 10: Comparative synthesis of the scope, recurring aquifer evidence and management interpretation of the reviewed publications. Values and patterns are literature-derived rather than products of a new survey.

Aquifer resistivity is the most variable parameter across the studies and illustrates why fixed lithological thresholds are unreliable. Okiongbo and Akpofure (2012) reported an aquifer-horizon range of about 60–2868 Ωm across Yenagoa, whereas the integrated shallow-aquifer study reported freshwater-aquifer resistivities of 134–664 Ωm and thicknesses of 6.7–41.4 m (Okiongbo & Akpofure, 2016). Oborie *et al.* (2013) delineated the first aquifer at 74–562 Ωm in Yenagoa and 165–530 Ωm in Ogbia, while the deeper aquifers ranged from 327–903 Ωm and 360–634 Ωm, respectively. These overlapping ranges reflect differences in grain size, clay fraction, porosity, degree of saturation, pore-water ionic concentration and possible contamination, in addition to inversion and sampling differences. Resistivity therefore identifies electrical contrasts rather than lithology uniquely: low values may represent clay, saline or mineralised groundwater, and high values may indicate coarse freshwater sand or comparatively unsaturated material. The most defensible interpretation is obtained when resistivity is evaluated jointly with hydrochemical evidence and local borehole control (Agbalagba *et al.*, 2011; Okiongbo & Akpofure, 2016).

Aquifer depth and thickness show both agreement and meaningful spatial variation. In the Yenagoa–Ogbia study, the first aquifer occurred at average depths of approximately 7.6 and 8.0 m, with thicknesses of 23–59 m and 12–53 m, respectively. The second aquifer was identified at an average depth of 45.5 m in Yenagoa and 68.5 m in Ogbia, with corresponding thicknesses of 34–72 m and 24–51 m (Oborie *et al.*, 2013). A separate Yenagoa vulnerability study reported aquifer depths from 4.5 to 27.0 m, demonstrating substantial local variation even within the urban area (Okiongbo & Akpofure, 2012). The recurring conceptual model is therefore a shallow, generally unconfined aquifer and a deeper, locally semi-confined unit separated by discontinuous clay. The deeper aquifer is usually interpreted as less vulnerable and potentially more productive, but it is not automatically preferable because drilling cost, iron enrichment, salinity and local confinement may affect usability. Lateral continuity is strongest within sand-dominated sectors and weakest where clay lenses thicken, particularly toward parts of Ogbia and the estuarine transition.

Hydraulic interpretations similarly converge on high groundwater potential but differ in numerical estimates and calibration strength. Okiongbo and Odubo (2012) obtained pumping-test transmissivities of 1634–5292

m^2/day and geoelectrically estimated values of 721–8991 m^2/day, with a reported coefficient of determination of 0.92 between pumping-test transmissivity and longitudinal-conductance-derived estimates. These high values are consistent with thick, permeable Coastal Plain sands, but they should be transferred beyond the calibration locations cautiously. Other studies related aquifer thickness, resistivity, formation factor, transverse resistance and longitudinal conductance to hydraulic conductivity or transmissivity, supporting rapid preliminary appraisal where pumping tests are unavailable (Oborie & Nwankwoala, 2012; Okiongbo & Mebine, 2015). Agreement is strongest where electrical and hydraulic parameters were calibrated at nearby boreholes; it is weaker where empirical constants were applied without local pumping-test control. The synthesis therefore supports geoelectric estimation as a screening tool, not a substitute for properly designed pumping and recovery tests when sustainable abstraction rates are required.

Protective-capacity assessments reveal marked spatial variability. In the Yenagoa vulnerability study, longitudinal conductance above 0.5 S was associated with good protection, whereas values below 0.3 S identified vulnerable zones (Okiongbo & Akpofure, 2012). Other Bayelsa and regional Niger Delta studies reported classes ranging from poor or weak to good and very good, depending mainly on the thickness and conductivity of the overburden (Mgbolu *et al.*, 2019; Okiongbo *et al.*, 2011). The published evidence does not justify assigning one protective-capacity class to an entire town or local government area: thin sandy cover, discontinuous clay and shallow water tables can create vulnerable pockets close to better-protected locations. Moreover, high transmissivity and high groundwater potential may coexist with low protection. This distinction is central to management because the most productive shallow aquifers may also be the most rapidly contaminated by septic effluent, dumpsites, floodwater or hydrocarbon releases.

Validation practices account for much of the difference in confidence among studies. Borehole lithological logs were the most direct check on interpreted layer composition and aquifer depth, pumping tests provided hydraulic calibration, and hydrochemistry helped distinguish freshwater-bearing sands from saline, iron-rich or contaminated conductive zones. Static water levels and existing geological information supplied useful contextual control, while regional two-dimensional resistivity studies demonstrated the value of imaging lateral changes that one-dimensional VES may miss (Oborie *et al.*, 2013; Ohwoghere-Asuma *et al.*, 2020). Nevertheless, the availability and density of these validation data were inconsistent. Some investigations were strongly integrated; others relied mainly on modelled resistivity. Reported inversion errors, seasonal repeat measurements and independent validation were often limited. Consequently, numerical disagreement among studies may represent real geological variability, different depths of investigation or unequal validation rather than analytical failure.

The major areas of agreement are therefore clear: Bayelsa is dominated by sand–clay intercalations; more than one groundwater-bearing unit is common; productive freshwater occurs principally within fine- to coarse-grained sand; confining clay is laterally discontinuous; shallow aquifers are widely vulnerable; and reliable groundwater assessment requires geoelectric, borehole, hydraulic and hydrochemical integration. The principal uncertainties concern the resistivity threshold assigned to freshwater sand, the exact number and regional continuity of aquifer units, transmissivity outside calibrated sites, protective-capacity boundaries and the extent to which central Bayelsa findings can be transferred to unstudied coastal communities. For groundwater management, the synthesis supports site-specific geoelectric investigation before drilling, confirmation of lithology and screen depth from borehole logs, pumping tests for production wells, hydrochemical and microbiological certification, and a state-wide database that standardises VES spacing, inversion reporting and vulnerability classification. Such measures would convert a currently fragmented body of case studies into a more coherent basis for borehole siting, abstraction control, aquifer protection and future monitoring.

Critical Appraisal of the Existing Literature

The reviewed literature demonstrates that electrical-resistivity methods have made an important contribution to groundwater investigation in Bayelsa State and the wider Niger Delta. Vertical electrical sounding (VES), particularly with the Schlumberger array, has provided a comparatively inexpensive means of extending subsurface information beyond isolated boreholes, identifying sand-dominated groundwater-bearing intervals, estimating aquifer depth and thickness, and evaluating protective capacity from Dar–Zarrouk parameters. Studies in Yenagoa and adjoining areas also showed that geoelectric parameters can be related to transmissivity and hydraulic conductivity when pumping-test control is available, thereby improving the practical value of resistivity surveys for borehole siting and preliminary yield assessment (Okiongbo & Mebine, 2015; Okiongbo & Odubo, 2012). The ability of these surveys to distinguish major sand–clay alternations is particularly useful in the unconsolidated Benin Formation, where outcrop control is poor and borehole drilling is costly. Published investigations have consequently supplied practical guidance on target aquifer intervals, overburden protection and locations requiring more cautious groundwater development (Okiongbo & Akpofure, 2012, 2016).

A further strength is the gradual movement from purely descriptive sounding interpretation toward integrated hydrogeophysical assessment. Borehole lithological logs, pumping tests and hydrochemical observations were incorporated in some studies, allowing resistivity-derived layer models to be checked against direct geological and hydraulic evidence. Regional investigations in Ndokwa and Ogbe-Ijoh similarly combined VES or resistivity imaging with borehole, vulnerability or water-quality information, illustrating the benefit of treating geophysical signatures as one component of a wider aquifer-characterisation framework rather than as direct proof of lithology or potability (Mgbolu *et al.*, 2019; Ohwoghere-Asuma *et al.*, 2020). Hydrostratigraphic work across the Niger Delta also confirms the value of integrating geophysics with borehole logging and hydraulic data to resolve the discontinuous sandy and clayey units that control aquifer connectivity (Hassan *et al.*, 2019). Collectively, these studies establish a credible regional basis for recognising productive aquifer units, identifying areas of weak protective cover and framing groundwater-management recommendations.

Despite these contributions, the Bayelsa literature remains methodologically uneven. Several studies are based on relatively small numbers of soundings or on survey points clustered around accessible roads, campuses and urban communities. Such layouts are useful for local borehole decisions but do not necessarily represent the full lateral variability of deltaic channel sands, floodplain clays and estuarine deposits. Maximum current-electrode spacing, sounding orientation, data-repetition procedures, contact-resistance checks and criteria for rejecting noisy observations are not reported consistently. Inversion software is often named without adequate presentation of starting models, root-mean-square error, sensitivity, alternative equivalent models or confidence bounds. Consequently, visually acceptable one-dimensional fits may be interpreted more definitively than the data justify. Comparisons among publications are also complicated by differences in array geometry, investigation depth, sampling density, parameter definitions and the thresholds used to classify aquifer potential or protective capacity.

The widespread one-dimensional assumption is a major limitation in Bayelsa State because the Niger Delta is laterally heterogeneous. VES assumes that electrical properties change mainly with depth beneath the sounding centre, yet buried channels, clay lenses, creek margins, filled depressions, pipelines, buildings and saline-water fronts can introduce strong two- or three-dimensional effects. Under such conditions, a layered model may reproduce the field curve while misrepresenting the geometry or continuity of the aquifer. Electrical equivalence allows different combinations of resistivity and thickness to produce similar responses, while suppression can conceal thin but hydrogeologically important beds. These problems are especially consequential when a thin clay layer is used to infer protection or when an apparently thick sandy unit is assumed to be laterally continuous. The limited use of two-dimensional electrical resistivity tomography, closely spaced correlation profiles and borehole geophysical logging therefore reduces confidence in regional aquifer correlation. The review strengths, constraints and evidence gaps are summarised in Figure 11.

Resistivity–lithology ambiguity presents an additional challenge. Low resistivity may indicate clay-rich sediment, saline or brackish groundwater, high dissolved-ion content, organic material or contaminant-affected pore water; conversely, relatively high resistivity may represent freshwater-bearing sand, unsaturated sand or coarse material with limited saturation. Thus, a low-resistivity unit cannot automatically be classified as aquitard, nor can a high-resistivity unit automatically be regarded as a productive freshwater aquifer. The hydrochemical evidence from Yenagoa demonstrates that groundwater composition is influenced by recharge, water–rock interaction, ion exchange and anthropogenic inputs, all of which may modify bulk electrical response (Nwankwoala *et al.*, 2014; Okiongbo & Douglas, 2015). Coastal Niger Delta studies further show that salinity and human activities can generate conductive anomalies that resemble clay (Eyankware *et al.*, 2021; Ohwoghere-Asuma *et al.*, 2020). Site-specific calibration with borehole logs, groundwater electrical conductivity, major-ion chemistry and microbiological

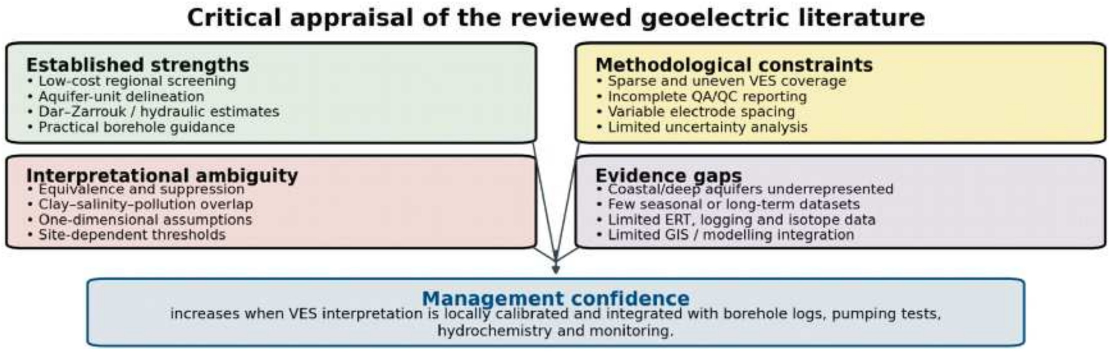

Fig. 11: Conceptual appraisal of strengths, methodological constraints, interpretational ambiguity and evidence gaps in the reviewed geoelectric literature. The framework is a synthesis of published studies, not a new field result.

testing is therefore essential before resistivity classes are translated into aquifer quality or vulnerability categories.

The empirical estimation of hydraulic properties is valuable but requires more rigorous calibration. Relationships between aquifer resistivity, formation factor, transverse resistance, hydraulic conductivity and transmissivity can be strongly affected by grain size, clay fraction, pore-water conductivity and anisotropy. Equations derived from a few pumping-test locations may perform well within the calibration area but may not transfer reliably to other parts of Bayelsa State. Some publications report agreement between geoelectric and pumping-test estimates, yet the number, spatial distribution and duration of the pumping tests are not always sufficient to establish prediction uncertainty. Storage coefficient, delayed yield, boundary effects and tidal responses are rarely considered. For management applications, empirical equations should therefore be treated as locally conditioned screening tools rather than substitutes for properly designed pumping and recovery tests (Okiongbo & Mebine, 2015; Okiongbo & Odubo, 2012).

Geographical coverage is also markedly unbalanced. Yenagoa and nearby Ogbia communities dominate the available evidence, whereas much of Sagbama, Kolokuma/Opokuma, Ekeremor, Southern Ijaw, Nembe and Brass has limited published coverage. Coastal islands, estuarine margins and communities exposed to tidal salinity are especially underrepresented, even though these settings may differ substantially from inland Yenagoa in aquifer geometry and water quality. Deep aquifers are less well resolved because many surveys were designed around relatively modest electrode separations and shallow water-supply targets. This spatial concentration restricts state-wide extrapolation and prevents confident correlation of aquifer units across local-government boundaries. The wider Eastern Niger Delta review similarly identifies the need for better observational networks, regional data integration and coordinated groundwater management (Abam & Nwankwoala, 2020).

Temporal evidence is even more limited. Most geoelectric surveys provide a single snapshot and do not assess wet- and dry-season changes in groundwater level, salinity, contaminant loading or river–aquifer exchange. Few studies revisit the same profiles after major floods, prolonged pumping, urban expansion or hydrocarbon incidents. This omission is important in a low-lying state where recharge, inundation, tidal influence and abstraction may alter saturation and pore-water conductivity. Long-term groundwater-quality trends, cumulative drawdown, saline-front movement and climate-related changes therefore remain poorly constrained. A layer interpreted as freshwater-bearing under one set of conditions may experience later quality deterioration without a change in lithology, underscoring the need to combine static geoelectric delineation with repeated water-level and hydrochemical monitoring.

The principal data-integration gap is the absence of a common state-wide framework linking VES, two-dimensional resistivity imaging, borehole logs, pumping tests, hydrochemistry, stable isotopes, geographic information systems and numerical groundwater models. Existing studies often demonstrate one or two of these components, but seldom integrate them at a scale sufficient to evaluate recharge pathways, aquifer connectivity, sustainable yield, contaminant migration and saline intrusion simultaneously. Stronger future studies should use VES for regional vertical control, ERT for lateral geometry, borehole geophysics and lithological logs for calibration, pumping and recovery tests for hydraulic properties, hydrochemistry and isotopes for water source and quality, and time-series monitoring for seasonal behaviour. These datasets can then support GIS-based vulnerability analysis and calibrated flow and transport models.

Overall, the existing literature provides a useful foundation but not yet a complete groundwater-management evidence base for Bayelsa State. The strongest conclusions are that sand–clay intercalations form multilayer aquifer systems, productive sands are widespread, and the protection of shallow aquifers varies considerably. Confidence decreases when numerical resistivity thresholds, transmissivity estimates or vulnerability classes are extrapolated beyond the locally investigated sites. Groundwater-development decisions should therefore adopt an evidence hierarchy: geoelectric surveys for screening and correlation; borehole and pumping-test data for confirmation of geometry and yield; hydrochemical and microbiological analyses for fitness of use; and repeated monitoring and modelling for sustainability. Applying this hierarchy would preserve the cost advantage of electrical resistivity while reducing the risks associated with non-uniqueness, salinity, contamination and inadequate spatial or temporal coverage.

Groundwater-Management Implications

The published case studies collectively show that geoelectric information can improve groundwater development in Bayelsa State when it is used as a decision-support tool rather than as a substitute for drilling, hydraulic testing and water-quality assessment. Vertical electrical sounding and related resistivity methods define the depth, thickness, resistivity and lateral persistence of sand-dominated units, while Dar-Zarrouk parameters provide an initial indication of transmissive potential and the protective character of the overburden. These outputs are especially valuable in the heterogeneous Benin Formation, where productive sands are interbedded with clay, silt and organic-rich deposits and where apparently similar surface locations may have different subsurface conditions. The reviewed Yenagoa studies demonstrate that resistivity-derived aquifer geometry and transverse resistance can be related to borehole and pumping-test observations, whereas regional investigations in Ndokwa, Ogbe-Ijoh and other coastal Niger Delta settings confirm that integrated geophysical, hydraulic and hydrochemical evidence provides a more reliable basis for groundwater planning than any single dataset (Hassan *et al.*, 2019; Mgbolu *et al.*, 2019; Ohwoghere-Asuma *et al.*, 2020; Okiongbo & Mebine, 2015; Okiongbo & Odubo, 2012).

For borehole siting, the most direct management benefit is the identification of thick and reasonably continuous aquifer units and the avoidance of clay-dominated intervals, thin sand lenses and electrically anomalous zones that may reflect salinity or contamination. A site should not be selected merely because a single sounding displays a high-resistivity layer; the target should also have sufficient thickness, plausible continuity across neighbouring soundings, favourable transverse resistance and consistency with the local geological setting. Conversely, very low resistivity should not be interpreted automatically as clay because saline water, high dissolved-ion content, organic material and contaminant-affected pore water can generate similar responses. Correlation of adjacent VES models, use of two-dimensional resistivity imaging where lateral variation is strong, and confirmation by a pilot borehole can reduce failed or low-yield completions. This approach is particularly important in floodplain, creek-margin and estuarine environments, where channel sands and clay lenses may terminate abruptly and where surface access can encourage drilling at convenient rather than hydrogeologically suitable locations (Hassan *et al.*, 2019; Ohwoghere-Asuma *et al.*, 2020; Okiongbo & Akpofure, 2012, 2016).

The reviewed evidence also has practical implications for drilling depth and screen placement. Geoelectric sections can distinguish shallow unconfined zones from intermediate and deeper semi-confined aquifers and can identify clayey intervals that should be preserved as natural hydraulic barriers. Screen intervals should therefore be selected from the confirmed saturated sand thickness rather than from the total drilled depth, and long screens crossing clay separations or multiple aquifers should be avoided because they can create artificial hydraulic connections between shallow vulnerable water and deeper, better-protected units. In coastal or estuarine locations, conductive layers require hydrochemical confirmation before completion, since a deep, thick sand may still contain brackish water. Borehole lithological logs, drilling returns and, where available, borehole geophysical logs should be compared with the pre-drilling model before final screen and gravel-pack placement. Proper casing, grout seals and raised sanitary platforms are also required in low-lying communities to prevent direct entry of floodwater and contaminated shallow drainage into the annulus. Thus, geoelectric targeting should be treated as the first stage of an adaptive construction process in which the final completion design is revised using evidence obtained during drilling. The evidence-to-management pathway is outlined in Figure 12.

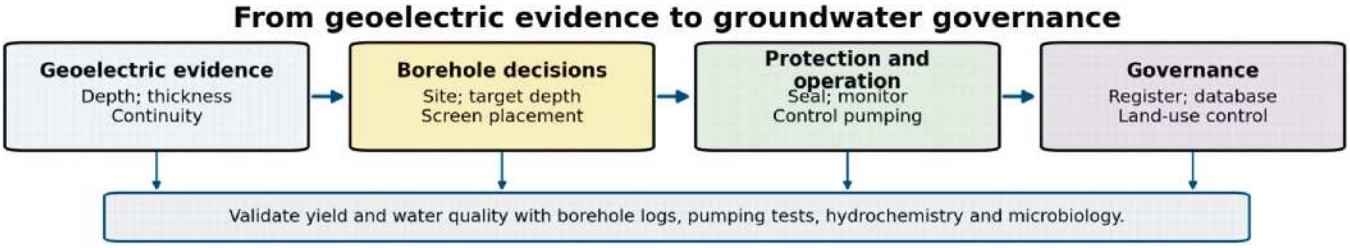

Fig. 12: Literature-based framework linking geoelectric aquifer evidence to borehole development, groundwater protection, monitoring and governance. The diagram is a conceptual synthesis and not a new field result.

Protective-capacity assessments have equally important implications for groundwater-quality protection. Areas characterised by thin sandy overburden, shallow water tables or low longitudinal conductance should be regarded as priority protection zones because contaminants from septic systems, refuse dumps, leaking fuel facilities, workshops and floodwater can move relatively quickly toward the aquifer. Published vulnerability work in Yenagoa and regional Niger Delta studies indicates that protection varies over short distances and should not be inferred solely from administrative location or aquifer depth (Mgbolu *et al.*, 2019; Okiongbo & Akpofure, 2012). Sanitary setback distances between wells and potential contaminant sources should therefore be determined conservatively and increased in weakly protected, highly permeable or flood-prone settings. Wellheads should be located above predictable flood levels, surrounded by sealed aprons and drainage, and protected from wastewater pooling. Waste disposal and petroleum-storage facilities should be restricted in recharge and wellhead-protection areas, while commercial and institutional boreholes should undergo periodic chemical and microbiological certification rather than one-time testing at commissioning.

Management of vulnerable shallow aquifers requires a stronger monitoring emphasis because electrical resistivity delineates geological and hydrogeological conditions but does not establish potability. Hydrochemical studies in Yenagoa show that major-ion chemistry and groundwater suitability reflect recharge, mineral dissolution, ion exchange and anthropogenic inputs, while multivariate analysis can help distinguish natural geochemical controls from pollution-related signals (Nwankwoala *et al.*, 2014; Okiongbo & Douglas, 2015). Shallow wells in densely developed or frequently flooded areas should therefore be prioritised for wet- and dry-season analysis of pH, electrical conductivity, total dissolved solids, chloride, nitrate, iron, manganese and microbial indicators. Where hydrocarbon activities or spills are present, petroleum-related parameters should be added. Results should be assessed together with water-level trends and land-use information because a stable geoelectric layer can experience substantial temporal deterioration in pore-water quality. Public-health surveillance and risk communication are also needed where communities depend on wells that are productive but chemically or microbiologically unsuitable.

Published estimates of transmissivity and hydraulic conductivity can support preliminary yield classification, pump selection and abstraction planning, but the empirical nature of many geoelectric-hydraulic relationships requires local calibration. A high transverse resistance or thick sandy aquifer may indicate favourable groundwater potential, yet sustainable yield also depends on recharge, storage, hydraulic boundaries, interference from neighbouring boreholes and seasonal water-level behaviour. Pumping and recovery tests should therefore be mandatory for high-capacity public, commercial and industrial wells. Test results should guide pump capacity and allowable abstraction rather than pump size being selected only from the apparent instantaneous yield during drilling. In areas of increasing borehole density, spacing decisions should consider likely cones of depression and shared aquifer connectivity, and production wells should be fitted with access points for water-level measurement and, where feasible, flow meters. Periodic comparison of static and pumping levels would reveal cumulative drawdown, declining well efficiency or over-abstraction before supply failure becomes severe (Hassan *et al.*, 2019; Okiongbo & Mebine, 2015; Okiongbo & Odubo, 2012).

Coastal and estuarine aquifers require additional controls because conductive geoelectric signatures may reflect brackish water and because excessive abstraction can alter freshwater-saline-water relationships. The Ogbe-Ijoh and broader coastal-aquifer studies demonstrate the value of combining resistivity with groundwater electrical conductivity and ion chemistry when assessing saline influence (Eyankware *et al.*, 2021; Ohwoghere-Asuma *et al.*, 2020). In Bayelsa's riverine and tidal settings, baseline and repeat measurements of electrical conductivity, total dissolved solids and chloride should accompany water-level monitoring, particularly in dry seasons and around high-capacity abstractions. Freshwater lenses or locally protected sand bodies should be developed cautiously, with pumping rates adjusted when increasing salinity or sustained drawdown is detected. New boreholes should not be completed solely on the basis of a resistive sand body if nearby water-quality evidence indicates saline encroachment, and clustered abstractions should be avoided where their combined drawdown could induce lateral or upward migration of saline water. A state-wide groundwater information system is necessary to convert the dispersed case-study evidence into an operational management resource. The database should assign a unique identifier to every registered public, institutional and commercial borehole and store coordinates, ground elevation, drilling date, lithological and geophysical logs, aquifer and screen depths, casing details, pumping-test results, static and dynamic water levels, abstraction capacity, geoelectric data, hydrochemical and microbiological results, vulnerability class and monitoring history. Standardised metadata are essential because existing publications report aquifer parameters and survey designs in different formats. Geographic information system integration would allow agencies to visualise borehole density, aquifer depth, protective capacity, flood exposure, salinity trends, contaminant sources and areas lacking reliable water supply. The database should also retain unsuccessful boreholes and poor-quality aquifers, since these records are critical for avoiding repeated mistakes and refining regional conceptual models (Abam & Nwankwoala, 2020; Hassan *et al.*, 2019).

The regulatory implication is that hydrogeophysical investigation should form part of a tiered approval process for high-capacity boreholes, but approval should also require drilling records, pumping-test evidence, sanitary-completion details and certified water-quality results. Commercial and public wells should be registered, periodically inspected and linked to an identified responsible operator. Minimum completion standards should prohibit screens across multiple aquifers, require effective annular sealing, and mandate flood-resilient wellhead construction in low-lying communities. Recharge areas, wellhead zones and locations with weak protective capacity should be incorporated into land-use planning, while septic systems, dumpsites, petroleum storage and other contaminant sources should be controlled using hydrogeological rather than uniform administrative setbacks. The state should also establish routine monitoring networks in rapidly urbanising Yenagoa, coastal settlements and hydrocarbon-affected areas, with predefined responses to declining water levels or deteriorating salinity and quality.

In summary, the reviewed literature supports a management hierarchy in which geoelectric surveys guide regional screening and target selection; drilling and borehole logging confirm the aquifer; pumping tests establish operational yield; hydrochemical and microbiological analyses determine fitness for use; and repeated monitoring, data integration and regulation protect long-term sustainability. This hierarchy preserves the speed and cost advantages of resistivity methods while recognising their ambiguity in clay-rich, saline and contaminated environments. Applied consistently, it can reduce unsuccessful boreholes, improve screen placement, protect vulnerable shallow groundwater, prevent excessive abstraction and provide Bayelsa State with a defensible evidence base for water-supply planning and aquifer conservation.

Research Gaps and Future Directions

The existing literature has established the usefulness of vertical electrical sounding and related resistivity methods for identifying aquifer-bearing sands, estimating aquifer geometry and assessing protective capacity in Yenagoa and selected parts of Bayelsa State. Nevertheless, the evidence base remains geographically uneven, methodologically heterogeneous and weakly connected to long-term groundwater monitoring. Most published investigations are concentrated in Yenagoa and a limited number of adjoining communities, whereas large coastal, estuarine and riverine areas remain poorly represented. Future research should therefore move beyond isolated site investigations toward a state-wide, stratified programme that deliberately includes Brass, Nembe, Southern Ijaw, Sagbama, Kolokuma/Opokuma and other under-investigated local-government areas, as well as rapidly urbanising settlements, hydrocarbon-impacted locations and communities reporting saline or brackish groundwater. Such expansion is essential because aquifer architecture, clay continuity, recharge conditions and salinity risk vary strongly across the Niger Delta, and findings from inland or urban Yenagoa cannot automatically be transferred to tidal islands and coastal settings (Abam & Nwankwoala, 2020; Eyankware *et al.*, 2021; Hassan *et al.*, 2019).

A major methodological priority is the integration of one-dimensional VES with two-dimensional and, where feasible, three-dimensional electrical resistivity imaging. VES remains efficient for resolving vertical layering and estimating the depth and thickness of laterally extensive units, but its one-dimensional assumption is vulnerable where channel sands, clay lenses, abandoned distributary fills and saline fronts vary laterally. Future surveys should use VES to provide depth control and broad regional coverage, while ERT profiles should intersect representative geomorphic and land-use settings to reveal lateral continuity, structural boundaries, contaminant plumes and freshwater-saline-water interfaces. Survey orientation should be guided by river channels, inferred groundwater-flow direction and expected depositional trends rather than convenience alone. Multi-electrode imaging should also be repeated seasonally at selected sentinel sites to determine whether changes in bulk resistivity reflect water-table movement, salinity variation or contaminant migration. This combined strategy would address interpretational ambiguities reported in coastal Niger Delta studies and improve the transferability of aquifer models across neighbouring communities (Mgbolu *et al.*, 2019; Ohwoghere-Asuma *et al.*, 2020).

Stronger subsurface validation is equally important. Many published studies compare geoelectric models with a small number of existing boreholes or infer lithology directly from resistivity ranges. Future investigations should incorporate test drilling at strategically selected geophysical targets, detailed sample-based lithological logs, depth-referenced drilling returns and documented screened intervals. Borehole geophysical logging, including natural gamma, spontaneous potential, resistivity and, where possible, electromagnetic conductivity, should be used to distinguish clay-rich intervals, verify aquifer boundaries and identify vertical changes in groundwater salinity. Direct correlation between the inverted geoelectric model and the borehole record should be reported quantitatively, including depth mismatches and uncertainty, rather than presented only as qualitative agreement. This approach is necessary because low resistivity can signify clay, saline groundwater, organic-rich sediments or contamination, while high resistivity can represent either freshwater-bearing sand or unsaturated material. Borehole control would therefore convert resistivity interpretation from a plausible geological model into a defensible hydrostratigraphic framework (Hassan *et al.*, 2019; Okiongbo & Akpofure, 2016).

Hydraulic calibration also requires substantial improvement. Although some Bayelsa studies have related transverse resistance, aquifer resistivity and thickness to transmissivity or hydraulic conductivity, these relationships are empirical and may not remain valid across different grain-size distributions, pore-water salinities and clay contents. Future work should pair geoelectric soundings with properly designed constant-rate pumping tests, recovery observations and, for major abstractions, observation wells. Reporting should include pumping duration, discharge stability, well construction, drawdown correction, analytical method, boundary effects and uncertainty in transmissivity and storage coefficient. Local regression or petrophysical relationships should be developed separately for hydrostratigraphically comparable zones and tested with withheld borehole data before being used for prediction. Repeated pumping tests or step-drawdown tests at selected production wells would further distinguish aquifer decline from well-efficiency loss. Such calibration would strengthen the management use of geoelectric parameters for yield classification, borehole spacing and sustainable abstraction (Ben-Owope & Agbasi, 2025; Okiongbo & Mebine, 2015; Okiongbo & Odubo, 2012).

Future hydrogeophysical studies should also incorporate a fuller hydrochemical, microbiological and isotopic component. Major ions, trace metals, nitrate, chloride, iron, manganese, electrical conductivity, total dissolved solids and redox-sensitive parameters are needed to determine whether a geoelectrically favourable sand body contains potable freshwater. Microbial indicators are particularly important in shallow, densely settled and flood-prone environments, whereas petroleum-related analytes are required near oil-production, transport and storage facilities. Stable isotopes of water and selected solutes can help distinguish recent rainfall recharge, river or creek leakage, evaporative concentration, palaeowater and possible mixing between shallow and deeper aquifers. Seasonal sampling should be synchronised with groundwater-level and resistivity measurements so that chemical changes can be interpreted in relation to recharge, flooding, tidal influence and pumping. Hydrochemical facies and multivariate analysis already demonstrate that Bayelsa groundwater is shaped by both geogenic processes and human activities; adding isotopic and microbiological evidence would reduce uncertainty in source attribution and vulnerability assessment (Aladejana *et al.*, 2020; Nwankwoala *et al.*, 2014; Okiongbo & Douglas, 2015). Figure 13 presents the proposed progression from current gaps to an integrated framework.

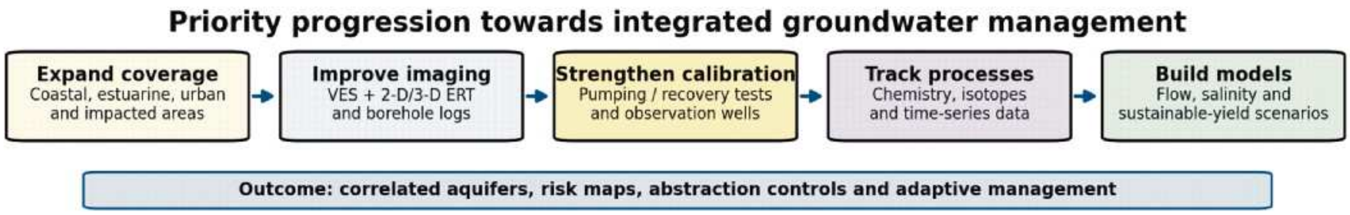

Fig. 13: Conceptual progression from current evidence gaps to an integrated regional groundwater-management framework for Bayelsa State.

Long-term monitoring is the principal missing link between site characterisation and sustainable groundwater management. Most studies provide a snapshot of subsurface conditions, yet Bayelsa aquifers are exposed to pronounced wet-dry season contrasts, recurrent flooding, tidal forcing, urban expansion and increasing abstraction. A network of nested monitoring wells and representative production boreholes should record groundwater level, electrical conductivity, temperature and abstraction at consistent intervals, supplemented by seasonal analyses of chloride, nitrate, iron, manganese and microbial indicators. In coastal and estuarine locations, higher-frequency measurements may be required to separate tidal oscillation from pumping effects and to detect inland or upward salinity movement. Monitoring should also follow major flood events and documented spills because rapid recharge through weakly protected overburden can alter water quality without changing the geometry of the aquifer. Time-series data would permit trend analysis, identify threshold exceedances and support adaptive restrictions before irreversible deterioration occurs (Eyankware *et al.*, 2021; Ohwoghere-Asuma *et al.*, 2020; Owoyemi *et al.*, 2019).

Regional aquifer correlation should form the organising framework for future studies. Existing case studies identify multiple sand bodies separated by discontinuous clay and silt, but they rarely establish whether named shallow, intermediate and deeper aquifers are laterally continuous between local-government areas. A coordinated programme should standardise aquifer nomenclature, datum correction, depth intervals and data formats, then integrate VES, ERT, borehole logs, water levels, chemistry and geomorphology within a geographic information system. Cross-sections should follow inland-to-coast, interfluve-to-channel and urban-to-rural transects, allowing identification of recharge and discharge zones, confining-layer terminations and hydraulic connections between shallow and deeper units. Regional correlation would also clarify whether reported differences in aquifer depth and resistivity reflect genuine hydrostratigraphic changes or merely differences in survey depth, inversion approach and local calibration. The resulting framework could support state-wide vulnerability mapping, wellhead-protection planning and prioritisation of areas requiring additional exploration (Abam & Nwankwoala, 2020; Hassan *et al.*, 2019).

The accumulated geoelectric and hydraulic information should ultimately support progressively more sophisticated groundwater models. The first requirement is a transparent conceptual model defining aquifer units, confining layers, recharge mechanisms, river-aquifer exchange, tidal boundaries, abstraction centres and possible saline sources. This should be followed by calibrated groundwater-flow models that test seasonal recharge, urban abstraction, well interference and flood-related water-level responses. In coastal sectors, variable-density or solute-transport models are needed to evaluate freshwater-lens behaviour and saline intrusion under alternative pumping and sea-level conditions. Contaminant-transport models could examine nitrate, microbial or hydrocarbon migration from identified sources, while scenario analysis should estimate sustainable yields and the effects of proposed municipal or industrial wellfields. Model uncertainty must be reported and reduced through targeted monitoring rather than concealed by apparently precise maps. The most valuable models will therefore be iterative management tools that identify critical data gaps, guide new surveys and are updated as observations accumulate (Abam & Nwankwoala, 2020; Ben-Owope & Agbasi, 2025; Hassan *et al.*, 2019).

Future research should progress from isolated VES interpretations to an integrated observation-and-modelling system that broadens spatial coverage, combines VES and ERT, strengthens borehole and pumping-test calibration, incorporates hydrochemical and isotopic tracers, establishes long-term monitoring, correlates aquifers regionally and develops calibrated flow and transport models. A state protocol for survey design, reporting, archiving and uncertainty would support sustainable management across inland, urban, riverine and coastal settings.

Conclusion and Recommendations

The published literature demonstrates that electrical-resistivity methods, particularly Schlumberger vertical electrical sounding, have made a substantial contribution to the understanding of groundwater occurrence in Bayelsa State. The case studies are concentrated mainly in Yenagoa and selected surrounding communities, with fewer investigations in the coastal, estuarine and riverine parts of the state. Collectively, the studies portray the shallow subsurface as a heterogeneous sequence of topsoil, clay, silt, sandy clay and freshwater-bearing sand within the Benin Formation and younger deltaic deposits. The reported hydrostratigraphy commonly comprises a shallow unconfined aquifer, one or more intermediate aquifer units and locally deeper semi-confined or confined sands separated by discontinuous clay and silt layers. This multilayer arrangement explains the marked spatial variation in aquifer geometry and the difficulty of transferring resistivity thresholds or drilling targets from one locality to another (Abam & Nwankwoala, 2020; Hassan *et al.*, 2019; Okiongbo & Akpofure, 2016).

Across the reviewed studies, aquifer depth, thickness, resistivity and protective capacity vary considerably because of changes in depositional facies, clay content, grain size, saturation, pore-water chemistry and survey depth. Productive groundwater is generally associated with sufficiently thick and laterally persistent sand units, whereas thin sands, clay-rich intervals and zones affected by brackish water or contamination may produce ambiguous electrical responses. Longitudinal conductance and related Dar-Zarrouk parameters have been useful for identifying aquifers with poor, weak, moderate or stronger natural protection, while transverse resistance and empirically derived relationships have supported preliminary estimates of transmissivity and hydraulic conductivity. Nevertheless, the protective and hydraulic classifications reported for different sites are not always directly comparable because electrode spacing, sounding density, inversion procedures, calibration data and classification thresholds differ among publications (Okiongbo & Akpofure, 2012; Okiongbo & Mebine, 2015; Okiongbo & Odubo, 2012).

The principal contribution of VES is therefore not the provision of a universal resistivity value for groundwater, but its capacity to organise subsurface electrical variations into testable aquifer models that guide borehole siting, target depth and screen placement. When supported by borehole lithology, pumping tests, static water levels and hydrochemical data, geoelectric interpretation can reduce unsuccessful drilling, distinguish thin or discontinuous aquifers from more favourable units, and identify shallow groundwater systems requiring greater protection. However, resistivity alone cannot establish lithology, aquifer productivity or potability with certainty. Low resistivity may represent clay, saline or brackish water, organic-rich material or contamination, while high resistivity may indicate dry sand as well as freshwater-bearing sand. Published hydrochemical investigations further show that a geoelectrically favourable aquifer may still contain elevated iron, manganese, dissolved solids or anthropogenic contaminants, making independent chemical and microbiological assessment indispensable (Nwankwoala *et al.*, 2014; Ohwoghere-Asuma *et al.*, 2020; Okiongbo & Douglas, 2015).

The review also reveals important geographical and methodological gaps. Large areas of Brass, Nembe, Southern Ijaw, Sagbama, Kolokuma/Opokuma and other coastal or estuarine settings remain poorly represented, and the continuity of aquifer units across local-government boundaries is still uncertain. Many studies are based on relatively small numbers of one-dimensional soundings, provide limited information on field-quality control and inversion error, and lack adequate borehole, pumping-test or hydrochemical validation. Seasonal changes in groundwater level, salinity, flooding influence, tidal response and abstraction are rarely monitored, while the combined use of VES, two-dimensional electrical resistivity tomography, borehole geophysical logging, hydrochemistry, isotopes, GIS and groundwater modelling remains uncommon. Consequently, the available publications provide a valuable but fragmented evidence base rather than a fully correlated state-wide aquifer framework (Abam & Nwankwoala, 2020; Eyankware *et al.*, 2021; Hassan *et al.*, 2019). The review's evidence-to-action synthesis is shown in Figure 14.

Accordingly, Bayelsa State should: compile geoelectric, borehole, pumping-test, water-level and chemistry records in a quality-controlled database; recalibrate published interpretations against logs, screens, tests and water quality; require hydrogeophysical investigation and drilling confirmation for major wells; prioritise weakly protected, flooded, densely populated and petroleum-affected areas for chemical and microbiological monitoring; use ERT where lateral heterogeneity or salinity is expected; regulate

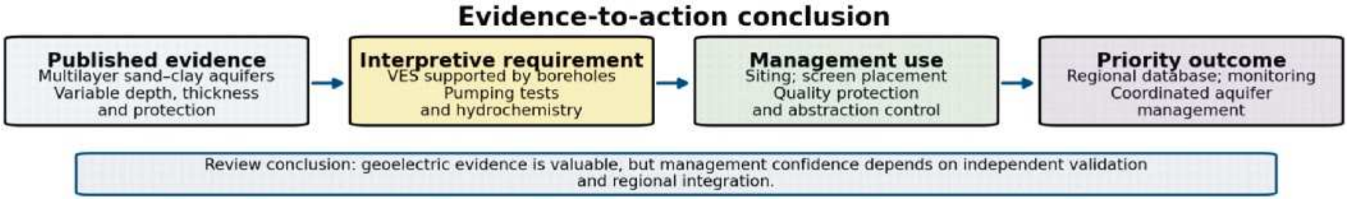

Fig. 14: Literature-based synthesis linking geoelectric evidence to groundwater-management action in Bayelsa State.

abstraction using aquifer-specific yield, drawdown, recovery and spacing; expand coordinated coastal and tidal research; and progress toward regional correlation, long-term observation and calibrated flow, contaminant and saline-intrusion models. These actions would convert dispersed case studies into a coherent basis for sustainable borehole development and aquifer protection.

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