ISSN:
Print - 2277 - 0593
Online - 2315 - 7461
© FUNAAB 2025

Journal of Natural Science, Engineering and Technology

CHARACTERIZATION OF GROUNDWATER SOURCES USING HYDROGEOPHYSICAL AND BIOGEOCHEMICAL TECHNIQUES IN PAPALANTO, SOUTH-WEST NIGERIA

S.A. ISHOLA

Department of Earth Sciences, Olabisi Onabanjo University Ago-Iwoye, P.M.B 2002, Ago-Iwoye, Ogun State, Nigeria
Corresponding Author: ishola.sakirudeen@oouagoiwoye.edu.ng. **Tel:** +2348166595080

ABSTRACT

The necessity for aquifer characterization and consequent assessment of extent of leachate infiltration in groundwater system for the growing water demands and overall health benefits of inhabitants cannot be overemphasized. Although groundwater provides potable water to billions of people worldwide daily, it also serves as a basic sustenance to other forms of biological populations. The vulnerability status of boreholes and hand-dug wells to contaminant seepages in the Papalanto community of Ogun State, South-Western Nigeria was analyzed in this study. It was designed to assess and present the extent of leachate and pollution from Ewekoro community. Qualitative assessment was determined utilizing vertical electrical sounding (VES) methods that revealed lower resistivity mostly in traverses 1, 4 and 5, thus suggesting possible leachate to depths above 24.9 m. The depth to the aquifer varied from 8.5m to 100m while the longitudinal unit conductance (S) and the protective capacity (P_c) values were generally less than 1.0 Siemens ($P_c < 1.0$ Siemens) except in few locations around VESPAP2, VESPAP4, VESPAP10, VESPAP12, VESPAP13, VESPAP20 alongside VESPAP21 and VESPAP22 that were classified as low aquifer protective zone and were characteristics of depositional successions of overburden layers with no significant impermeable clay/shale overlying rock. Most quality determinants in the sampled water were within the set guidelines. pH, Temperature, EC, TDS, TSS, TS and TH were the physico-chemical parameters; NO^{3-} , NO^{2-} and SO_4^{2-} represented the anions; Na^{2+}, Mg^{3+}represented the cations while Cu^{2+}, Pb^{2+}, $Cd^{2+,}$ Mn^{2+}, Cr^{3+}, Ni and Al^{3+} were the heavy metals. Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Alkalinity (ALK), Cl^-, HCO_3^-, Zn^{2+} and Fe^{3+} were found to exhibit elevated concentration values using the integrated permissible limits of the approved national and international water quality standards for both water sources. It was concluded that not all the borehole water sources were safe for consumption and many of the hand-dug well waters were of poorer bacteriological qualities; indicative of health risk to the inhabitants of the area.

Keywords: Leachate; Vulnerability; Resistivity tomography; Protective capacity; Coliforms; Hand-dug well.

INTRODUCTION

The significance of quantitative and qualitative groundwater sources to most forms of life cannot be overemphasized. Though, groundwater provides potable water to approximately 8.2 billion people worldwide daily with annual growth rate of 0.85% (UN-WS, 2025),it serves as a basic sustenance to other forms of biological populations which include forest plants, arable plants, ornamental plants and livestock (Ishola *et al.,* 2019). It has been established to be the most reliable resource for meeting rural water demand in sub-Saharan Africa (MacDonald and Davies, 2000). The United Nations World Water Development focusing on technical and policy responses required to improve water management and critical issues revealed the needs to address global water crisis, especially in the area of groundwater production and sanitation (UNWWDR/UNESCO, 2025). From 2021estimates, the agricultural sector dominates freshwater withdrawals (72%), followed by industry (15%) and domestic or municipal use (13%). Sector-specific freshwater withdrawals vary considerably as a function of a country's level of economic development. Higher-income countries use more water for industry, whereas lower-income countries use 90% or more of their water for domestic use and agricultural irrigation (UNWWDR/UNESCO, 2025). Over the period of one year starting from 2000 to2001, global freshwater withdrawals increased by 14%, corresponding to an average growth rate of 0.7% per year(DFID, 2001; UN-WS, 2025). Most of the increase occurred in cities, countries and regions still undergoing rapid economic development (Bjornlund *et al.,* 2018; UNWWDR/ UNESCO, 2025; UNICEF/WHO, 2025). Population growth does not appear to play a highly significant role in increasing demand for water. Countries where per capita water use is low, including several countries in sub-Saharan Africa, are often those with fastest growing populations, most especially Nigeria (UNWWDR, 2020; Mdee *et al.,* 2022). Twenty-five countries which serve as home to one-quarter of the world's population face extremely high water stress every year. Approximately 4 billion people or half of the world population experience water scarcity for a part of the year (Oliver and Boarz, 2019; UNWWDR/UNESCO, 2025). Pollution, land and ecosystem degradation, and natural hazards can further compromise the availability of water resources (Brown and Kookana, 2019; Venot *et al.,* 2021). The situation concerning sanitation is worse, with 3.5 billion people worldwide lacking access to these services in Latin America and the Caribbean, and central and Southern Asia with a mere coverage of 24% in Sub-Saharan Africa (Wanger *et al.,* 2009; Siebrits *et al.,* 2014; UNWWDR, 2017; Piesse, 2020; Setty *et al.,* 2020). Artesian wells equipped with hand-pumps are a common technology adopted by poor rural communities, and there were over 250,000 hand-pumps in Africa in 2003 but recent studies indicate that about 25% with approximately one in four hand pumps in sub-Saharan Africa are non-functional at any given time while a 2015 estimate for sub-Saharan Africa showed that 175,000 out of 680,000 hand-pumps were not functional (Foster *et al.,* 2020). In 1994, estimation reports revealed that 40-50% of existing hand-pumps in sub- Saharan Africa were not functioning (IBRD, 1994; Bello *et al*., 2013).This assertion is backed by supportive data and water report from Uganda (DWD, 2002) and South Africa (Hazelton, 2000), which indicated similar operational failure rates. Specifically in Nigeria, a significant proportion of water schemes are non-functional, with some sources indicating that around 50% of rural hand-pumps are dysfunctional and about 46% of water schemes in the country are not functional (Adeniran *et al.,* 2021). The primary reason for these high failure rates, and hence low sustainability, is insufficient attention to the operation and maintenance of the pump (Harvey and Reed, 2004). This results in decreased well yield and production, higher operation costs, and in severe cases, pump failure, well closure and depletion of groundwater resources (PPS, 2023). Considering the negative impacts of poor operation and maintenance, mineral deposits (incrustation) and biological growth (biofouling) can clog the well screen and aquifer, reducing the rate at which water can be pumped thereby reducing not only the overall well yield but also the sanitary quality of the groundwater system (PADCNR/PAGWIS, 2022; Glennon, 2025 WWJ, 2025). Saltwater intrusion is another quality challenge because over-pumping; often due to poorly-managed operations can draw saltwater into freshwater aquifers, most especially in coastal areas, rendering the water undrinkable. The impacts on the system efficiency and longevity are also observable in higher energy cost, a pump that is not well maintained must work harder and longer to achieve the same output leading to higher energy costs. Poor operation and maintenance can shorten the operational lifespan of the pump and well, making the entire water system unsustainable in the long-term (Chen *et al.,* 2016; Glennon, 2025) and while maintenance has costs, the long term expenses of poor maintenance including pump replacement, water treatment as well as overall costs of well rehabilitation are significantly higher (CLSM, 2024; Glennon, 2025; WWJ, 2025). The consequent failure of water infrastructure like hand-pumps in Nigeria negatively impacts access to sufficient and quality water, particularly in the rural area (MacAlhster *et al.,* 2022; Adeniran *et al.,* 2021). Despite the beneficial impacts of groundwater through borehole sources, its utilization sometimes has proven to be source of principal health concerns to the users (UNEP, 2001; Ajayi and Adejumo, 2011). Each year, about two million people die as a result of poor sanitation and contaminated water, with 90% of these victims being children. Centre for Disease Control reported 1.4 million deaths from waterborne diseases, poor sanitation and hygiene. Although diarrhea deaths have decreased, they still represent a major preventable cause of death prevailing among young children associated with approximately 1.035 million deaths with over 273,000 of those occurring under five years old (WHO/UNICEF, 2025). These hazardous effects emanating from the presence of toxic elements of environmental concern in groundwater system; elements such as Pb, Cd, As, Cr, many of these metals have been found to act as biological poisons even at low concentration of parts of per billion(ppb) levels (Okoronkwo *et al.,* 2005). Bairds (1995) also observed that these aforementioned elements, though toxic in the form of cations but when bonded to short chains of atoms, may not really be toxic as free elements. Even the most notable metals with significant commercial applications are also exempted and hence undesirable for their indiscriminate release into the environment (Bunce, 1990). This research aimed at showcasing the effectiveness of integrating non-invasive hydro-geophysical methods with widely employed biogeochemical (physico-chemical and microbiogical interactions) approach in groundwater assessment of Papalanto communities. The two basic approaches would go a long way in characterizing the groundwater conditions and proffering solutions to the problems of groundwater production and quality in the study area.

MATERIALS AND METHODS

Study Area

Papalanto area is at longitude 3.19^0 E, latitude 6.89^0 N, located in Ogun-State, Nigeria (Ishola, 2019; Maptons, 2025). It harbors one of the largest outcrops of Ewekoro limestone that easily attracts attention. It extends from Ibesse, 4 km east of Papalanto, along Papalanto-Shagamu road to Ogun River, 5km east of Iro community. The Ewekoro formation at the type locality is composed of 11m to 12m of limestone. It is sandy at the Base, grading downward into the Abeokuta Formation. The Ewekoro formation is overlain by phosphatic glauconitic grey shale (Jones and Hockey, 1964; Ishola *et al.,* 2021).

The local geology of the study area is Ewekoro formation and is generally consistent with the regional geology of eastern part of the Dahomey Basin with corresponding lithostratigraphic units (Figure 1) while the google earth imagery of the selected investigated study area within in Ewekoro LGA (Figure 2). It predominantly comprises of the non-crystalline and highly non-fossiliferous limestone and thinly laminated fissile and probably non-fossiliferous shale (Ushie *et al.,* 2014). It is the sedimentary terrain of southwestern Nigeria displayed in the map of Ogun state showing Ewekoro formation as the typical local geology of the study areas (Figure 3). The geographical divisions of the study area within Nigerian continental environment are shown alongside Ewekoro, Itori and Wasinmi and their surrounding autonomous communities (Figure 4). The individual investigated and sampled locations in the study within Ewekoro Local Government Area (LGA) are displayed (Figure 5). The Ewekoro formation consists of intercalations of argillaceous sediment. The rock is soft and friable but in some places cemented by ferruginous and siliceous materials. The lithological units in Ewekoro formation are clayey sand, clay, shale, marl, limestone and sandstone. The Abeokuta formation was found to consist of grits, loose sands, sandstones, kaolinitic clay and shale and was further characterized as usually having a basal conglomerate or basal ferruginized sandstone (Ishola, 2019; Ishola *et al.,* 2021).

The Abeokuta formation on surface outcrops comprises mainly of sand with sandstone, siltstone, silt, clay, mudstone and shale interbeds. It usually has a basal conglomerate which may measure about 1m in thickness and usually consists of poorly rounded quartz pebbles with silicified and ferruginized sandstone matrix or a softly gritty white clay matrix. Where there is no conglomerate in surface outcrops of Abeokuta formation, a coarse, poorly-sorted pebbly sandstone with abundant white clay constitutes the basal bed. The overlying sands are coarse-grained clayey, micaceous and, poorly -sorted and indicative of short distances of transportation or short duration of weathering and possible derivation from the granitic rocks located to the north. Subsurface data on the Abeokuta formation were obtained from Ise-2, Afowo-1, Orimedu-1, Bodashe, Ileppawi, Ojo-1 and Itori boreholes by Okosun (1998). The formation has a thickness of 849 m, 898 m, 624 m, 54.4 m and 888 m in Ise-2, Afowo-1, Ileppawi, Itori and Ojo-1, boreholes, respectively. In the Ise-2 borehole, the essentially arenaceous sequence between 1261.5 m and 2142.1 m which consists of sands, grits, sandstone, siltstone, clay and shale constitutes the formation (Archibong, 1978). The interval 1076 m – 1907 m which was made up of very coarse loose sands with sporadic thin intercalations of multicoloured shale and limestone represents the formation in Ojo–1 borehole (Chene, 1978; Ishola, 2019). The strata from 44m to 98.4m in the Itori borehole, consisted of coarse-fine and medium-grained sand, silt and sandy clay horizons constitute the upper portion of the formation. The Ise-2 borehole also penetrated a basal conglomerate.

Jones and Hockey (1964) presented Ewekoro limestone and the accompanying overlying Akinbo shale to be of lateral equivalents of the Imo formation of eastern Nigeria origin. Investigations of other authors on the stratigraphy and depositional characteristics of limestone and clay/shale deposits in south-western Nigeria also revealed similar lithostatigraphical pattern (Okosun, 990; Omatshola and Adegoke, 1991; Oladeji, 1992). Extensive and comprehensive geological survey and commercial appraisal of Ewekoro limestone and shale beds for commercial cement production were also undertaken by The West African Portland Cement Company also conducted (Ishola *et al.,* 2021).

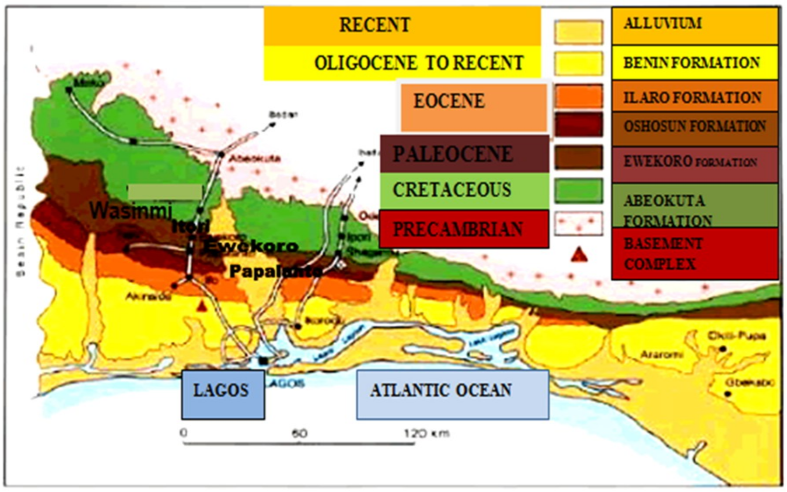


Figure 1: Geological Map of Selected Locations in the Study Area

Figure 2: Google Earth Imagery of the selected Investigated Study Area within Ewekoro LGA, Southwest Nigeria

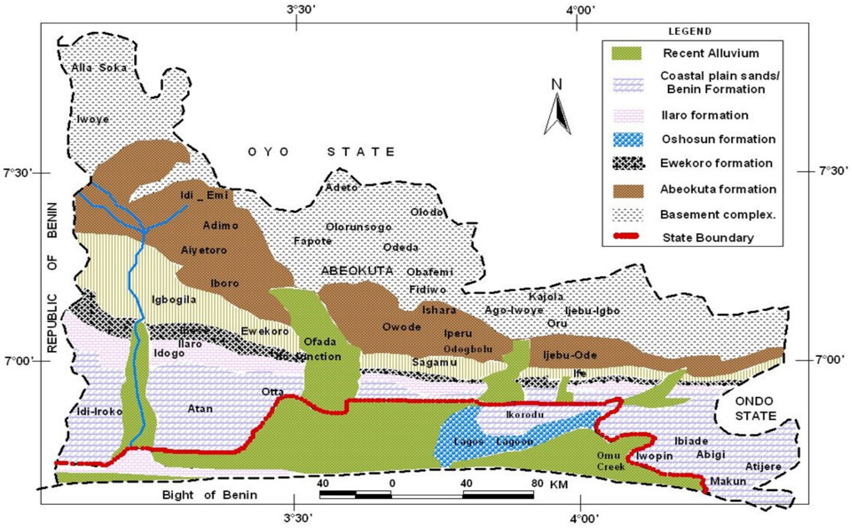


Figure 3: Geological map of the study Area

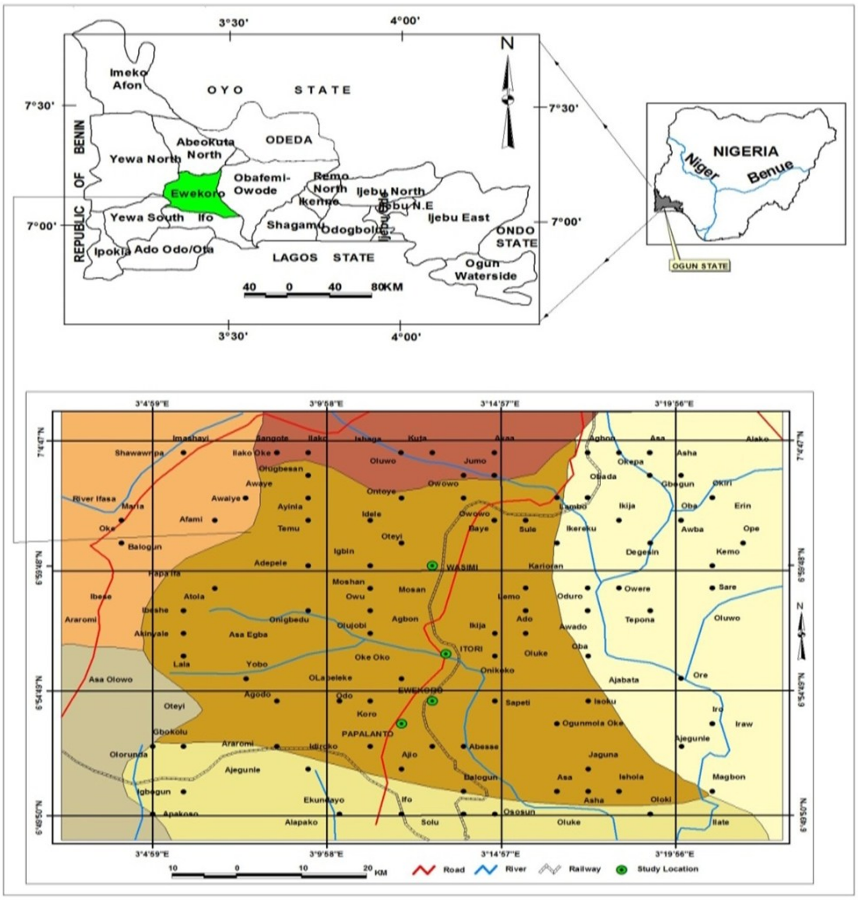


Figure 4: Map of the Study Areas in Ogun State, Nigeria using Esri Data Nigeria Political Information in ArcView GIS 3.2A Environment (Ishola, 2019).

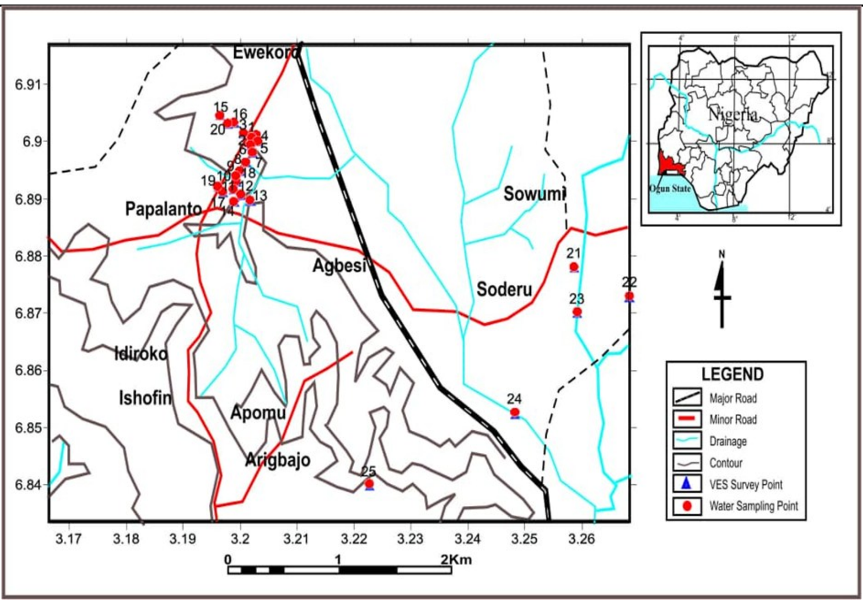


Figure 5: Data Acquisition Map of the Investigated Locations in Papalanto Study Area in Ewekoro LGA, Southwest Nigeria

Electrical Resistivity Method

The principal field equipment utilized for the study was AGI Super Sting Earth Resistivity meter which displays the apparent resistivity value digitally as computed from Ohm's law. Other materials that accompany the equipment were measuring tape, 4 reels of multi-core cables, 4 hammers, where 4 metal electrodes were used for VES (Figure 6). In the VES where Schlumberger configuration was adopted, the four electrodes were symmetrically positioned along a straight line putting the current electrodes on the outside and the potential electrodes on the inside. To change the depth range of the measurements, the current electrodes were displaced outwards while the potential electrodes, in general, were left at the same position. When the ratio of the distance between the current electrodes to that between the potential electrodes became too large, the potential electrodes were displaced outwards otherwise the potential difference would become too small to be measured with sufficient accuracy (Koefoed, 1979; Alile and Amasadun, 2008). Measurements of current and potential electrode positions were marked such that AB/2 ≥ MN/2.

Where AB/2 = Current electrode spacing and MN/2 = Potential electrode spacing.

Generally, the arrangement consisted of a pair of current electrodes and a pair of potential electrodes. These were driven into the earth in a straight line to make a good and firm contact with the earth. The current electrode spacing was expanded over a range of specified values for field measurements in the study area. The values of AB/2 increased as the measurements progressed while the potential electrodes separations were guided accordingly. The potential electrodes were kept at small separations relative to the current electrodes separations (Alile and Amasadun, 2008). Twenty five (25) depth soundings were conducted, with current electrode spacing (AB) ranging from 200-340m, using Schlumberger Configuration (Figure 6).

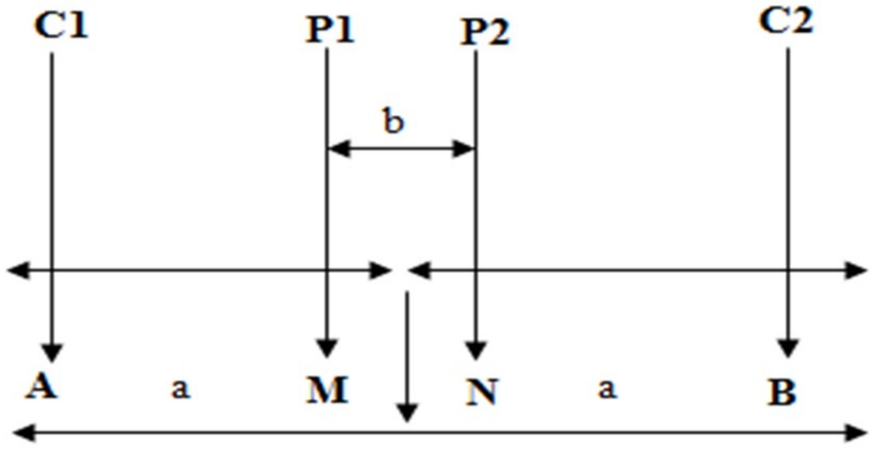


Figure 6: Schlumberger Electrode Configuration on the Field (Ishola, 2016)

The outputs of observed apparent resistivity dataset for the vertical electrical resistivity soundings were systematically plotted against half-current electrode spacing (AB/2) on bi-logarithmic graph sheets. The obtained field-curves from the plots were then curve-matched with Schlumberger master curves for the delineation of the underlying formations and their number of layers in successions and the estimation of the corresponding resistivity and thickness of each of the delineated layers. The estimated geoelectric parameters were thereafter used as initial models for computer iterative modeling on a Win-Resist program to obtain model geoelectric parameters for the delineated layers (Vander–Velpen, 2004). The lithology of the delineated geoelectric layers was established by integrating available information from lithologic samples collected from boreholes and hand-dug wells, known local geology and previous studies (Fidelis *et al.,* 2014; Ishola, 2019; Ishola *et al.,* 2025).

Hydro-geochemical Analyses of Water Samples

The procedure for data collection started with a reconnaissance survey of the area. The study initially identified functional wells and boreholes as those that are frequently in use with a level of patronage (use) greater than 30 persons per day. Through this approach, 50 existing and functional groundwater sources in the dry season (25 boreholes and 22 wells) were randomly and strategically selected, with their coordinates recorded. Water samples were collected in 1-litre plastic bottles. Prior to sample collection, all plastic bottles were rinsed three times with the sample water. After sampling, the containers were tightly covered. Physico-chemical analyses of the water samples were also undertaken to identify and quantify the physical properties and chemical components of water. This included pH, TSS, Turbidity, Chloride Cations, Anions, Trace Elements, Total Hardness, which were determined using standard laboratory methods of water quality analyses (APHA, 1998). Major metals and trace metals were determined using the Inductively Coupled Mass Spectrometer (ICP-MS) and Inductively Coupled Optical Emission Spectrometry (ICP-OES). In order to improve accuracy and to prevent cloudiness of the water, water samples were filtered to less than 0.45 µm using a Pall Corporation GN-6 metricell sterilized membrane. Minute clay particles were removed before analysis. ICP-OES is useful in measuring higher concentrations, such as high levels of contamination. When lower levels of contamination were identified, ICP-MS was utilized because of its additional service for lower detection limits in analytical measurement. Cell-based ICP-MS provided an additional tool for the removal of interferences that might prevent the detection of a contamination incident. Mn, Cr, Zn, Pb and Cd among others were trace elements and heavy metals analyzed. These analyses were undertaken for the purpose of determining the level of concentration of elements in water samples and the impacts of the prevailing and elevated concentration levels on the groundwater system of the study area.

Bacteriological Quality Determination

The facilities used for this study such as petri-dishes, pipettes, inoculation loops and culture media, were adequately sterilized using appropriate laboratory methods (DIFCO, 1984; Ajayi and Adejumo, 2011). Nutrient agar (NA), Eosine Methylene Blue (EMB), and MacConkey broth were the media used for these analyses and each of them serves as a differential medium for the consequent isolation of gram negative bacteria and screens the isolates for lactose fermentation. Glucose, Mannitol, Lactose, Fructose and Galactose were primarily utilized as sugars used for the fermentation test. Motility indole ornithine fluid media were utilized for the motility and indole test. The preparation of all the media were in accordance with approved laboratory standards as well as the manufacturer's instructions and specifications, coupled with adequate sterilization in an autoclave at the temperature of 121°C for 15 minutes time interval (Ajayi and Adejumo, 2011; Bello *et al.,* 2013).

Total Bacterial Count

The determination of the total bacterial count was carried out in the laboratory by application of the pour plate technique, using standard methods (APHA, 1985; Bello *et al.,* 2013). The enumerations of bacteria in the samples were achieved by using the Nutrient agar medium. Isolations of Staphylococcus aureus were achieved by using the Mannitol salt agar (MSA) because of its high salt content (7.5 – 10%) that selectively inhibits the growth of most bacteria allowing only salt tolerant staphylococci to flourish meaning that the high salt level created an osmotic environment that was lethal to most bacteria but can be tolerated by staphylococci. The selectivity prevented the growth of other bacteria including most gram-negative bacteria and other gram-positive bacteria that are salt tolerant. The presence of mannitol and phenol red acted as a differential agent as staphylococcus aureus fermented mannitol thereby producing acids that turned the medium's colour from red to yellow indicating positive results (Aryal, 2022). The combination of selective and differential properties makes MSA a valuable tool for isolating and presumptively identifying pathogenic staphylococcus aureus from mixed samples while Salmonella-Shigella agar (SSA) was utilized for the isolation of Salmonella species because its formulation selectively inhibits the growth of gram-positive bacteria and coliforms, allowing Salmonella species to thrive. The medium was differential using lactose to differentiate non-lactose-fermenting Salmonella from lactose-fermenting bacteria, and incorporates ferric citrate and thiosulphate to produce black-centered colonies from hydrogen sulphide produced by Salmonella (Dekker and Frank, 2015). Also, the combination of the selective and differential properties made SSA a valuable for isolating Salmonella from the analyzed groundwater samples in the study area.

Total Coliform Count

The determination of the total coliform count was accomplished by adopting the Most Probable Number (MPN) method using MPN index with 3-3-3 regimen (Rijal, 2025; Addo *et al.,* 2009). MacConkey broth was utilized for this purpose as the resultant production of acid and gas on incubation at the temperature of 37^0C for 48 hours time intervals was utilized to indicate positive outputs (Fawole and Oso, 2001; Ajayi and Adejumo, 2011; Bello *et al.,* 2013).

Faecal Coliform Count

Eosin Methylene Blue medium was employed in the pour plate technique for the determination of faecal coliform count. E. coli strains appeared as greenish metallic sheen colonies on the Eosin Methylene Blue (EMB) agar, which was further confirmed by the capacity of the identified organism to ferment lactose at temperature of 44.5^0C while Aerobacteraerogenes appeared as large pinkish mucoid colonies (Burnett and Beuchat, 2001; Ajayi and Adejumo, 2011).

Biogeochemical Tests and Identification of Microbial Isolates

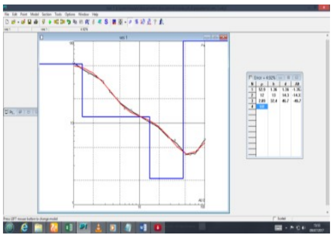
Identifications of all isolates were undertaken by adapting to standard methods in accordance with the accompanied laboratory procedures as described by APHA, (1985), Fawole and Oso, (2001) and Burnett and Beuchat, (2001). Morphological and biogeochemical characteristics of the microbial isolates were used for the identification of the isolates according to Baron *et al.*, (1990), Benson (1990) and Bitton (1994). The Bergey's Manual of determinative bacteriology by Buchanan and Gibbons (1974) was used to compare the characteristics with the results obtained.

RESULTS AND DISCUSSIONS

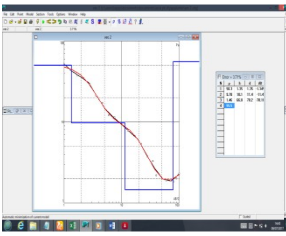
Representative inverse model curves for the geoelectric parameters obtained from the computer iteration of the resistivity soundings revealed that the resistivity sounding curves obtained from the surveyed area were representative of a typical 4–layer (H type), with a few 5-layer (KH). The H-type curve, with about 82.4% of occurrence and the KH -type curve, with about 17.6% of occurrence, were deduced from the area (Figure 7). The H and KH curves, which are often associated with groundwater possibilities (Omosuyi, 2010) were pertinent to the study area. The interpreted geoelectric parameters provide information on aquifer thickness and transmissivity allowing for estimations of potential groundwater yield and suitability for boreholes. The shape of the sounding curves (H, KH types) reflects the variations in electrical resistivity with depth, allowing for the identification of different subsurface layers including topsoil, clay, weathered/ fractured and fresh basement rock (Oyedele and Adeyemo, 2001; Omosuyi *et al.,* 2008). The geoelectric parameters of the lithologic units were delineated from the interpreted sounding curves (Table 1). Geoelectric parameters from Vertical Electrical Sounding (VES) interpret subsurface lithology and hydrology, directly impacting groundwater production by identifying aquifer depths, thicknesses, and potential yields. Sounding curves reveal variations in resistivity, indicating weathered/fractured zones for groundwater storage while lower resistivity can suggest saline water or contamination, impacting groundwater development and quality since electrical resistivity methods primarily reflect variations in ground resistivity (Okafor and Mamah, 2012; Aizebeokhai and Oyebanjo, 2013; Aizebeokhai and Oyeyemi, 2014). Low resistivity zones within these layers particularly in weathered/fractured basement were interpreted as potential water saturated zones or aquifers while high resistivity could indicate dry non-aquiferous layer (Aizebeokhai *et al.,* 2010a; Aizebeokhai *et al.,* 2010b). Interpreted geoelectric units such as weathered/fractured basement, are directly correlated to potential aquifer locations for development, while the protective capacity of underlying layers, like clay, is essential for groundwater quality maintenance. The geoelectric parameters of the delineated layers showed consistency among the sounding curves; particularly in the deeper sections where the model resistivities and thicknesses were relatively uniform (Table 1). The delineated geoelectric sections (from the topmost layer to the underlying layers) were characterized as top soil, sandy clay/clayey sand, shale/clay, sand lens, lateritic/kaolinitic clay, clayey sand, clay/shale, sandstone, weathered limestone and saturated sandstone. The topsoil was mainly composed of lateritic and alluvium soil and was characterized with low to high resistivity value that ranged from 9.78 – 157.23Ωm with a mean value of 157.23±316.80. The top soil was underlained by a relatively high resistive layer that was laterally continuous across the study area; this layer is described as sandy clay/clay/clayey sand. The large variation observed in the model resistivity of this layer can be linked to the possible effect of differences in the extent of compaction of the unit alongside the lateral changes in mineralogy. Underlying the second geoelectric layer was a low resistivity sandy-clay or shale/clay unit observed to be laterally discontinuous in the study area while the aquiferous lithological units were karstic limestone, saturated sandstone and sand (Ishola, 2019).

In the entire study locations, where the longitudinal conductance (*S*) and hence, the protective capacity (P_c) values in the study areas were less than 1.0 Siemens ($P_c < 1.0$ Siemens); they were classified as low aquifer protective capacity and were characteristics of depositional successions of overburden layers with no significant impermeable clay/shale overlying rock. Such subsurface model is an indication of high infiltration rates from precipitation as well as surface contaminants into the aquifer system. However, the investigated locations where the protective capacity values were greater than 1.0 ($P_c < 1.0$ Siemens) imply that these locations have considerable layers of clay separating the subsurface aquiferous zones (Table 1). In addition to high transmissivity and low protective capacity values in most of the investigated locations in the study area, 92% of the aquifers were very close or relatively close to the surface (<100m) and thus prone or vulnerable to contamination over large areas, once the aquifer receives a load of contaminant dose from surface to near surface. Nevertheless, despite the vulnerability status of the subsurface aquiferous zone of the study area to contaminant seepages emanating from the surface, the groundwater potential of the study area in terms of yield was high due to the recorded high transverse unit resistance (*R*) values making it a suitable terrain for the development of boreholes of potable water supply (Ishola, 2019).

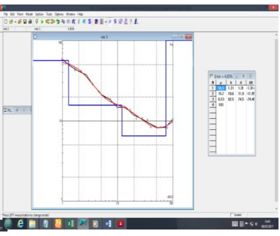
VESPAP1



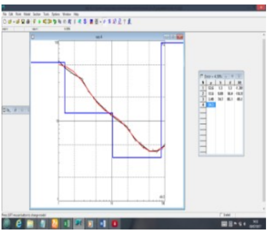
VESPAP2



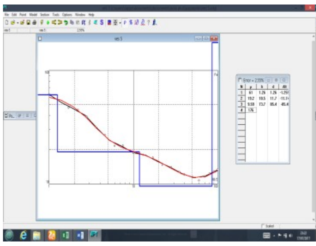
VESPAP3



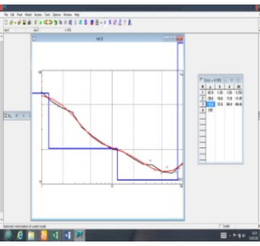
VESPAP4



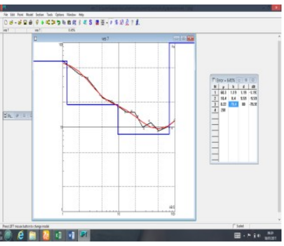
VESPAP5



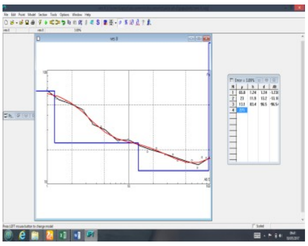
VESPAP6



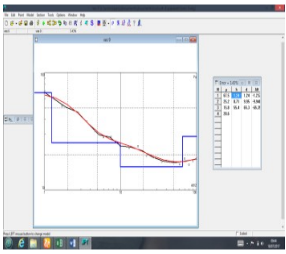
VESPAP7



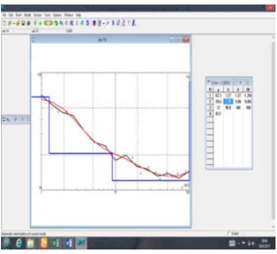
VESPAP8



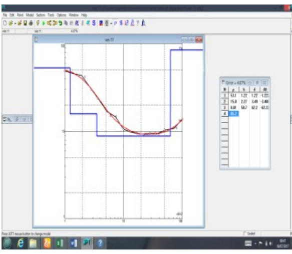
VESPAP9



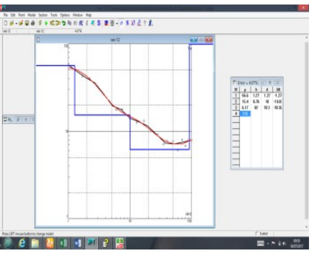
VESPAP10



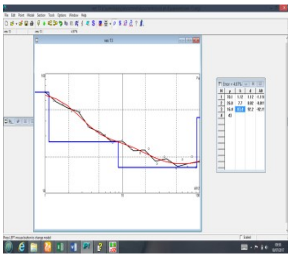
VESPAP11



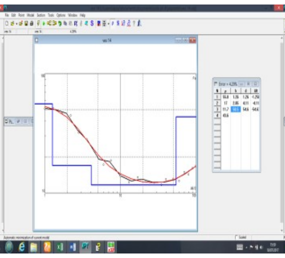
VESPAP12



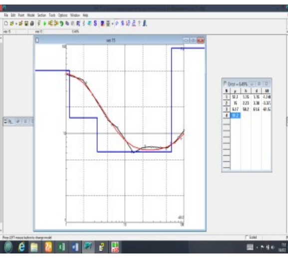
VESPAP13



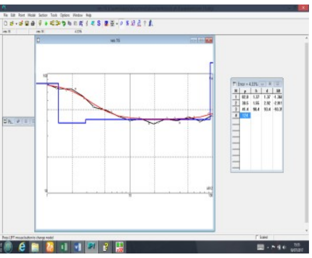
VESPAP14



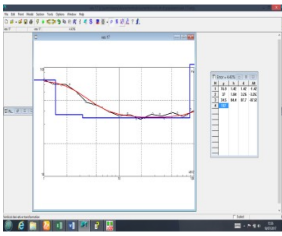
VESPAP15



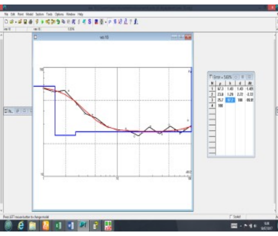
VESPAP16



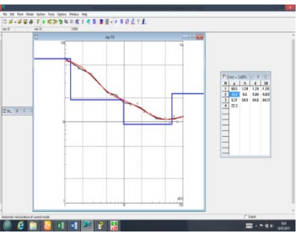
VESPAP17



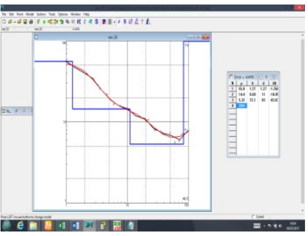
VESPAP18



VESPAP19



VESPAP20



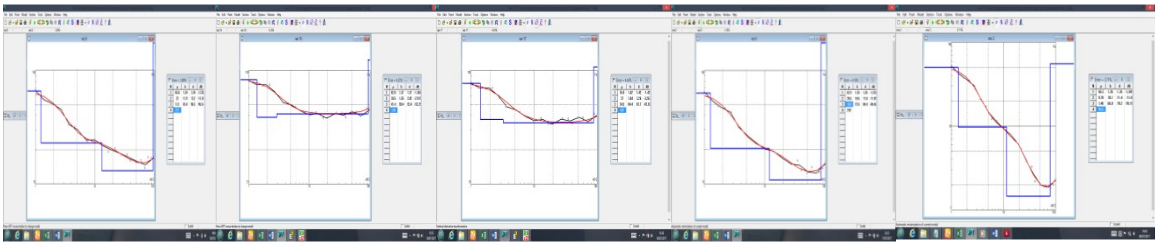

VESPAP21 **VESPAP22** **VESPAP23** **VESPAP24** **VESPAP25**

Figure 7: Cross section through VESPAP1 to VESPAP25

Table 1A: Computed Geoelectric Parameters of Papalanto

VES Station	Top Soil Resistivity (Ωm)	Depth to Aquifer m)	Longitudinal Conductance (*S*)	Probable Aquifer System
VESPAP1	52.9	46.7	0.2779927	Confined
VESPAP2	**9.78**	78	0.6681476	Confined
VESPAP3	56.5	74.5	0.4145107	Confined
VESPAP4	53.6	85.1	0.3463714	unconfined
VESPAP5	61	85.4	0.3475925	Confined
VESPAP6	62.9	84.4	0.2509664	Confined
VESPAP7	60.3	80	0.2174386	Confined
VESPAP8	65.8	96.5	0.2587825	Confined
VESPAP9	67.5	65.3	0.4762947	Confined
VESPAP10	62.5	**100**	0.5595971	Confined
VESPAP11	53.1	62.2	0.3818059	Confined
VESPAP12	56.6	92.1	0.4767821	Confined
VESPAP13	70.1	92.2	0.5898912	Confined
VESPAP14	55.8	54.6	0.4262295	Confined
VESPAP15	51.1	61.6	0.3768276	Confined
VESPAP16	82.8	93.4	0.3257761	Confined
VESPAP17	76.9	87.7	0.3431142	Confined
VESPAP18	67.3	**100**	0.4612546	Confined
VESPAP19	60.5	64.8	0.5839416	Confined
VESPAP20	55.8	83	0.2308633	Confined
VESPAP21	125	38.7	**0.1983077**	Unconfined
VESPAP22	**1428**	**8.5**	**0.7264337**	Confined
VESPAP23	36	45.14	0.2551724	Unconfined
VESPAP24	244	13.4	0.6824669	Unconfined
VESPAP25	915	20.44	0.0168369	Unconfined

Table 1B: Computed Geoelectric Parameters of Papalanto

VES Station	Inferred Lithology	Hydraulic Conductivity (m/s)	Transmissivity $(\mathrm{m}^2 s)$	Protective Capacity $(Siemens)$
VESPAP1	Limestone/ Sandstone	25.99945×10^{-3}	899.57924×10^{-3}	697.1194×10^{-3}
VESPAP2	Limestone /Sandstone	36.07765×10^{-3}	1284.3642×10^{-3}	**1270.718×10^{-3}**
VESPAP3	Limestone	25.99945×10^{-3}	1039.9764×10^{-3}	946.2723×10^{-3}
VESPAP4	Limestone/Sandstone	27.28436×10^{-3}	914.02590×10^{-3}	**1221.122×10^{-3}**
VESPAP5	Limestone /Sandstone	15.15111×10^{-3}	524.22824×10^{-3}	972.7759×10^{-3}
VESPAP6	Limestone /Sandstone	9.420362×10^{-3}	335.36487×10^{-3}	895.0159×10^{-3}
VESPAP7	Limestone /Sandstone	7.114063×10^{-3}	284.56253×10^{-3}	920.3866×10^{-3}
VESPAP8	Limestone /Sandstone	7.645165×10^{-3}	**256.11304×10^{-3}**	947.0069×10^{-3}
VESPAP9	Limestone	43.78772×10^{-3}	1532.5703×10^{-3}	601.8433×10^{-3}
VESPAP10	Limestone	29.44822×10^{-3}	883.44667×10^{-3}	**1052.631×10^{-3}**
VESPAP11	Limestone	29.13189×10^{-3}	1101.1855×10^{-3}	800.4118×10^{-3}
VESPAP12	Limestone/ Sandstone	23.50642×10^{-3}	655.82905×10^{-3}	**1178.201×10^{-3}**
VESPAP13	Limestone	39.47523×10^{-3}	1097.4115×10^{-3}	**8137.687×10^{-3}**
VESPAP14	Limestone	39.30507×10^{-3}	1391.3994×10^{-3}	646.1538×10^{-3}
VESPAP15	Limestone	27.90019×10^{-3}	1629.3710×10^{-3}	852.2359×10^{-3}
VESPAP16	Limestone /Sandstone	22.03150×10^{-3}	586.03803×10^{-3}	574.0627×10^{-3}
VESPAP17	Limestone /Sandstone	24.90014×10^{-3}	804.27456×10^{-3}	590.1750×10^{-3}
VESPAP18	Limestone/ Sandstone	26.18727×10^{-3}	785.61815×10^{-3}	856.1643×10^{-3}
VESPAP19	Limestone	45.81967×10^{-3}	1612.8524×10^{-3}	730.7996×10^{-3}
VESPAP20	Limestone /Limestone	6.962047×10^{-3}	257.59575×10^{-3}	**1099.046×10^{-3}**
VESPAP21	Limestone+Sand	**47.60194×10^{-3}**	1489.9407×10^{-3}	**2172.471×10^{-3}**
VESPAP22	Limestone+Sand	**2.894540×10^{-3}**	**9117.8015×10^{-3}**	**4.997065×10^{-3}**
VESPAP23	Limestone+Sand	36.49566×10^{-3}	1273.6987×10^{-3}	366.9919×10^{-3}
VESPAP24	Limestone+Sand	30.24326×10^{-3}	804.47081×10^{-3}	7.114774×10^{-3}
VESPAP25	Limestone+Sand	38.91086×10^{-3}	762.65272×10^{-3}	17.48502×10^{-3}

Biogeochemical characteristics of Papalanto Groundwater Sources

The mean value of pH for Papalanto borehole was 6.78±0.11 while that of temperature was 26.56±0.87 (Table 2). The standard deviation values for both parameters showed that the variation between the measured values was not much. The pH of the groundwater in the study area varied from 6.4 to 6.87 with an average value of 6.78±0.11 in boreholes (Table 2); and 6.70 to 7.85 with an average value of 7.11±0.40 in hand-dug wells indicating alkaline nature of the samples; this was confirmed by the very high detected values of Alkalinity in the study area with a value range of 180.74 to 1481.11 and a mean value of 487.75±515.95 in boreholes and a value range of 286.78 to 1711.11 with a mean value of 408.85±391.94 in wells (Table 3); these could still be in the normal ranges for waters purported to be safe and wholesome for consumption. This pH range was close to neutrality and would allow the growth of most bacterial species.

Eniola *et al.,* (2007) obtained similar pH ranges of 6.54 – 7.80 and 6.54 to 7.90 for borehole water samples stored indoor and outdoor in containers of different colours. The Electrical Conductivity (EC) values varied from 645.00 μS/cm to 911.00 μS/cm with an average value of 487.75±515.95 μS/cm in boreholes (Table 2) and 630.00 μS/cm to 845.00 μS/cm with an average value of 757.16±56.61 μS/cm in wells (Table 3). This is directly related to the ionic concentrations present in the groundwater and its lower values contribute to lower salinity and total dissolved concentration. The TDS values in boreholes were very low and varied between 6.90 and 8.98 mg/L, with a mean value of 8.41±0.71 mg/L and varied in wells for drinking purpose between 7.80 to 10.40 mg/L with a mean value of 8.08±0.66 mg/L; the maximum allowable TDS guideline value prescribed by the WHO (WHO, 2012) is 1000 mg/L. All the groundwater samples both boreholes (Tables 2) and hand-dug wells (Tables 3) came under fresh water type and were very much suitable for drinking purpose; as the values of TDS in them were lower than 1000 mg/L. The lower TDS may be due to lack of serious percolation of channel water containing solids, agricultural wastes, and industrial seepages. Although the country rocks are also important sources of increasing dissolved solids in the groundwater, other sources of dissolved solids in the groundwater of the study area included human activities like agricultural runoff, wastewater discharges and road particulate matters as well as other natural surface phenomena like saltwater intrusions into coastal part, leaching of salt deposits and saline soils. These sources can introduce contaminants and minerals into the groundwater system, increasing the concentration of the total dissolved solids (TDS) beyond were naturally present in the bedrock (Benham, 2024). Dissolved Oxygen (DO) ranged from 6.70 to 7.84 with a mean value of 7.00±0.32 in boreholes (Tables 2), and 7.20 to 8.98 with a mean value of 8.56±0.52 in wells (Tables 3), making well water higher than the set permissible standards.

The SO_4^{2-} ranges were between 0.03 and 11.88 mg/L; with an average of 9.60±3.65 mg/L in boreholes; in wells, it ranged between 9.37 and 14.62 mg/L; with an average value of 10.31±1.32 mg/L which is very important and widespread environmental problem in many irrigated agricultural regions. Sulphate concentration was less than 400 mg/L in the groundwater samples; indicating the lower influence of accumulation of soluble salts in the soil, anthropogenic activity and lower sulphate fertilizer application. NO_3 concentrations were found to range between 0.12 to 0.14 mg/L with an average of 0.12±0.008 mg/L in boreholes and 0.11 to 0.14 mg/L with an average of 0.13±0.007 mg/L in wells, making both results falling below the WHO recommended a value of 45 mg/L. The highest mean value of 403.81±318.40 was recorded for HCO_3^- followed by 314.80±88.15 for Cl^- while the lowest mean value of 0.0001±0.0003was recorded for Al^{3+}. COD, BOD and DO exhibited an increasing order of value concentrations of and COD>BOD>DO respectively. The elevated value of standard deviation over the mean in the boreholes (Table 1) compared to the hand-dug wells revealed a wider variation in the distribution of alkalinity in the borehole water sources of the sampled parameters in the hydrogeologic environment of the study area (Tables 1 and 2). Very high variability in the concentrations of both the physico-chemical and elemental parameters (e.g. HCO_3^-, Ni, Cr, Co, Al^{3+}, Pb^{2+}) resulted in the standard deviation being higher than the mean values for such elements (Tables 2). Unlike the heavy metals, Sulphur is a non-metallic element also detected in small concentrations in both water sources exhibiting a mean concentration of 1.41±0.65 in boreholes and 3.28±1.41 in hand-dug wells. Sulphur is not a heavy metal and its oxidation state varies commonly, ranging from −2 to +6 rather than having a fixed charge like Zinc. The sources and processes responsible for the present behaviour of sulphur principally present as SO_4^{2-} in the groundwater system of both water sources in the study area could probably be attributed to possible infiltration of river water from the oxidative dissolution of the constituent formation rock (Massmana *et al.,* 2003). In natural conditions, the concentration of NO_3^- does not exceed 10 mg/L in groundwater; concentrations beyond this is an indication of anthropogenic pollution, which is mainly due to poor sanitary conditions and indiscriminate use of higher fertilizers for higher crop yields (Subba-Rao *et al.,* 2012).

The concentration of bicarbonate was observed from 90.37 to 778.62 mg/L, with a mean value of 403.81±318.40 in boreholes and 143.38 to 855.11 mg/L with a mean value of 203.94±196.01 in wells, making samples from both groundwater sources higher than the available set standards; the higher concentration of HCO_3^- compared to chloride concentration in the groundwater infers that mineral dissolution also occurs (Subba-Rao *et al.*, 2017; Selvam *et al.,* 2018). This is supported through the use of a bubble plot displaying the dominant hydro-geochemical parameter which is principally harnessed to illustrate the ranking contribution and relationship between the water quality parameters and their respective aquifer characteristics such as rock-water interaction for dominant groundwater chemistry (Figure 8).

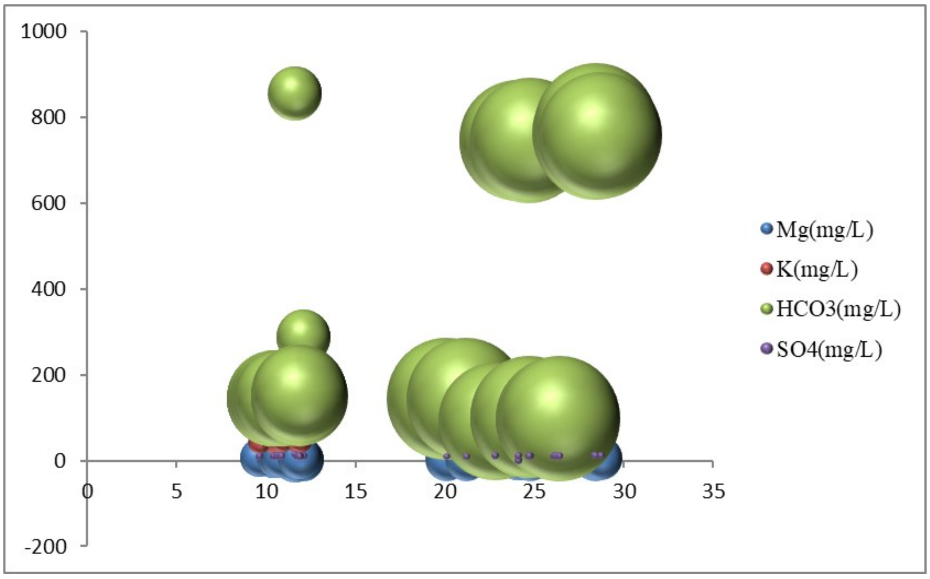


Figure 8: Bubble plot of Dominant Hydro-geochemical Parameters of Papalanto

Table 2A: Descriptive Statistics of the Concentration Values of Physico-Chemical and Elemental Parameters of Papalanto Boreholes (N=25)

Parameters	Min	Max	Range	Mean±SD
pH	6.40	6.87	0.47	6.78±0.11
TEMP (^{0}C)	25.00	28.00	3.00	26.56±0.87
EC (μScm^{-1})	645.00	911.00	266.00	703.48±92.31
DO (mg/L)	6.70	7.84	1.14	**7.00±0.32**
BOD (mg/L)	16.90	21.65	4.75	**20.02±1.84**
COD (mg/L)	25.00	38.88	13.88	**32.38±3.05**
TDS (mg/L)	6.90	8.98	2.08	8.41±0.71
TSS (mg/L)	0.12	0.31	0.19	0.23±0.05
TS(mg/L)	0.66	0.99	0.33	0.86±0.10
TURB (NTU)	0.10	1.11	1.01	0.24±0.33
ALK (mg/L)	180.74	1481.11	1300.37	**487.75±515.95**
TH (mg/L)	12.06	29.96	17.90	26.91±4.91
THC (mg/L)	0.12	0.21	0.09	0.19±0.03
Na^{2+}(mg/L)	38.40	45.87	7.47	42.58±2.04
K^{+}(mg/L)	48.60	58.47	9.87	55.17±2.60
Ca^{2+}(mg/L)	12.10	28.72	16.62	24.02±4.17
Mg^{3+}(mg/L)	1.94	4.47	2.53	3.47±0.66
Cl^{-} (mg/L)	71.80	382.04	310.24	**314.80±88.05**
NO$_3^-$ (mg/L)	0.12	0.14	0.02	0.12±0.008
NO$_2^-$ (mg/L)	0.01	0.02	0.01	0.02±0.003
SO$_4^{2-}$ (mg/L)	0.03	11.88	11.85	9.60±3.65
NH$_4^+$ (mg/L)	0.80	1.78	0.98	1.47±0.28
PO$_4^{3-}$(mg/L)	8.70	10.77	2.07	10.14±0.57
HCO$_3^-$(mg/L)	90.37	778.62	688.25	**403.81±318.40**
MgCO$_3$(mg/L)	8.72	13.98	5.26	**11.54±1.40**
Cu^{2+} (mg/L)	0.00	0.03	0.03	0.02±0.01
Pb^{2+} (mg/L)	0.00	0.0006	0.0006	0.0006±0.0005
Cd^{2+} (mg/L)	0.00	0.0004	0.0004	0.0004±0.0005
Mn^{2+}(mg/L)	0.01	0.03	0.02	0.02±0.009
Zn^{2+} (mg/L)	1.11	1.85	0.74	**1.43±0.25**
Fe^{3+} (mg/L)	0.03	1.17	1.14	**0.40±0.42**
Cr (mg/L)	0.00	0.0004	0.0004	0.0004±0.0005
Ni (mg/L)	0.00	0.0003	0.0003	0.0003±0.0005
S (mg/L)	0.38	2.47	2.09	1.41±0.65
Al^{3+} (mg/L)	0.00	0.0001	0.0001	**0.0001±0.0003**
I (mg/L)	0.02	0.04	0.02	0.03±0.008

Table 2B: Descriptive Statistics of the Concentration Values of Physico-Chemical and Elemental Parameters of Papalanto Boreholes (N=25)

Parameters	**WHO (mg/L)**	**NESREA (mg/L)**	**NSDWQ (mg/L)**	**USEPA (mg/L)**	**NAFDAC (mg/L)**
pH	6.5 – 9.5	7.00-8.50	6.50-8.50	6.50-8.50	6.50-8.50
TEMP (^{0}C)	27	NA	NA	27	27
EC (μScm^{-1})	1200	NA	900	1200	1000
DO (mg/L)	7.5	NA	7.5	NA	NA
BOD (mg/L)	10	NA	10	NA	NA
COD (mg/L)	NA	NA	NA	NA	NA
TDS (mg/L)	100	1500	500	500	500
TSS (mg/L)	> 10	>10	NA	NA	NA
TS(mg/L)	1500	NA	NA	NA	NA
TURB (NTU)	< 4	5.0	5.0	5.0	5.0
ALK (mg/L)	200	500	100	100	100
TH (mg/L)	< 200	100 -300	500	NA	100
THC (mg/L)	NA	NA	NA	NA	NA
Na^{2+}(mg/L)	< 200	NA	200	NA	200
K^+(mg/L)	12	200	NA	200	10
Ca^{2+}(mg/L)	75	NA	NA	75	75
Mg^{3+}(mg/L)	20	15	NA	20	20
Cl^- (mg/L)	250	200	250	100	100
NO_3^- (mg/L)	50	45	NA	10	10
NO_2^- (mg/L)	< 3.0	NA	NA	NA	NA
SO_4^{2-} (mg/L)	400	500	200	250	100
NH_4^+ (mg/L)	1.50	NA	NA	NA	NA
PO_4^{3-}(mg/L)	NA	NA	NA	NA	NA
HCO_3^-(mg/L)	100	NA	NA	NA	NA
$MgCO_3$(mg/L)	10	NA	NA	NA	NA
Cu^{2+} (mg/L)	2.0	NA	1.0	1.3	1.0
Pb^{2+} (mg/L)	0.01	0.01	0.01	0.01	0.01
Cd^{2+} (mg/L)	0.003	0.003	0.001	0.005	0.005
Mn^{2+}(mg/L)	0.1	0.2	0.5	0.4	2.0
Zn^{2+} (mg/L)	0.01	NA	NA	NA	NA
Fe^{3+} (mg/L)	0.3	0.3	0.3	0.3	0.3
Cr (mg/L)	0.05	0.05	0.05	0.05	0.05
Ni (mg/L)	0.02	0.05	NA	NA	0.05
S (mg/L)	250	NA	NA	NA	NA
Al^{3+} (mg/L)	0.2	NA	NA	0.2	0.5
I (mg/L)	NA	NA	NA	NA	NA

Drinking Water Standard Specifications given by WHO (2004), NESREA (2010), NSDWQ (2007), USEPA (2007) and NAFDAC (2011) and Statistical Information of ion Concentrations.

KEY: **NA**− Not Available in the National Guidelines and Standards Drinking Water Quality; **WHO**−World Health Organization; **NESREA**−National Environmental Standard Regulation Agency; **USEPA**−United State Environmental Protection Agency; **NSDWQ**−National Standards for Drinking Water Quality; **NAFDAC**−National Food and Drug Administration and Control.

Table 3A: Descriptive Statistics of the Concentration Values of Physico-Chemical and El-

Parameters	**Min**	**Max**	**Range**	**Mean±SD**
pH	6.70	7.85	1.15	7.11±0.40
TEMP (^{0}C)	22.00	31.00	9.00	25.12±1.99
EC (μScm^{-1})	630.00	845.00	215.00	757.16±56.61
DO (mg/L)	7.20	8.98	1.78	**8.56±0.52**
BOD(mg/L)	17.90	22.75	4.85	**19.76±1.48**
COD (mg/L)	31.40	36.83	5.43	**34.38±1.38**
TDS (mg/L)	7.80	10.40	2.60	8.08±0.66
TSS (mg/L)	0.35	0.53	0.18	0.45±0.04
TS (mg/L)	0.61	1.04	0.43	0.90±0.10
TURB (NTU)	0.11	0.34	0.23	0.24±0.05
ALK (mg/L)	286.78	1711.11	1424.33	**408.85±391.94**
TH (mg/L)	14.84	29.76	14.92	19.34±3.61
THC (mg/L)	0.00	0.43	0.43	**0.04±0.12**
Na^{2+} (mg/L)	34.40	52.64	18.24	41.53±4.03
K^{+} (mg/L)	41.61	61.44	19.83	45.37±4.94
Ca^{2+} (mg/L)	9.61	11.95	2.34	11.10±0.75
Mg^{3+} (mg/L)	4.24	9.99	5.75	7.42±1.26
Cl^{-} (mg/L)	70.61	226.39	155.78	**196.40±56.00**
NO_3^{-} (mg/L)	0.11	0.14	0.03	0.13±0.007
NO_2^{-} (mg/L)	0.01	0.05	0.04	0.03±0.009
SO_4^{2-} (mg/L)	9.37	14.62	5.25	10.31±1.32
NH_4^{+} (mg/L)	0.11	0.75	0.64	0.17±0.17
PO_4^{3-} (mg/L)	8.60	9.85	1.25	9.25±0.42
HCO_3^{-} (mg/L)	143.38	855.11	711.73	**203.94±196.01**
$MgCO_3$(mg/L)	10.43	14.64	4.21	11.25±1.04
Cu^{2+} (mg/L)	0.03	0.06	0.03	0.05±0.01
Pb^{2+} (mg/L)	0.00	0.02	0.02	0.007±0.005
Cd^{2+} (mg/L)	0.00	0.0009	0.0009	0.0009±0.0003
Mn^{2+} (mg/L)	0.02	0.06	0.04	0.04±0.01
Zn^{2+} (mg/L)	0.84	4.23	3.39	**2.31±1.26**
Fe^{3+} (mg/L)	0.05	1.52	1.47	**0.80±0.38**
Ni (mg/L)	0.00	0.00	0.0006	**0.0006±0.0005**
S (mg/L)	1.14	5.25	4.11	3.28±1.41
Al^{3+} (mg/L)	0.00	0.01	0.01	**0.002±0.004**
I (mg/L)	0.00	0.06	0.06	0.04±0.02
Si (mg/L)	0.00	0.04	0.04	**0.01±0.01**

Table 3B: Descriptive Statistics of the Concentration Values of Physico-Chemical and Elemental Parameters of Papalanto Hand-Dug Wells (N=25)

Parameters	WHO (mg/L)	NESREA (mg/L)	NSDWQ (mg/L)	USEPA (mg/L)	NAFDAC (mg/L)
pH	6.5 – 9.5	7.00-8.50	6.50-8.50	6.50-8.50	6.50-8.50
TEMP (^{0}C)	27	NA	NA	27	27
EC (Scm^{-1})	1200	NA	900	1200	1000
DO (mg/L)	7.5	NA	7.5	NA	NA
BOD(mg/L)	10	NA	10	NA	NA
COD (mg/L)	NA	NA	NA	NA	NA
TDS (mg/L)	100	1500	500	500	500
TSS (mg/L)	> 10	>10	NA	NA	NA
TS (mg/L)	1500	NA	NA	NA	NA
TURB (NTU)	< 4	<5.0	<5.0	<5.0	<5.0
ALK (mg/L)	200	500	100	100	100
TH (mg/L)	< 200	100 -300	500	NA	100
THC (mg/L)	NA	NA	NA	NA	NA
Na^{2+} (mg/L)	< 200	NA	200	NA	200
K^{+} (mg/L)	12	200	NA	200	10
Ca^{2+} (mg/L)	75	NA	NA	75	75
Mg^{3+} (mg/L)	20	15	NA	20	20
Cl^{-} (mg/L)	250	200	250	100	100
NO$_3^-$ (mg/L)	50	45	NA	10	10
NO$_2^-$ (mg/L)	< 3.0	NA	NA	NA	NA
SO$_4^{2-}$ (mg/L)	400	500	200	250	100
NH$_4^+$ (mg/L)	1.50	NA	NA	NA	NA
PO$_4^{3-}$ (mg/L)	NA	NA	NA	NA	NA
HCO$_3^-$ (mg/L)	100	NA	NA	NA	NA
MgCO$_3$(mg/L)	NA	NA	NA	NA	NA
Cu^{2+} (mg/L)	2.0	NA	1.0	1.3	1.0
Pb^{2+} (mg/L)	0.01	0.01	0.01	0.01	0.01
Cd^{2+} (mg/L)	0.003	0.003	0.001	0.005	0.005
Mn^{2+} (mg/L)	0.1	0.2	0.5	0.4	2.0
Zn^{2+} (mg/L)	0.01	NA	NA	NA	NA
Fe^{3+} (mg/L)	0.3	0.3	0.3	0.3	0.3
Ni (mg/L)	0.02	0.05	NA	NA	0.05
S (mg/L)	250	NA	NA	NA	NA
Al^{3+} (mg/L)	0.2	NA	NA	0.2	0.5
I (mg/L)	NA	NA	NA	NA	NA
Si (mg/L)	NA	NA	NA	NA	NA

Drinking Water Standard Specifications given by WHO (2004), NESREA (2010), NSDWQ (2007), USEPA (2007) and NAFDAC (2011) and Statistical Information of Ion Concentrations.

KEY: **NA**– Not Available in the National Guidelines and Standards Drinking Water Quality; **WHO**–World Health Organization; **NESREA**–National Environmental Standard Regulation Agency; **USEPA**–United State Environmental Protection Agency; **NSDWQ**– National Standards for Drinking Water Quality; **NAFDAC** – National Food and Drug Administration and Control.

Colour is an important physical quality of water which affects its acceptability by consumers. Ninety percent (90%) of the borehole water samples were within the acceptable limit of 5 TCU (WHO, 1985; NSDWQ, 2007). The mineral composition of the site could affect the colour of the water especially if iron compounds are present. The turbidity of the borehole water samples ranged from 0.10 to1.11NTU in boreholes (Tables 2) and 0.11 to 0.34NTU in hand-dug wells (Table 3). The variations in turbidity exhibited between boreholes and hand-dug wells in the study area were possibly due to their distinct construction and depth, leading to different exposure to surface contamination and aquifer conditions. The hand-dug wells are more susceptible to higher turbidity because the shallower depths, direct infiltrations, wider openings and over exposure to the environment, human and animal wastes among others; allowing surface runoff, pollutants and sediment to infiltrate easily. Boreholes, being deeper with higher aquifer protection status, often screened and much more controlled and engineered with materials and construction methods create a protective barrier against infiltration from the surface, prevent larger sediment and particulate matter from entering the well and access naturally filtered and more protected deeper aquifers, resulting in significantly lower turbidity (Odu *et al.,* 2020; Osayande and Umukoro, 2025; Gromicko, 2025; Ishola *et al.,* 2025). This is also in conformity with the acceptable values (NSDWQ, 2007). Turbidity results from the presence in the borehole water samples of particulate matters such as clay, silt, finely divided organic matter etc. These colloidal materials provide adsorption sites for chemicals that may be harmful to health or cause undesirable tastes or unpleasant odours (Adekunle *et al.,* 2007). The temperature of any water body affects the rate of proliferation of microorganisms (Pelczar *et al.,* 2005). The temperature range of 25-28 ^{0}C in the case of borehole water samples (Table 5) and 22-31 ^{0}C for well water samples could be regarded to be suitable for the growth of heterotrophic bacterial species when present in the sample (Table 6). On the morphological characteristics of the bacteria isolates, all the twelve (12) isolates had smooth colony surface, 17% (2) and 83% (10) respectively exhibited irregular and circular shape. Based on the displayed colour pigmentations, 25% (3) were white, 50% (6) were milky white, while black, green and pink exhibited 8% (1) each. On the basis of optical characteristics 58% were translucent while 42% were opaque based on the optical characteristics. On the general response to spore formation, 8% showed positive response to spore formation while 92% showed negative response to spore formation (Table 4).

The total hetetrophic bacterial count in borehole waters sampled ranged from zero to 6.83×10^2 cfu/ml and 3.2×10^2 to 9.8×10^2 cfu/ml, respectively. Similarly, the total coliform count of the borehole waters analyzed ranged from zero (0) to sixteen (16) MPN index of coliform/100 ml (Table 5) while that of well waters ranged from 10 to 1216 MPN index of coliform/100 ml of the water samples (Table 6). All the borehole samples are well below the limit of 100 cfu/ml (Table 5) while about 76 % of the well water samples having count within the limit of 100 cfu/ml allowed for potable water (NSDWQ, 2007). Generally, almost all the borehole water samples had zero count of faecal coliform except in PAPBH7, PAPBH10 and PAPBH22 while in well water samples, the faecal coliform count ranged from zero to 4.1×10^2cfu/ml (Table 6). Bello *et al.,* 2013 reported Total bacterial count examination of borehole and well water samples in Ijebu-Ode (another town in Ogun State) South-West Nigeria ranged from zero to 2.5×10^2 cfu/ml and zero to 8.1×10^2 cfu/ml respectively, total coliform count of the borehole waters analyzed ranged from zero to 16 MPN index of coliform/100 ml while that of well waters ranged from 16 to 1100 MPN index of coliform/100 ml of the water samples. Erah *et al .,*(2002) in a study conducted on the quality of ground water in Benin City, Nigeria found unacceptable levels of aerobic bacteria and fungi present in borehole water of Teboga District of Benin City. In another similar work, Eniola *et al.,* 2007 obtained a range of 5.0×10^2 to 7.0×10^2 cfu/ml for stored borehole water samples. In this study, almost all the borehole water samples were devoid of faecal coliform except PAPBH9, PAPBH10 and PAPBH22 whose faecal coliform count ranged from 0.6×10^2 to 2.5×10^2 cfu/ml. These affected boreholes and other boreholes might not be free of total coliforms which were probably from the environmental sources that were non-faecal in origin. WHO, 2017 specified that potable drinking water should be devoid of total coliform in any given sample. The borehole water (PAPWW4) with the highest bacterial count also had the highest total coliform count of 1216×10^2 cfu/ml (Table 6). 20% of the borehole water samples had zero total coliform counts while none was observed for the well water samples. Results of total coliforms obtained in this study is dissimilar to that of Rogbesan *et al.,*(2002) who in their study reported the presence of total coliform outside the range allowed by WHO in over sixty percent of their samples.

Twelve (12) genera of bacteria were isolated from both borehole (Table 7) and well waters (Table 8). These included: *Staphylococcus aureus spp, Enterococcus spp, Escherichia coli spp, Klebsiella spp, Salmonella spp, Aerobacter aerogenes spp, Proteus spp, Pseudomonas aeroginosa spp, Baccilus spp, Streptococcus spp, Alcaligenes spp, and Flavobacterium spp.* On Eosin Methylene Blue (EMB) agar, E. coli strains appeared as greenish metallic sheen colonies while *Aerobacter aerogenes* appeared as large pinkish mucoid colonies (Table 4). *Baccilus spp* and *streptococcus spp* were not isolated in borehole but jointly had a frequency of occurrence of 7.83% in hand-dug wells. It was, however, observable that *Enterococcus spp* were most dominant in the borehole waters analyzed as they were isolated (Table 7) while *Enterococcus spp and Escherichia coli spp* were much more dominant with other genera in hand-dug wells (Table 8).

Table 4A: Morphological Characteristics of Bacterial Isolates

Isolate Type	Pigmentation /color	Shape	Edge	Optical characteristics
Staphylococcus aureus spp	White	Circular	Entire	Translucent
Enterococcus spp	White	Irregular	Lobate	Translucent
Escherichia coli spp	Milky white	Circular	Entire	Opaque
Klebsiella spp	Milky white	Circular	Entire	Translucent
Salmonella spp	Black	Circular	Entire	Translucent
Aerobacter aerogenes spp	Milky white	Circular	Entire	Opaque
Proteus spp	White	Irregular	Lobate	Translucent
Pseudomonas spp	Milky white	Circular	Entire	Opaque
Baccilus spp	Milky white	Circular	Entire	Opaque
Streptococcus spp	Green	Circular	Entire	Translucent
Alcaligenes spp	Pinkish	Circular	Entire	Opaque
Flavobacterium spp	Milky white	Circular	Entire	Translucent

Table 4B: Morphological Characteristics of Bacterial Isolates

Isolate Types	Consistency	Colony surface	Spore formation	Gram's reaction	Motility
Staphylococcus aureus spp	Butyrous	Smooth	Negative	-verod	+
Enterococcus spp	Viscid	Smooth	Negative	-verod	+
Escherichia coli spp	Butyrous	Smooth	Negative	-verod	+
Klebsiella spp	Swarmy	Smooth	Negative	-verod	+
Salmonella spp	Butyrous	Smooth	Negative	-verod	+
Aerobacter aerogenes spp	Butyrous	Smooth	Positive	+verod	+
Proteus spp	Viscid	Smooth	Negative	-verod	+
Pseudomonas spp	Butyrous	Smooth	Negative	-verod	+
Baccilus spp	Mucoid	Smooth	Negative	-verod	+
Streptococcus spp	Butyrous	Smooth	Negative	-verod	+
Alcaligenes spp	Mucoid	Smooth	Negative	-verod	+
Flavobacterium spp	Viscid	Smooth	Negative	-verod	+

Table 5: Bacteriological Counts of Borehole Water Sample in Papalanto

SAMPLE CODE	DO (mg/L)	BOD (mg/L)	COLOUR (TCU)	THBC ($\times 10^2$cfu/ml)	TCC (MPN/ 100ml)	FCC ($\times 10^2$cfu/ml)
PAPBH1	6.70	17.90	5	6.25	16	0
PAPBH2	6.75	17.94	5	6.28	16	0
PAPBH3	6.80	16.90	5	0	0	0
PAPBH4	6.80	16.92	6	0	0	0
PAPBH5	6.80	18.70	5	5.63	16	0
PAPBH6	6.80	18.60	5	5.01	13	0
PAPBH7	7.80	17.10	4	5.32	11	0
PAPBH8	7.84	17.60	5	4.32	13	0
PAPBH9	7.84	17.62	5	4.84	16	2.5
PAPBH10	6.94	20.50	5	5.83	11	0.6
PAPBH11	6.82	20.70	5	6.83	9	0
PAPBH12	6.87	21.22	5	6.43	11	0
PAPBH13	6.91	21.58	5	5.76	10	0
PAPBH14	6.96	21.40	5	6.34	12	0
PAPBH15	6.94	21.60	5	5.83	6	0
PAPBH16	6.97	21.63	5	5.32	11	0
PAPBH17	6.96	21.10	5	2.27	15	0
PAPBH18	6.96	21.12	5	2.25	14	0
PAPBH19	6.96	21.12	5	2.28	11	0
PAPBH20	6.96	21.62	6	5.32	13	0
PAPBH21	6.96	21.63	4	0	14	0
PAPBH22	6.98	21.63	5	0	13	0.9
PAPBH23	6.98	21.65	5	0	0	0
PAPBH24	6.98	21.63	5	1.43	0	0
PAPBH25	6.98	21.63	5	1.62	0	0

Standard Specifications by WHO (1996); USEPA (2002) Guidelines

Key: PAPBH = Papalanto Borehole Water; DO = Dissolved Oxygen; BOD= Biological Oxygen Demand; THBC = Total Heterotrophic Bacteria Counts; TCC = Total Coliform Counts; FCC = Total Faecal Coliform Counts

Table 6: Bacteriological Counts of Well Water Sample in Papalanto

SAMPLE CODE	DO (mg/L)	BOD (mg/L)	COLOUR (TCU)	THBC ($\times 10^2$cfu/ ml)	TCC (MPN/100ml)	FCC ($\times 10^2$cfu/ ml)
PAPWW1	8.00	18.60	5	5.6	43	2.0
PAPWW2	8.40	18.64	10	4.6	68	2.7
PAPWW3	8.10	17.90	10	5.2	42	4.5
PAPWW4	8.10	17.94	15	9.8	1216	8.3
PAPWW5	8.12	17.98	10	6.2	74	3.8
PAPWW6	8.70	19.10	10	3.2	65	4.7
PAPWW7	8.80	20.21	5	5.2	38	4.3
PAPWW8	7.40	18.91	5	6.1	32	3.2
PAPWW9	7.20	18.61	5	8.5	1102	7.6
PAPWW10	8.90	19.72	10	6.25	10	3.6
PAPWW11	8.92	19.72	5	6.83	18	4.1
PAPWW12	8.95	19.75	5	5.88	15	4.5
PAPWW13	8.92	20.11	5	8.8	200	2.8
PAPWW14	8.96	20.72	5	6.1	22	0
PAPWW15	8.20	17.96	6	4.0	98	0
PAPWW16	8.25	17.94	6	7.9	115	0
PAPWW17	8.31	18.21	5	7.9	325	0
PAPWW18	8.96	20.71	5	8.1	28	0
PAPWW19	8.94	20.90	5	8.0	78	2.8
PAPWW20	8.94	21.20	10	9.6	1023	8.3
PAPWW21	8.92	21.43	5	7.2	38	4.4
PAPWW22	8.98	21.41	6	6.1	14	2.6
PAPWW23	8.96	21.49	5	6.2	27	0
PAPWW24	8.96	22.15	5	6.3	19	0
PAPWW25	8.98	22.75	5	6.4	24	0

Standard Specifications by WHO (1996); USEPA (2002) Guidelines

Key: PAPBH = Papalanto Borehole Water; DO = Dissolved Oxygen; BOD= Biological Oxygen Demand; THBC = Total Heterotrophic Bacteria Counts; TCC = Total Coliform Counts; FCC = Total Faecal Coliform Counts

Table 7A: Biogeochemical Characterization of Bacteria Isolates in Borehole Water Samples (PAPBH1−PAPBH8) of Papalanto Southwest Nigeria

Bacteria Isolates	**Freq (%)**	**PAP BH1**	**PAP BH2**	**PAP BH3**	**PAP BH4**	**PAP BH5**	**PAP BH6**	**PAP BH7**	**PAP BH8**
Staphylococcus aureus spp	2 (5.88)	−	−	−	−	−	−	−	−
Enterococcus spp	6 (17.7)	+	+	−	−	+	−	−	−
Escherichia coli spp	3 (8.82)	−	−	−	−	−	−	−	−
Klebsiella spp	3 (8.82)	−	−	−	−	−	−	−	+
Salmonella spp	4 (11.8	−	−	−	−	−	−	−	−
Aerobacter aerogenes spp	5 (14.7)	+	+	−	−	−	+	+	−
Proteus spp	5 (14.7)	−	−	−	−	−	−	−	−
Pseudomonas spp	3 (8.82)	−	+	−	−	+	+	−	−
Baccilus spp	−	−	−	−	−	−	−	−	−
Streptococcus spp	−	−	−	−	−	−	−	−	−
Alcaligenes spp	2 (5.88)	−	−	−	−	−	−	+	−
Flavobacterium spp	2 (5.88)	−	−	−	−	−	−	−	−

Key: + =Positive Test; − = Negative Test.

Table 7B: Biogeochemical Characterization of Bacteria Isolates in Borehole Water Samples (PAPBH9−PAPBH16) of Papalanto Southwest Nigeria

Bacteria Isolates	Freq No (%)	PAP BH9	PAP BH10	PAP BH11	PAP BH12	PAP BH13	PAP BH14	PAP BH15	PAP BH16
Staphylococcus aureus spp	2 (5.88)	−	−	−	−	−	−	−	−
Enterococcus spp	6 (17.7)	+	−	−	−	−	−	−	−
Escherichia coli spp	3 (8.82)	−	−	−	−	−	−	−	+
Klebsiella spp	3 (8.82)	+	+	−	−	−	−	−	−
Salmonella spp	4 (11.8	−	−	−	−	+	+	−	−
Aerobacter aerogenesspp	5 (14.7)	−	−	+	−	−	−	−	−
Proteus spp	5 (14.7)	−	−	−	+	−	−	+	−
Pseudomonas spp	3 (8.82)	−	−	−	−	−	−	−	−
Baccilus spp	−	−	−	−	−	−	−	−	−
Streptococcus spp	−	−	−	−	−	−	−	−	−
Alcaligenes spp	2 (5.88)	−	−	−	−	−	+	−	−
Flavobacterium spp	2 (5.88)	−	+	−	−	−	−	−	+

Key: + =Positive Test; − = Negative Test.

Table 7C: Biogeochemical Characterization of Bacteria Isolates in Borehole Water Samples (PAPBH17−PAPBH25) of Papalanto Southwest Nigeria

Bacteria Isolates	**Freq No (%)**	**PAP BH17**	**PAP BH18**	**PAP BH19**	**PAP BH20**	**PAP BH21**	**PAP BH22**	**PAP BH23**	**PAP BH24**	**PAP BH25**
Staphylococcus aureus spp	2 (5.88)	−	−	−	−	+	+	−	−	−
Enterococcus spp	6 (17.7)	+	+	−	−	−	−	−	−	−
Escherichia coli spp	3 (8.82)	+	+	−	−	−	−	−	−	−
Klebsiella spp	3 (8.82)	−	−	−	−	−	−	−	−	−
Salmonella spp	4 (11.8	−	−	−	−	+	+	−	−	−
Aerobacter aerogenes spp	5 (14.7)	−	−	−	−	−	−	−	−	−
Proteus spp	5 (14.7)	−	−	+	+	+	−	−	−	−
Pseudomonas spp	3 (8.82)	−	−	−	−	−	−	−	−	−
Baccilusspp	−	−	−	−	−	−	−	−	−	−
Streptococcus spp	−	−	−	−	−	−	−	−	−	−
Alcaligenes spp	2 (5.88)	−	−	−	−	−	−	−	−	−
Flavobacterium spp	2 (5.88)	−	−	−	−	−	−	−	−	−

Key: + =Positive Test; − = Negative Test.

Table 8A: Biogeochemical Characterization of Bacteria Isolates in Well Water Samples (PAPWW1−PAPWW8) of Papalanto Southwest Nigeria

Bacteria Isolates	**Freq. No (%)**	**PAP WW1**	**PAP WW2**	**PAP WW3**	**PAP WW4**	**PA PWW5**	**PAP WW6**	**PAP WW7**	**PAP WW8**
Staphylococcus aureus spp	15(9.05)	−	−	−	+	+	+	+	−
Enterococcus spp	19(11.7)	+	+	−	+	+	+	+	−
Escherichia coli spp	18(10.5)	+	+	−	−	+	+	+	−
Klebsiella spp	14(8.43)	+	+	+	+	−	−	−	−
Salmonella spp	14(8.43)	+	+	+	+	−	−	−	−
Aerobacteraerogenes spp	9(5.42)	−	−	−	−	−	+	−	−
Proteus spp	13(7.83)	−	−	+	+	+	+	−	−
Pseudomonas spp	12(7.23)	−	−	−	−	+	+	+	+
Baccilus spp	13(7.83)	−	−	−	−	+	+	+	+
Streptococcus spp	13(7.83)	+	+	−	−	+	+	+	+
Alcaligenes spp	13(7.83)	+	+	+	+	+	+	−	−
Flavobacterium spp	13(7.83)	+	+	+	+	−	−	−	−

Key: +=Positive Test; − =Negative Test.

Table 8B: Biogeochemical Characterization of Bacteria Isolates in Well Water Samples (PAPWW9−PAPWW16) of Papalanto Southwest Nigeria

Bacteria Isolates	**Freq No (%)**	**PAP WW9**	**PAP WW10**	**PAP WW11**	**PAP WW12**	**PAP WW13**	**PAP WW14**	**PAP WW15**	**PAP WW16**
Staphylococcus aureus spp	15(9.05)	+	+	−	−	+	+	−	−
Enterococcus spp	19(11.7)	+	+	−	−	+	+	−	−
Escherichia coli spp	18(10.5)	+	+	+	+	+	+	+	+
Klebsiella spp	14(8.43)	+	+	−	+	+	+	+	+
Salmonella spp	14(8.43)	−	−	−	+	+	+	+	+
Aerobacter aerogenes spp	9(5.42)	−	−	+	+	−	−	−	+
Proteus spp	13(7.83)	+	+	+	+	−	−	−	+
Pseudomonas spp	12(7.23)	−	−	+	+	−	−	+	+
Baccilus spp	13(7.83)	−	−	−	−	+	+	+	+
Streptococcus spp	13(7.83)	−	−	+	+	+	+	+	+
Alcaligenes spp	13(7.83)	−	−	+	+	+	−	−	+
Flavobacteriumspp	13(7.83)	−	+	+	+	+	+	−	−

Key: +=Positive Test; − = Negative Test.

Table 8C: Biogeochemical Characterization of Bacteria Isolates in Well Water Samples (PAPWW17−PAPWW25) of Papalanto Southwest Nigeria

Bacteria Isolates	Freq No(%)	PAP WW17	PAP WW18	PAP WW19	PAP WW20	PAP WW21	PAP WW22	PAP WW23	PAP WW24	PAP WW25
Staphylococcus aureus spp	15(9.05)	+	+	+	+	−	−	+	+	+
Enterococcus spp	19(11.7)	+	+	+	+	+	+	+	+	+
Escherichia coli spp	18(10.5)	+	+	+	+	−	−	−	+	−
Klebsiella spp	14(8.43)	−	−	+	+	−	−	−	−	−
Salmonella spp	14(8.43)	−	−	+	+	−	−	−	+	+
Aerobacteraerogenes spp	9(5.42)	+	−	+	+	+	+	−	−	−
Proteus spp	13(7.83)	+	−	−	−	−	−	+	+	+
Pseudomonas spp	12(7.23)	−	−	+	+	−	−	−	+	+
Baccilus spp	13(7.83)	+	+	−	−	+	+	−	+	+
Streptococcus spp	13(7.83)	−	−	−	−	+	+	−	−	−
Alcaligenes spp	13(7.83)	+	−	+	+	−	−	−	−	−
Flavobacterium spp	13(7.83)	+	+	+	−	−	+	−	−	−

Key: += Positive Test; − = Negative Test.

The presence of *Klebsiella spp* and *Aerobacter aerogenes spp* in some of the borehole and well water samples is unacceptable from the public health point of view. These organisms could be pathogenic. Therefore, there is need for caution when using these contaminated water sources for any purpose. The depth of the borehole ranged from 32 m to 108 m with average depth of 75.36 m while that of the hand-dug wells ranged from approximately 5 m to 17 m with an average depth of 8 m. Three of the well openings were unraised but however, not at ground level while the remaining twenty-two were pronouncedly raised above ground level. Out of the twenty-five wells, seven wells were not fully covered though concrete internal rings were present in the three while the remaining eighteen are usually covered after use. All well waters sampled for analyses were being used for drinking, cooking and washing purposes by the households and some other inhabitants of the community.

CONCLUSION

The study area generally has high groundwater potential in terms of yield due to its high transverse unit resistance. However, 28% of the study area, comprising of VESPAP2, VESPAP4, VESPAP10, VESPAP12, VESPAP13, VESPAP20, and VESPAP21 possessed high aquifer protective capacities while the remaining locations (72%) exhibited low aquifer protective capacities. In the entire study locations, where the longitudinal conductance (S) and hence, the protective capacity (P_c) values were less than 1.0 Siemens ($P_c < 1.0$ Siemens), they were classified as low aquifer protective capacity and were characteristics of depositional successions of overburden layers with no significant lithological barriers (impermeable clay/shale) or overlying rock. Despite the vulnerability status of the subsurface aquiferous zone of the study area to contaminant seepages emanating from the surface, the groundwater potential of the study area in terms of yield is high due to the recorded high transverse unit resistance (*R*) values making it a suitable terrain for the development of boreholes of potable water supply.

Generally, aquifers in the study area are not naturally protected by any lithological barrier to leachate seepage except in few locations. The integrated methods have proven to be effective tools for groundwater quality assessment. Groundwater potential in this study area is high due to high transverse unit resistance (*R*). Physico-chemical parameters and anions such as Dissolved Oxygen, Biochemical Oxygen Demand, Chemical Oxygen Demand, Alkalinity, Chlorine, Bicarbonates, and Magnessium carbonates, were higher than the allowable limit in groundwater. All trace and heavy metals analyzed were within the allowable limits, going by the standards employed except Zinc and Iron in boreholes and hand-dug wells which were slightly higher than the approved standards. The continuous accumulation of these metals, if not checked could result in pollution status with possible lethal effect to both terrestrial and aquatic organisms within the environment and beyond.

This investigation suggests that not all borehole waters are safe for consumption and well waters were of poorer bacteriological qualities indicative of health risk to the inhabitants of the geographical location. The sites of boreholes and wells are very important as clean and hygienic environment promote safety of water. Any chosen sites should be far from dumpsites and latrine (≥35m). Moreover, the populace needs to be educated on the importance of maintaining clean and hygienic environment around the borehole and well waters to ensure the safety of water from such sources.

RECOMMENDATION

There is need to carry out a comprehensive epidemiological study to determine the number of people suffering from diseases or illnesses related to the microbial water quality problems identified in the area of study. This will go a long way in providing medical information on the prevailing actual health problems that could be attributed to the usage of untreated groundwater.

REFERENCES

Adekunle, I.M., Adekunle, M.T.,Gbadebo, A.M., and Banjoko., O.B. 2007. Assessment of Ground water Quality in a Typical Rural Settlement in Southwest Nigeria. *International Journal of Environmental Research and Public Health.* 4(4):307 – 318.

Adegoke O.S., Dessauvagie T.F.J., Kogbe C.A., Ogbe F.G.A. 1971. Type section, Ewekoro Formation, Biostratigraphy and Microfacies, *4th African Micropal.Coll.*Abidjan. 37.

Adeniran,A., Daniel, K.A., and Pittock, J. 2021. Water Infrastructure Development in Nigeria: Trends, Size and Purpose. 22-26. https://doi.org/10.3390/w13112416

Addo, K., Mensah, G.I., Donker, B and Akyeh, M.L. 2009. Bacteriologicalquality of bottled water sold on the Ghanian Market. *African Journal of Food Agriculture Nutrition and Development* 9(6): 33-37.

Aizebeokhai A. P., Alile O. M., Kayode J. S., and Okonkwo F. C. 2010a. Geophysical Investigation of some Flood Prone Areas in Ota, Southwestern Nigeria. *American-Eurasian Journal of Science Research.* 5(4):216–

229.

Aizebeokhai A. P., Olayinka A. I., Singh V. S. 2010b. Application of 2D and 3D Geoelectrical Resistivity Imaging for Engineering Site Investigation in a Crystalline Basement Terrain, Southwestern Nigeria. *Environmental Earth Science*. 61(7):1481–1492. https://doi.org/10.1007/s12665-010-0474

Aizebeokhai, A.P. and Oyebanjo, O.A. 2013. Application of Vertical Electrical Soundings to Characterize Aquifer Potential in Ota, Southwestern Nigeria. *International Journal Physical Sciences*.8(46):2077–2085.

Aizebeokhai, A.P, Oyeyemi, K.D. 2014. The use of Multiple-Gradient Array Forgeo-Electrical Resistivity and Induced Polarization Imaging. *Journal of Applied Geophysics*. 111(1):364–376. https://doi.org/doi:10.1016/j.jappgeo.2014.10.023

Ajayi, A. O. and Adejumo, T. O. 2011. Microbiological Assessment and some Physico-Chemical Properties of Water Sources in Akungba-Akoko, Nigeria *Journal of Toxicology and Environmental Health Sciences*. 3(13): 342-346. https://www.academicjournals.org/JTEHS.https://doi.org/10.5897/JTEHS11.068

Alley, W.A., Reilly, T.E., and Franke, O.L. 1999. Sustainability of Groundwater Ressources.*United States Geological Survey.* Circular 1186, Denver Colorado, 310-312.

Alile, O. M. and Amadasun, C.V.O. 2008. Direct Current Probing of the Subsurface Earth for Water Bearing Layer in Oredo Local Government Area, Edo State, Nigeria. Nigeria *Journal of Applied Science* 25 (1): 107-116.

American Public Health Association (APHA). 1998. American Public Health Association. Standard Method for Examination of Water and Waste Water, *20th Ed. American Public Health Associated/ American Water Work Associated.* Inc, New York. 45- 46.

American Public Health Association (APHA) 1985. American Public Health Association: Standard Methods for the Examination of Water and Wastewater. 14thEdition.*American Public Health Association*, Washington D.C. 1985.

American Public Health Association (APHA) 1995. Standard Methods for the Examination of Water and Wastewater, 19th.Edition, *American Public Health Association*, Washington, DC, 1995.

Archibong, E.E 1978. The Stratigraphy of Ojo-1 Borehole, Department of Geology, University of Ife, Nigeria. 43.

Aryal, S. 2022. Mantol Salt Agar for the Isolation of Staphylococcus Aureus.1-5. microbiologyinfo2025.com.

Bairds, C. 1995. "Environmental Chemistry," W.H. Free-man and Company, New York, 1995: 384-387.

Baron E.J, and Sydney M.F.1990. Bailey and Scott's Diagnostic Microbiology. The C.V. Mosby Co., St. Louis, 861.

Bello, O.O., Osho, A.,Bankole, S.A. and Bello, T. K. 2013. Bacteriological and Physicochemical Analyses of Borehole and Well Water Sources in Ijebu-Ode, Southwestern Nigeria. *IOSR Journal of Pharmacy and Biological Sciences*.8(2):18-25. www.iosrjournals.org.

Benham, B. 2024. Virginia Cooperative Extension/Virginia State University/United States Department of Agriculture/Local Government Authority: Virginia Household Water Quality Program: Total Dissolved Solids (TDS) in Household Water. *Publications and Educational Resources.* (BSE-364P): 442-666. www.wellwater.bse.vt.edu/resources.p

Billman, H.G. 1992. Offshore Stratigraphy and Paleontology of the Dahomey (Benin) Embayment, West Africa, 1st. *NAPE Bull.* No. 2, 7(1): 121 – 130.

Bitton, G. 1994. Waste Water Microbiology. Gainesville, New York Wiley.118.

Bjornlund, H., Nickum, J.E., and Stephan, R.M. 2018. The Wicked Problems of Water Quality Governance. *Water International.* 43(1): 323-326. https://doi.org/10.1080/02508060.2018.1452864.

Brown, R and Kookana, R. 2019. The Future of Urban Clean Water Scarcity and Sanitation. *One Earth.* 1(1): 10-12.

Buchanan R.E, and Gibbons N.E. 1974. Bergey's Manual of Determinative Bacteriology, 8th Edition. *The Williams and Wilkins Co.,* Baltimore, 124 −127.

Bunce, N. J. 1990. Environmental Chemistry. *Winers Publishing Ltd.,* Winnipeg. 110-113.

Burnett, S.L. and Beuchat., L.R. 2001. Human Pathogens Associated with Raw Produce and Unpasteurized Juices, and Difficulties in Contamination. *Journal of Industrial Microbiology and Biotechnology* 27(6): 104-110.

Chen, J., Wu, H., Qian, H.A., Li, X. 2016. Sustainable Groundwater Management in an Agricultural Plain along Silk Road Economic Belt, North-West China. *International Journal of Water Resources Development* 34(3): 354-368. https://doi.org/10.1080/07900627.2016.1238348

Chene J. 1978. Biostratigraphical study of the Borehole Ojo -1 South West Nigeria. *Rene de micropal* 21: 123-139.

Commercial Lift Station Maintenance (CLSM). 2024. Commercial Lift Station Maintenance: In Maintaining Wastewater and Storm water Lift Stations. *AQUALIS Bulletin and Professional Monthly Newsletter.*3-7.

Dekker, D and Frank, E. 2015. National Institute of Health/National Laboratory of Medicine/National Centre for Biotechnology Information: Salmonella, Shighella and Versiniu.Clinical Laboratory Medicine. 35(2): 225-246. https://doi.org/10.1016/j.cll.2015.02.002

Department for International Development (DFID). 2001. Addressing the Water Crisis: Healthier and More Productive Lives for Poor People, Strategies for Achieving the International Development Targets. *Department for International Development Bulletin, United Kingdom.*2 – 3.

Digestive Ferment Company (DIFCO). 1984. Dehydrated Culture Media and Reagents for Microbiology. Manual of Culture Media and Reagents.10th Edition, *DIFCO Laboratories in Detroit*, Michigan. 7(1): 1149-1155.

Directorate of Water Development (DWD). 2002. Directorate of Water Development: in Overview of the Water Sector, Reform, SWAP and Financial Issues. Ministry of Water, Lands and Environment, *The Republic of Uganda.* 1(1): 12-15.

Eniola, K.I.T. Obafemi, D.Y. Awe, S.F. Yusuf , I.I. and Falaiye, O.A. 2007. Effects of Containers and Storage Conditions on Bacteriological Quality of Borehole Water.*Nigerian Journal of Microbiology.* 21(3): 1578 – 1585.

Erah, P.O. Akujieze, C.N. and Oteze, G.E. 2002. The Quality of Groundwater in Benin City: A Baseline Study on Inorganic Chemicals and Microbial Contaminants of Health Importance in Boreholes and Open Wells. *Tropical Journal of Pharmaceutical Research.* 1(2): 75-82.

Fawole, M.O. and Oso, B.A. 2001. Laboratory Manual of Microbiology.Ibadan, Nigeria Spectrum Books.15-45.

Fidelis U., Thomas H. and Uduak A. 2014. Reserve Estimation from Geoelectrical Sounding of the Ewekoro Limestone at Papalanto, Ogun State, Nigeria. *Journal of Energy Technologies and Policy* 4(5): 28-33. ISSN 2225-0573.

Foster, T., Furey, S., Banks, B and Willets, J. 2020. Functionality of Hand-Pump Water Supplies: A review of Data from sub-Saharan Africa and the Asia-Pacific Region. *International Journal of Water Resources Development.* 36(5): 855-869. https://doi.org/10.1080/07900627.2018.1543117

Glennon, R. 2025. The Perils of Groundwater Pumping.Issues in Science and Technology.National Academy of Science, *Arizona State University Journal.* 19(1): 6-9.

Gromicko, N. 2025. International Association of Certified Home Inspection (InterNACHI): Hand-dug Wells Inspection; Construction and Safety Construction. *InterNACHI Bulletin.* 25-29.

Handzel. T. 2008. The Effect of Improved Drinking Water Quality on the Risk of Diarrheal Disease in an Urban Slum of Dhaka, Bangladesh: A Home Chlorination Intervention Trial. Doctoral Dissertation.*Department of Environmental Sciences and Engineering. University of North Carolina,* Chapel Hill, 2008, UNC: 110-104.

Harvey, P.A. and Reed, R.A. 2004. Rural Water Supply in Africa: Building blocks for hand-pump sustainability. *WEDC, Loughborough University*, United Kingdom. 46- 49.

Hazelton, D. 2000. The Development of Community Water Systems using Deep and Shallow Well Hand-pumps' Report No, TT132/00, *Water Research Centre*, S A. 22-24.

Hoekstra, A.Y. 2010. The Relation between International Trade and Freshwater Scarcity. Handbook on Trade and the Environment: *WTO Staff Working Paper in Economic Research and Statistics Division* (ERSD-2010-05). 39-46.

International Bank for Reconstruction and Development (IBRD). 1994. Joint committee of International Bank for Reconstruction and Development (IBRD) and International Development Association (IDA). Deveopment Projets in Middle and Low-income Countries with World Bank Group. Consult Diwi. and Bureau d'Ingénierie pour le Développement Rural (BIDR). Etudes d' Réhabilitation des Points d' EauExistants.11-13.

Ishola S.A., Makinde V., Aina J.O., Ayedun H., Akinboro, F.G.,Okeyode I.C., Coker J.O., and Alatise O.O 2016. Aquifer

Protection Studies and Groundwater Vulnerability Assessment in Abeokuta South Local Government Area, South-West Nigeria, *Journal of Nigerian Association of Mathematical Physics*. 33 (1): 347-362.

Ishola S.A 2019. Characterization of Groundwater Resource Potentials using Integrated Techniques in Selected Communities within Ewekoro Local Government Area South-West Nigeria. *Department of Physics, FUNAAB Ph.D Thesis.*

Ishola, S.A., Makinde, V., Gbadebo, A.M., Mustapha, A.O and Orebiyi E.O. 2021. Quality Assessment of Groundwater System in Itori Community of Ewekoro Local Government Area, South-West Nigeria. *International Journal of Science and Technology in Science and Technology Publishing.*5 (12): 1060-1061. www.scitechpub.org

Ishola, S.A., Emumejaye, K., Olagbaju, P., Aluko, T.J and Bukar, M. 2025. Hydraulic Characterizations for Aquifer Productive Capacity in a Typical Sedimentary Terrain, South-West Nigeria. *International Journal of Environmental Research and Earth Sciences*. 8(4): 11-49.https://doi.org/10.70382/caijeres.v8i4.013

Jones H.A, Hockey R.D 1964. The Geology of Parts of Southwestern Nigeria. Geol Survey Nig. Bull. 1964, 31(1): 22 – 24.

Koefoed, O. 1979. Geo-sounding Principles I: Resistivity Sounding Measurements. Elservier. Oxford. 215.

MacDonald, A.M. and Davies, J. A. 2000. Brief Review of Groundwater for Rural Water Supply in Sub-Saharan Africa. *British Geological Survey Technical Report* WC/00/33, Nottingham, UK.9-10.

Maptons. 2025. Papalanto on the Map of Nigeria. 2-3. Location Maps in Southwest Nigeria. https://tt.maptons.com/2901387">papalanto on the map of Nigeria

Massma, G., Tichominowa, M., Merz, C and Pekdeger, A. 2003. Sulphide-Oxidation and Sulphate Reduction in a Shallow Groundwater System (Odebruch Aquifer) Germany.*Journal of Hydrology.* 278(1-4): 231-243. https://doi.org/10.1016/s0022-1694(03)00153-7.

McaAlhster, D.J., Nedaw,D., Kebede, S., Mkandawire, T., Makuluni, P., Shaba, C., Okullo, J., Owor, M., Carter, R., Chilton, J., Casey, Y.M., Casey, Y., Fallas, W., MacDonald, A.M. 2022. Contribution of Physical Factors to Hand-Pump Functionality in Africa *Science of Total Environment.* 851 (2): 3331-338. https://doi.org/10.1016/j.scitotenv.2022.158343

Mdee, A., Ofori, A., Lopez-Gonzalez, G., Stringer, L., Martin-Ortega, J., Ahrari, S., Dougill, A., Evans, B., Holden, J., Kay, P., Kongo, V., Obani, P., Tillotson, M., Camargo-Valero, M.A. 2022. The top 100 Global Water Questions: Results of A scoping Exercise. *One Earth.* 5(5): 563-573. https://doi.org/10.1016/s0022-1694(03)00153-7.

Nigerian Standard for Drinking Water Quality (NSDWQ). 2007. National Standard for Drinking Water Quality.*NSDWQ Annual Report.*1-22.

Odu, N.N., Amadi, L.O., Makililo, M. 2020. Comparative Assessment on the Physico-chemical Water Quality of Wells and Boreholes in Two Rivers State Communities, Nigeria.International Journal of Research

Studies in Microbiology and Biotechnology. 6(3): 5-20. https://doi.org/10.20431/2454-9428.0603002

Okafor, P. and Mamah. L. 2012. Integration of Geophysical Techniques for Groundwater Potential Investigation in Katsina-Ala, Benue State, Nigeria.*Pacific Journal of Science and Technology.* 13(2): 463-474.

Okoronkwo, N. Igwe, J. C. and Onwuchekwa, E. C. 2005. Risk and Health Implications of Polluted Soils for Crop Production. *African Journal of Biotechnology* 4(13): 1521-1524.

Okosun, E.A. 1990. A Review of the Cretaceous Stratigraphy of the Dahomey-Embayment, West Africa. *Cretacaceous Resources.*11(1): 17–27.

Okosun, E.A. 1998. Review of the Early Tertiary Stratigraphy of Southwestern Nigeria, *Nigerian Journal of Minning and Geology* 34 (1): 27–35.

Oladeji B.O 1992. Environmental Analysis of Ewekoro Formation at the Shagamu Quarry. *Nigerian Journal of Mining and Geology* 28(1): 148–156.

Oliver, K and Boaz, A. 2019. Transforming Evidence for Policy and Practice; Creating Space for New Conversations. *Palmgrave Comm.* https://doi.org/10.10.1057/541599-019-0266-1

Omosuyi, G.O. 2010.Geoelectric assessment of groundwater prospect and vulnerability of overburden aquifers at Idanre, Southwestern Nigeria. *Ozean Journal of Applied Sciences.* 3(1): 19-28.

Omosuyi, G.O., Ojo, J.S., and Olorunfemi, M.O. 2008. GeoelectricSounding to Delineate Shallow Aquifers in the Coastal Plain Sands of Okitipupa Area, Southwestern Nigeria.*PacificJournalof Science and Technology* 9(2):562–577.

Osayande, A. and Umukoro, I.A. 2025. Water Quality Assessment of Hand-dug wells, Boreholes, and Surface Water in Sobe, Edo State and Hand-dug wells in Elegbeka, Ondo State.*Journal of Geography Environment and Earth Science International.* 29(4): 22-66. https://doi.org/10.9734/jgeesi/2025/429i4878

Oyedele, K.F. and A.O. Adeyemo. 2001. Surface Electrical Resistivity Measurement in the Characterization of Groundwater Potentials of the Typical Basement Terrain, Northern Nigeria. *African Journal of Environmental Studies.* 2(1):52 - 54.

Pennsylvanian Department of Conservation and Natural Resources and Pennysylvania Goundwater Information System (PADCNR/PAGWIS). 2022. Joint committee of Pennysylvania Department of Conservation and Natural Resources and Pennysylvania Goundwater Information System on Water Well Maintenance and Rehabilitation. College of Agricultural Sciences, the Pennysylvanian State University.323, Agricultural Admnistration Building University Park, PA 16802.*PADCNR Bulletin.*10-11.

Pelczar, M.J., Chan, E.C.S and Noel, R.K. 2005. *Microbiology.*5th Edition, Tata McGraw Hill, New Delhi. 35(1): 571-572

Piesse, M. 2020. Global Water Supply and Demand Trends Point towards Rising Water Insecurity. *Future Directions International.* 1-8.

Packaged Pumps Systems (PPS). 2023. Packaged Pumps Systems on How Often Should Your Service Your Basement Sump Pump System. *PPS Bulletin.* 3-5. Retrieved August 28, 2025.

Rijal, N. 2025. Most Probable Number test, principle, pressure and results. *Microbe Online* 147-119.

Rogbesan, A.A. Eniola, K.I.T. and Olayemi., A.B. 2002. Bacteriological Examination of some Boreholes within University of Ijebu-Ode. Nigerian *Journal of Pure and Applied Science* 5(3): 117 – 223.

Selvam, S., Singaraya, C., Venkatramanan, S., Ching, S.Y. 2018. Geochemical Appraisal of Groundwater Quality in OttapidaramTaluk, Thoothukudi District, Talminedu using Graphical and Numerical Method. *Journal of Geology Society of India.* 92 (1): 313-320.

Salty, K., Jimenez, A., Willets, J., Leifels, M., and Bartram, J. 2020. Global Water Sanitation and Hygiene Research Priorities and Learning Challenges under Sustainable Development Goal 6.*Development Policy Review.* 38(1): 64-84. https://doi.org/10.1111/dpr.12475.

Siebrits, R.M., Winter,K., Barnes, J., Dent,M.C., Ekama, G., Ginster,M., Harrison, J., Jackson, B., Jacobs, I., Kasan, H.C. 2014. Priority Water Research Questions for South Africa Developed through Participatory Processes. *Water SA.* 40(1): 199-210. https://doi.org/10.4314/wsa.v4012.2

Subba-Rao, N., Surya-Rao, P., Venktran-Reddy, G., Nagamani, M., Vidyasagar, G., and Satyanarayana, NLVV. 2012. Chemical Characteristics of Groundwater and Assessment of Groundwater Quality in Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India. *Environmental Monitoring Assessment* 184(1): 5189-5214.

Subba-Rao, N., Marghade, D., Dinakar, A., Chandana, I., Sunitha, B., Ravindra, B and Balaji, T. 2017. Geochemical Characteristics and Controlling Factors of Chemical Composition of Groundwater in a Part of Guntur District, Andhra Pradesh, India.*Environmental Earth Sciences* 76(1): 747-749.

United Nation Environment Programme (UNEP). 2001. United Nation Environment Programme:State of Water Sanitation and Health Programme Nepal. *UNEP Bulletin*, 2001: 7-13.

United Nations International Children Education Fund and World Health Organizaton (UNICEF/WHO). 2025. Joint Report on Progress on Household Drinking Water and Sanitation: 2000-2024. *UNICEF Bulletin.*5-12.

United Nations Worldometer and Statistical (UN-WS). 2025. United Nations Worldometer and Statistical on World Population Clock: World Population Section and Prospects, Past, Present and Future. https://www.worldometer.info. Retrieved on August 27, 2025.

United Nation World Water Development and Report and United Nations Education, Scientific and Cultural Organizations (UNWWDR/UNESCO). 2025. Joint Committee of United Nation World Water Development and Report and United Nations Education, Scientific and Cultural Organizations. Mountains and Glaciers.*Water Towers* (EN/AR/RH/ZH/DE/HI/IT/KO/NE/IT/VI). 3-5. https://doi.org/10.54679/LHPJ5153. https://www.unesco.org

United Nation World Water Development (UNWWDR). 2020. United Nation World Water Development and Report on Water and Clmate Change. *UNICEF World Water Assessment Programme.* 605(2): 174. https://www.unwater.org/publications/world-water-development-report-2020.

United Nation World Water Development and Report (UNWWDR). 2017. United Nation World Water Development and Report on Wastewater: the Untapped Resources. UNWWDR Report Bulletin. 11-27. https://www.wastewater.org/publications/world-water-development-report-2017

Ushie, F., Harry, T., and Affiah, U. 2014. Reserve Estimation from Geoelectrical Sounding of the Ewekoro Limestone at Papalanto, Ogun State, Nigeria. *Journal of Energy Technologies and Policy* 4(5): 28.

Vander-Velpen, B.P.A. 2004. "WIN RESIST™". Electrical Resistivity Inversion Program.1-3.

Venot, M.M., Vos, L.M, Mille, C.P, Zwarteveen, F., Veldwisch, G.J., Kiper, F., Mdee, A., Ertsen, E., Boclens, L., Clever, F.G. 2021. Water Governance, Sustainability and the Role of Institutions: The Case of Water Scarcity. *Nature Sustainablity (Nature Publishing Group).* 5(1): 92-95. https://doi.org/10.1038/541893=021-00835-y.

West African Portland Cement Company (WAPCO). 2000. Environmental Audit Report of The West African Portland Cement Plc, Ewekoro and Shagamu Quarries submitted to the Federal Ministry of Environment, Abuja. *The West African Portland Cement Plc, Elephant* House, Alausa-Ikeja Lagos. 1-155.

West African Portland Cement Company (WAPCO). 2001. Environmental Impact Assessment of the Proposed Clinker Line of The West African Portland Cement Plc, at Ewekoro Submitted to The Federal Ministry of Environment, Abuja. *The West African Portland Cement Plc,* Elephant House, Alausa-Ikeja Lagos, Nigeria. 1-155.

Ward, S.H. 1990. Geotechnical and Enviromental Geophysics. Vol. I. Review and Tutorial; Vol. II: Enviromental and Groundwater; Vol. III: Geotechnical. *Society of Exploration Geophysicist, Tulsa.*389, 342 and 300.

Wenger, S.J., Roy, A.H., Jackson, C.R., Bernhardt, E.S., Carter, T.L., Filoso, S., Gibson, C.A., Hession, W.C., and Kaustal, E.2009. Twenty-six Key Research Questions in Urban Sream Ecology. *Journal of North America Benthol Social*: 1080-1098. https://doi.org/10.1899/08-186.1

World Health Organization (WHO). 1985. World Health Organization. International Standards for Drinking Water.*WHO Water Quality Report Newsletter.*10-15.

World Health Organization/United Nations International Children Education Fund (WHO/UNICEF). 2025. Joint Committee of WHO/UNICEF Report onWater, Sanitation and Health (WASH) on Disease Burden: Practices in Africa. *WHO/UNICEF Circular.*11-14.

Williams, J., Bouzarovski, S and Swyngeodouw, E. 2019. The urban Resource Nexus: on the Politics of Relationality Water-Energy Infrastructure and the Fallacy of Integration. *Environmental Planning Committees on Political Sp*. 652-669. https://doi.org/10.1177/126377.4x18803370 .

(Manuscript received: 15th February, 2024; accepted: 22nd November, 2025.