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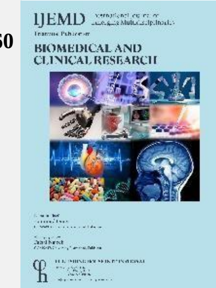

Physicochemical Analysis of Hand-Dug Well and Borehole Water in Obi Local Government Area

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Abstract

This study investigates the physicochemical quality of water from selected hand-dug wells and boreholes in Obi Local Government Area (LGA), Nasarawa State, Nigeria. Forty-four water samples were analyzed for parameters such as pH, temperature, total dissolved solids (TDS), total hardness (TH), nitrate, acidity, alkalinity, and dissolved oxygen (DO). Results showed that TDS values ranged from 35.67 to 2313 mg/L, with several samples exceeding the WHO and SON permissible limit of 500 mg/L, indicating high mineralization and potential palatability issues. Total hardness ranged from 0.5 to 91 mg/L, classifying the water as soft, which while non-harmful, may contribute to corrosion. Nitrate concentrations were between 2.46 and 24.26 mg/L, within safe limits (≤50 mg/L), but suggest surface runoff influence. Acidity levels reached up to 82.33 mg/L, significantly exceeding the acceptable range of 4.5–8.0 mg/L, with implications for corrosion and potential pollution. Additionally, dissolved oxygen ranged from 2.03 to 6.23 mg/L, with lower values in some areas potentially impacting water chemistry. These findings stress the need for improved water treatment and periodic monitoring to safeguard public health.

Keywords: Dissolved oxygen ; Corrosion ; Total hardness ; Irrigation ; Groundwater

INTRODUCTION

Clean and safe water is crucial for meeting the health needs of every individual. However, the availability and quality of both surface and groundwater have been significantly compromised by factors such as rapid population growth, urbanization, excessive groundwater extraction, agricultural activities, and industrialization [49]. These factors have led to increasing health challenges associated with water contamination.

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Water quality in any given area or source can be assessed through physical, chemical, and biological parameters. When the values of these parameters exceed acceptable limits, they pose significant risks to human health [78] Hence, the suitability of water sources for drinking and other domestic purposes is best evaluated through continuous water quality monitoring.

Water, being an indispensable solvent, is widely used in domestic and industrial activities. It naturally exists in three main sources: rainwater, surface water, and groundwater [97]. As water infiltrates the ground, it undergoes partial natural purification through various layers of soil and rock. This process can improve its clarity, color, taste, and odor by the time it reaches the surface via well shafts, springs, or boreholes [98].

Access to clean drinking water is essential for human life and well-being and remains a fundamental necessity for all communities [5]. Besides being vital for drinking, water resources are crucial in sectors such as agriculture, livestock production, forestry, industry, hydroelectric power, fisheries, and various creative industries.

According to the World Health Organization [126], approximately 1.1 billion people worldwide lack access to safe drinking water. In Nigeria, only 58% of people in urban and semi-urban areas and 39% in rural areas have access to potable water. The remaining population depends on groundwater (from wells and boreholes) and surface water (from streams and rivers) for their domestic supply [39]. In many Nigerian cities, towns, and villages, residents spend valuable time and effort collecting water often of poor quality from distant sources [32].

Obi, a local government area in Nasarawa State with a population of nearly 150,000, faces severe water pollution due to high population density, inadequate sanitation practices, and weak enforcement of environmental sanitation laws. Groundwater pollutants in the area stem from municipal sources (e.g., leachate from landfills and septic tanks), industrial discharges (e.g., leakage from tanks and pipelines), and agricultural runoff (e.g., saline irrigation return flow) [108]. The close proximity of wells and boreholes to soak ways and pit latrines further exacerbates the risk of groundwater contamination.

Elevated concentrations of heavy metals such as lead (Pb), chromium (Cr), arsenic (As), and iron (Fe) originating mainly from industrial sources, present serious threats to both human health and aquatic ecosystems [91] , [101]. These metals can cause acute or chronic poisoning, and in severe cases, lead to death when consumed in untreated water. Additionally, pollutants contribute to increases in Biological Oxygen Demand (BOD), Total Dissolved Solids (TDS), Total Suspended Solids (TSS), and fecal coliform counts further degrading water quality and making it unsafe for drinking, irrigation, and other uses. Managing and mitigating these pollutants is essential for safeguarding public health and maintaining ecological balance [95]. This underscores the need for effective water treatment and pollution control strategies.

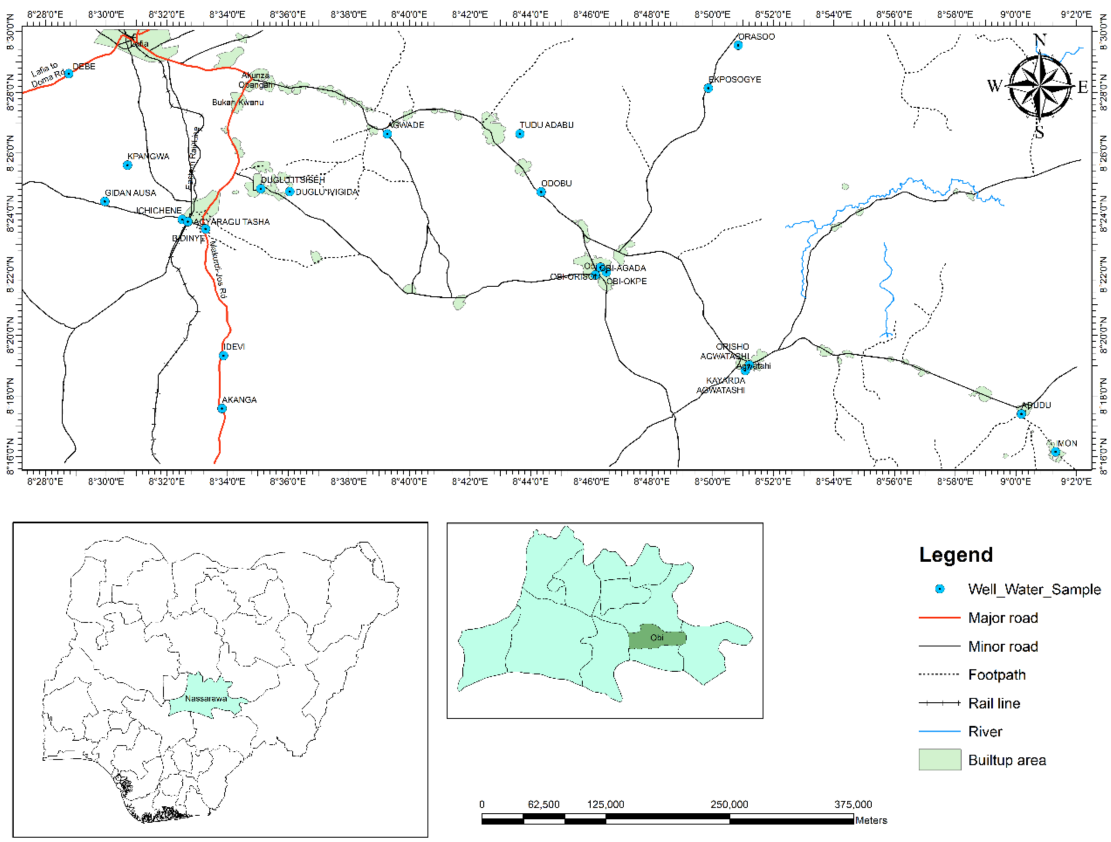

Figure 1: Sample Locations at Obi Local government area of Nasarawa State.

Generally, borehole water is considered to have superior microbial quality compared to water from hand-dug wells, as boreholes tap into deeper aquifers that are less prone to microbial contamination [43, 89, 37]. However, the increasing reliance on groundwater sources for domestic use is concerning, particularly in areas where water quality assessments are infrequent. In such cases, consumers risk exposure to severe illnesses caused by contaminated water (Dharwal et al., 2022; Orimoloye et al., 2015; Galadima et al., 2011).

While soil layers may filter out some microorganisms, especially larger bacteria and protozoa, groundwater contamination still occurs particularly near septic tanks or landfills [64]. This issue is notably prevalent in Obi Local Government Area due to poor sanitation infrastructure and proximity of water sources to pollution sites [82]. Communities that rely on untreated surface water or shallow groundwater sources are especially vulnerable to contamination from on-site sanitation and waste disposal [3 , 4]. In sub-Saharan African cities like Dakar, Lusaka, and parts of Nigeria, shallow wells have been reported to contain nitrate, bacterial, and heavy metal concentrations that exceed both national and international water quality guidelines [21 , 19]. This research investigates the physicochemical properties of water samples from selected hand-dug wells and boreholes in Obi Local Government Area. Parameters assessed include temperature, pH, electrical conductivity, total dissolved solids (TDS), total suspended solids (TSS), total hardness, total acidity, total alkalinity, chlorides, nitrates, carbonates, hydrogen carbonates, dissolved oxygen (DO), and biochemical oxygen demand (BOD).

The study is limited to selected hand-dug wells and boreholes in Obi Local Government Area. Therefore, its findings may not be directly applicable to other regions or water sources. Nonetheless, this research provides valuable insights into the quality of groundwater resources that serve as the primary drinking water supply for residents. By identifying potential contaminants and their concentrations, the study helps assess public health risks, particularly concerning waterborne diseases and heavy metal toxicity.

MATERIALS & METHODS

Study Area

This study was conducted in Obi Local Government Area (LGA) of Nasarawa State, located in the North-Central geopolitical zone of Nigeria. Geographically, Obi LGA lies between longitudes 8º30′ and 9º00′ E and latitudes 8º00′ and 8º30′ N. The area spans approximately 967 km² and experiences an average temperature of about 30°C. According to the 2006 census, Obi LGA had a population of 148,874, which has steadily grown over the years to over 150,000 due to natural increase and migration. This growing population places increasing pressure on the area's water resources.

Ecologically, the region is a transitional zone between savannah and tropical rainforest, a unique blend that influences local water availability and quality. Obi experiences two main seasons—dry and wet—with an average wind speed of 10 km/hr ().

Obi LGA is bordered by several other local government areas: Lafia to the north (the state capital), Awe to the east, Doma to the west, and further growth to the south. The area's geological setting is part of the Benue Trough, a significant formation in Nigeria rich in minerals and sedimentary rocks. The terrain is primarily underlain by sandstone, shale, and limestone, all of which influence the region's groundwater hydrology. These sedimentary layers, shaped over millions of years by tectonic processes, are crucial in determining the quantity and quality of available groundwater.

Several human activities pose threats to water quality in the region. These include agricultural runoff, mining operations, waste disposal sites, markets, and abattoirs, all of which can introduce pollutants into groundwater systems. Additionally, poor waste management, urban expansion, deforestation, and the over-extraction of groundwater further contribute to water quality degradation (Musa & Suleiman, 2020).

Collection of Water Samples

To ensure representative sampling across Obi LGA, the area was divided into four zones: northern, southern, eastern, and western. Water sources, specifically hand-dug wells and boreholes were identified in each zone based on their exposure to different levels of anthropogenic activities.

Samples were collected using standard methods as described by [12]. In each zone, at least one hand-dug well and one borehole were sampled. The sampling locations were:

- **West Zone:** Akanga, Idevi, Gidinye, Ichichene, Debe, Kpangwa, Agyaragyu Tasha, Gidan Ausa
- **North Zone:** Orasoo, Ekposogye, Odobu, Tudun Adubu, Agwade Itsi Zhenmodu, Duglu Ivigida, Duglu Itsise
- **South Zone:** Orisoh Agwatashi, Kayarda Agwatashi, Obi Okpe, Obi Agada, Obi Orison

- **East Zone:** Imon, Audu Ang Sama

A total of 44 water samples were collected for analysis from both hand-dug wells and boreholes.

Physicochemical Parameters

Water quality parameters were measured to assess the physicochemical characteristics of each sample:

- **pH:** Measured using the Wag WT 3020 pH meter, which was calibrated using buffer solutions of pH 4, 7, and 9 prior to measurement.
- **Temperature:** Recorded at the point of collection using a mercury-in-glass thermometer before the samples were transported to the laboratory.
- **Colour and Turbidity:** Determined using the Wag WT 3020 turbidimeter.

RESULTS & DISCUSSIONS

Access to clean and safe water is essential for all purposes—especially for drinking—when its quality meets acceptable standards [127]. However, when physicochemical parameters deviate from recommended guidelines, water must undergo treatment to improve its quality before it can be safely used.

Chloride Concentration

The concentration of chloride in the water samples collected across Obi Local Government Area ranged from 3.37 mg/L to 14.19 mg/L, as detailed in Tables 1 through 7. These values are significantly lower than the maximum permissible limit of 250 mg/L recommended by both the World Health Organization [124] and the Standards Organisation of Nigeria [103].

The lowest chloride concentrations were recorded in several locations across the study area. In Obi South, for example, values included OSR-2 (3.37 mg/L), OSA-2 (3.54 mg/L), OSK-1 (3.54 mg/L), and OSKA-1 (3.54 mg/L), as shown in Tables 6 and 7. Similar low levels were found in Obi West—such as OWI-1, OWI-2, OWD-1, OWKP-1, and OWGA-1 (each around 3.54–3.55 mg/L)—as presented in Tables 1 and 2. In Obi East, OEA-2 had a value of 3.55 mg/L (Table 3), while Obi North samples ONS-4, ONS-6, ONT-8, ONA-1, and ONI-11 also ranged around 3.54–3.55 mg/L (Tables 4 and 5). The highest chloride concentration was found in the OWG-2 sample from Gidinye, with a value of 14.19 mg/L.

These findings align with previous studies on rural water sources in Nigeria, which typically report chloride concentrations between 5 mg/L and 20 mg/L [110] , [17] Such consistency highlights the relatively unpolluted nature of rural groundwater sources, especially in areas with limited industrial activities. International studies have similarly reported low chloride levels in rural settings: for instance, over 40% of rural water supplies in the United States had chloride levels below 25 mg/L [115], while in Ontario, Canada, more than half of the rural water sources had concentrations under 10 mg/L (Health Canada, 2019).

Chloride concentrations exceeding 10 mg/L are often attributed to anthropogenic influences such as the discharge from sewage systems, leachates from landfills, runoff from fertilizers, and seepage from septic tanks [88] , [7] , [102] . The elevated level observed in Gidinye (OWG-2) may be linked to the prevalent use of chloride-containing fertilizers or the application of saline irrigation water, given the agricultural prominence of the area [134]. Other contributors may include domestic wastewater and improper disposal of cleaning agents.

Although the observed chloride levels do not currently exceed safety limits, elevated concentrations can pose risks. Excess chloride can give water an unpleasant salty taste, reduce its palatability, and potentially cause laxative effects. Additionally, it may accelerate corrosion in plumbing systems, resulting in increased maintenance costs and the risk of metal leaching into drinking water.

In summary, the analysis of chloride in the sampled water indicates that the concentrations are well within acceptable limits, suggesting minimal salt-related contamination and a generally good level of water quality in the study area.

Carbonate and Bicarbonate Levels

Tables 6 and 7 also show the levels of carbonate and hydrogen carbonate (bicarbonate) in water samples from Obi South. Carbonate concentrations were found to be quite low, ranging from 0.017 to 0.020 mg/L. Notably, carbonate was only detected in OSR-1 (0.017 mg/L) and OSK-1 (0.020 mg/L), while all other samples from Obi North, Obi West, and Obi East showed no detectable carbonate presence.

Hydrogen carbonate levels, on the other hand, were slightly more variable across zones. They ranged from a minimum of 1.03 mg/L—found in several samples from Obi West, Obi South, and Obi North—to a maximum of 6.07 mg/L recorded in sample OWKP-1 from Obi West.

Neither [124] nor [103] provide explicit guideline values for carbonates and hydrogen carbonates in drinking water. However, these ions play an indirect but important role in water quality assessments because they influence other key parameters such as pH, total hardness, and alkalinity [48] , [84]. For example, the WHO recommends a pH range of 6.5 to 8.5 for drinking water—a parameter often shaped by the concentration of carbonate and bicarbonate ions.

Although specific limits for carbonates and bicarbonates are not provided, their presence is monitored due to their contribution to the water's buffering capacity and alkalinity. Elevated levels may not pose direct health risks but can influence the taste, corrosiveness, and overall chemical balance of water.

In a similar study conducted by [9] in Lafia, the capital of Nasarawa State, carbonate levels in groundwater were found to be negligible—often below detectable limits. This observation aligns with the findings in Obi North, West, and East, where no carbonates were detected. However, bicarbonate levels in Lafia ranged from 3.2 to 7.5 mg/L, slightly higher but still comparable to the 1.03 to 6.07 mg/L range observed in Obi South.

Further supporting this pattern, [56] reported hydrogen carbonate concentrations of 2.5 to 8.0 mg/L in surface water samples from Lafia. These values fall within the same order of magnitude as those found in the Obi South samples, suggesting a consistent water chemistry profile across different regions of Nasarawa State. This consistency may be attributed to shared geological characteristics and similar weathering processes across these regions.

The levels of carbonates and hydrogen carbonates observed in Obi South are typical of those found in natural groundwater systems. High concentrations of bicarbonate are not generally hazardous to health but can influence the taste of water and contribute to water hardness. Although [124] and [103] standards do not specify exact limits for these ions, the measured concentrations are well within ranges generally deemed safe for domestic use.

The presence of carbonates in select locations—such as OSR-1 and OSK-1 in Obi South—and their absence in other areas suggest the influence of localized geological conditions. Specifically, the occurrence of carbonate minerals like calcite and dolomite in certain aquifers can lead to their dissolution into groundwater. This variation in concentration indicates differing degrees of mineral weathering and soil composition across the Obi region. As noted by [81], the dissolution of carbonate-bearing rocks is the primary source of both carbonate and bicarbonate ions in groundwater.

In Obi Orison (OSR-1) and Obi Okpe (OSK-1), the slight presence of carbonates may point to aquifers rich in carbonate-bearing minerals. Although human activities—such as agricultural runoff containing lime or industrial discharges—can also introduce carbonate compounds into water sources [128], no direct evidence of such influences was observed in this study. Therefore, natural geological processes are likely the dominant contributors.

While bicarbonates do not pose direct health risks, elevated alkalinity can affect water's organoleptic qualities and contribute to scaling in pipes, boilers, and other plumbing infrastructure, leading to increased maintenance costs and reduced system efficiency [116].

These findings are consistent with earlier research by [112] in Lafia, which also attributed similar carbonate and bicarbonate levels in groundwater to the natural dissolution of local geological formations. While all observed concentrations fall within safe limits, regular monitoring is recommended to ensure continued water quality, especially in the face of increasing anthropogenic pressures.

Nitrate Concentration

The concentration of nitrates in borehole and well water samples from all zones of Obi Local Government Area is presented in Tables 1–7. Nitrates are the end products of ammonia oxidation and are widely recognized as indicators of organic pollution in water sources [69] , [74]. Monitoring nitrate levels is critical, as elevated concentrations can pose serious health risks.

Exposure to high nitrate levels has been linked to methemoglobinemia (blue baby syndrome) in infants and nitrate poisoning in adults [124]. Pregnant women and infants under six months are particularly vulnerable [51]. In the current study, the highest nitrate concentration was observed in sample ONS-5 from Obi North at 24.26 mg/L, while the lowest was recorded in OWKP-1 from Obi West at 2.46 mg/L. Overall, nitrate levels across all water sources ranged from 2.46 to 24.26 mg/L, remaining well below [124] and SON [103] guideline value of 50 mg/L.

Interestingly, borehole water samples generally exhibited higher nitrate levels than well water. This pattern might reflect deeper infiltration of surface contaminants into borehole aquifers or differences in surrounding land use practices. Comparable studies by [35] and Yu et al. (2020) on surface water reported even higher nitrate concentrations than those found in this investigation, highlighting the relative safety of the groundwater sources in Obi LGA.

Common sources of nitrate contamination include agricultural runoff (especially from nitrogen-based fertilizers), leakage from septic systems, and improper waste disposal around water points [94]. The spatial variability in nitrate levels across zones emphasizes the need for effective land use planning and sanitary protection around groundwater sources.

Total Hardness

Water hardness refers to the presence of dissolved minerals—primarily calcium and magnesium which reduce the effectiveness of soap and promote scaling in pipes and heating systems [117] Total hardness (TH) originates from the dissolution of limestone and other calcium-rich materials, as well as from industrial effluents [44].

In this study, TH values (Tables 4.1 to 4.4) ranged from 0.50 mg/L in OSA-1 (Obi Agada, well water, Obi South) to 91.00 mg/L in ONI-12 (Duglu Itsise borehole water, Obi North). All values were within the acceptable WHO range of 100–300 mg/L. The hardness levels follow a general trend across the zones: Obi North > Obi East > Obi South > Obi West.

According to [122] classification: **Soft water:** 0–50 mg/L $CaCO_3$, **Moderately soft:** 50–100 mg/L, **Slightly hard:** 100–150 mg/L, **Moderately hard:** 150–200 mg/L, **Hard:** 200–300 mg/L, and **Very hard:** >300 mg/L

Based on this classification, water from all the sampled sources falls within the *soft* to *moderately soft* categories. This level of hardness is generally acceptable and poses no health risk, although extremely soft water may be slightly corrosive.

These findings are consistent with those of [36], who reported TH values of 19.21–32.98 mg/L in groundwater. They are, however, significantly lower than those recorded in other studies—such as Mulla et al. (2012), who reported 102–199.33 mg/L for groundwater, and [45], who observed 348–678 mg/L in river water.

Acidity

Acidity levels in the water samples varied significantly across the study area, ranging from 2.33 mg/L in Kpangwa well water (OWKP-1) from Obi West to 82.33 mg/L in Odobu well water (ONS-5) from Obi North. A noticeable trend of elevated acidity levels was observed. Notably, in Obi North, both the Odobu well (82.33 mg/L) and borehole (11.00 mg/L) exceeded the permissible limits set by [124], which recommend acidity levels in the range of 4.5–8.0 mg/L. Similarly, in Obi South, borehole water from Obi Orison (OSR-2), well and borehole water from Obi Okpe (OSK-1 and OSK-2), and Kayarda Agwatashi well water (OSKA-1) recorded acidity values of 11.67 mg/L, 11.67 mg/L, 9.93 mg/L, and 30.0 mg/L respectively, all surpassing recommended limits.

Samples from Obi West also showed elevated acidity: Debe well and borehole water (OWD-1 and OWD-2) and Gidinye borehole water (OWG-2) recorded 11.00 mg/L, 11.67 mg/L, and 14.33 mg/L, respectively.

In Obi East, borehole water from Audu Ang Sama (OEA-2) and well water from Imon (OEI-1) recorded acidity levels of 16.67 mg/L and 27.33 mg/L respectively.

Acidity in water reflects its capacity to neutralize a base, influenced by the presence of strong mineral acids, weak acids such as carbonic and acetic acid, and hydrolyzing salts like aluminum or iron sulfates [12]. The widespread exceedance of permissible acidity levels indicates the need for attention, particularly in locations like Obi North, Obi South, and Obi West, where values are significantly elevated. While natural processes such as organic matter decomposition and acid rain could contribute, localized anthropogenic influences cannot be ruled out.

Total Alkalinity

Total alkalinity, which indicates the buffering capacity of water against pH fluctuations, showed considerable variation across the study area. Values ranged from 12.0 mg/L in borehole water from Imon (OEI-2) in Obi East to 272.33 mg/L in both the Tudun Adubu borehole (ONT-8) in Obi North and Kayarda Agwatashi well (OSKA-1) in Obi South. Notably, thirteen samples across Obi North, Obi South, and Obi West exceeded [124] and SON (2016) recommended maximum of 120 mg/L for drinking water.

These include: **Obi North**: Ekposogye (ONS-4), Tudun Adubu (ONT-8), Duglu Nigida (OND-10) boreholes, and Odobu (ONS-5), Agwade Itsi Zleninedu (ONA-1), Duglu Nigida (OND-9), and Duglu Itisise (ONI-11) wells. **Obi South**: Orisoh Agwatashi (OSAO-2) borehole and Kayarda Agwatashi borehole and well (OSKA-2 and OSKA-1). **Obi West**: Gidan Ausa (OWGA-1), Debe (OWD-1) wells, and Idevi (OWI-2) borehole.

High alkalinity is often attributed to the presence of carbonates and bicarbonates, which may originate from the dissolution of carbonate-rich minerals or anthropogenic sources such as agricultural runoff. These results are consistent with studies from the Godavari River basin in India (Sreedevi et al., 2016) and the Niger Delta in Nigeria (Etim et al., 2013), where alkalinity levels of up to 260 mg/L and 250 mg/L, respectively, were observed. The findings suggest that both natural geological formations and human activities may be influencing the observed values in Obi LGA.

High alkalinity is beneficial for buffering against pH fluctuations, helping maintain a stable aquatic environment. However, values exceeding 120 mg/L, like those found in this study, may cause aesthetic and operational issues such as poor taste and scaling in pipes. Treatment methods like ion exchange, reverse osmosis, or acid neutralization may be necessary in affected areas. Conversely, low alkalinity, as seen in Imon (OEI-2), implies reduced buffering capacity and a greater vulnerability to acidification, warranting alkalinity adjustment or blending before consumption.

Water Temperature

Water temperature, a critical parameter influencing chemical solubility, biological activity, and microbial growth, ranged from 29.5°C in Imon well (OEI-1) from Obi West to 33.2°C in Gidinye well (OWG-1) in Obi West and Kayarda Agwatashi borehole (OSKA-2) in Obi South. Most values fell within [124] and SON (2016) recommended limits (up to 32°C), with only two samples—OWG-1 and OSKA-2—slightly exceeding this threshold.

Temperature variation in the study area is consistent with other tropical regions. For example, Li et al. (2022) in the Yangtze River Basin and [87] in the Ganges Basin reported temperature ranges of 20–35°C and 25–34°C respectively, attributing elevated values to climatic conditions, seasonal variations, and industrial discharges.

Slightly elevated temperatures, such as those observed in this study, can reduce dissolved oxygen levels, increase the metabolic rate of aquatic organisms, and promote algal growth and microbial activity. While most samples remained within safe limits, continuous monitoring is advised due to potential thermal pollution, particularly in areas exposed to anthropogenic heat sources.

It is worth noting that tropical climates naturally exhibit higher water temperatures, which local aquatic ecosystems may be adapted to [66]. Additionally, diurnal and seasonal fluctuations could affect temperature readings. Therefore, long-term monitoring would offer better insight into the thermal dynamics and help in identifying any emerging risks.

pH

The pH level of water is a critical indicator of its quality, reflecting its acidity or alkalinity, which influences various chemical reactions, biological processes, and the solubility and toxicity of contaminants. In this study, the pH values ranged from **5.5** in the Agwade Itsi Zleninedu well water sample (ONA-1) from **Obi North** to **8.3** in the Akanga well water sample (OWA-2) from **Obi West**. Most samples exhibited slightly acidic conditions, with only a few tending toward alkalinity. This pH variation suggests that groundwater in Obi LGA is generally acidic to near-neutral, with a few exceptions.

The pH values observed align with findings from various regions influenced by both natural and anthropogenic factors. In a study conducted in **Lafia**, the capital of Nasarawa State, [112] reported pH values ranging from **5.8 to 8.2**, which aligns with the current findings. They attributed these values to geological variability and anthropogenic inputs such as **agricultural runoff and domestic waste**. Similarly, [26] in a study conducted in **Keffi**, also in Nasarawa State, recorded pH levels between **6.0 and 7.8**, attributing the slightly acidic conditions to **CO_2 dissolution**, **organic acid accumulation from soil and vegetation**, and **acid rain**.

Comparable results have been reported across the African continent. For instance, [109] in Ghana found groundwater pH values between **5.6 and 7.9**, reflecting influences from local geology and anthropogenic pressures. Likewise, [29] in Malawi observed river water pH values ranging from **5.4 to 8.1**, linking the acidic conditions to **natural organic matter and agricultural runoff**.

In the context of Obi LGA, the slightly acidic pH values are likely due to local geological formations rich in organic material and the infiltration of acidic substances from surrounding land uses, including **subsistence farming**, **waste disposal**, and **rainwater leaching**. This is significant because water with a pH below 7 can have several implications: it may promote **pipe corrosion**, leach metals like lead or copper, and adversely affect **aquatic life and nutrient bioavailability** [2] , [7].

Conversely, the **slightly alkaline** pH observed in the **Akanga well water sample (OWA-2)** (pH = 8.3) poses fewer risks. Such conditions may **buffer acidic inputs**, protect plumbing infrastructure, and support aquatic life. However, **excessively alkaline water (pH > 8.5)**, though not observed in this study, can lead to **digestive discomfort**, **eye and skin irritation**, and **alterations in body pH homeostasis**, as highlighted by [104]. Maintaining pH within the recommended range of **6.5–8.5** [124] , [103] is essential for ensuring water quality for drinking, irrigation, and industrial use.

Total Dissolved Solids (TDS)

Total Dissolved Solids (TDS) measure the combined concentration of inorganic and organic substances in water, present in molecular, ionized, or colloidal form [76]. Elevated TDS levels can degrade water quality by imparting undesirable taste, contributing to scale formation, and potentially indicating the presence of harmful contaminants.

In Obi LGA, TDS concentrations ranged from **35.67 mg/L** in the **Obi Orison well water (OSR-1)** to **2313 mg/L** in the **Obi Okpe well water (OSK-1)**, both located in **Obi South**. Several samples across the study area exceeded [124] and [103] guideline value of **500 mg/L**. In **Obi West**, while most samples were within limits, elevated TDS was observed in well water samples from **Akanga (OWA-1)**, **Khichene (OWK-1)**, **Gidinye (OWG-1)**, **Agyaragyu Tasha (OWAT-1)**, and **Gidan Ausa (OWGA-1)**.

Similarly, in **Obi East**, borehole water from **Audu Ang Sama (OEA-2)** and **Imon (OEI-2)** exceeded permissible limits. In **Obi North**, elevated TDS values were found in **Ekposogye borehole (ONS-4)**, **Odobu borehole (ONS-6)**, and **Tudun Adubu well (ONT-7)**. In **Obi South**, both **Obi Okpe well water (OSK-1)** and **Kayarda Agwatashi borehole (OSKA-2)** showed high TDS concentrations.

These variations reflect both **natural geological processes** and **anthropogenic influences**. Groundwater naturally dissolves minerals as it flows through rocks and sediments, particularly in areas with **carbonates, sulfates, and chlorides**, contributing to high TDS levels. Studies conducted elsewhere confirm this trend. [27] in Ethiopia reported TDS levels between **45 mg/L and 2500 mg/L**, with higher values attributed to mineral dissolution from aquifer materials. **Sodanji et al. (2023)** in Keffi, Nasarawa State, recorded TDS levels between **50 mg/L and 1800 mg/L**, associating high values with **agricultural runoff** and **improper waste disposal**.

National-level studies corroborate these findings. For instance, [38] documented TDS concentrations in groundwater sources in **Ibadan** between **30 mg/L and 2100 mg/L**, affected by both **natural geology** and **human activities**.

High TDS levels can render water **unpalatable**, with users reporting **bitter or salty tastes**. The exceptionally high TDS in **Obi Okpe well water (2313 mg/L)** and other outlier samples may affect acceptability and point toward potential contamination. While TDS is not inherently toxic, elevated levels may indicate the presence of **nitrate, fluoride, or heavy metals**, which are linked to **kidney dysfunction**, **hypertension**, and other chronic conditions [42].

Furthermore, high TDS can impact **agricultural productivity** by contributing to **soil salinization**, reducing fertility, and inhibiting **plant water uptake**, especially in arid regions. This can pose a long-term risk to food security in agrarian communities like Obi LGA.

It is important to recognize that **elevated TDS levels may not always signal pollution** but rather the **natural baseline condition** of the aquifer. Hence, **seasonal monitoring** and **longitudinal studies** are crucial to distinguish between anthropogenic impacts and natural geochemical processes. This will aid in formulating effective water resource management strategies tailored to the region's hydrological realities.

The range of DO values recorded in the current study (2.03–6.23 mg/L) falls within acceptable limits for most groundwater systems but indicates varying degrees of oxygen availability that may influence microbial and chemical processes. The highest DO level (6.23 mg/L) observed in the Obi Agada well water sample (OSA-1) in the Southern zone suggests a relatively low level of organic contamination and potentially higher recharge or better aeration conditions. Conversely, the lowest DO level (2.03 mg/L) observed in Odobu (ONS-5) in the Northern zone may reflect limited recharge, high biological oxygen demand (BOD), or the presence of decaying organic matter. These findings are consistent with the studies by [30] and [92], both of which highlight the role of microbial activity and organic load in influencing DO levels in groundwater sources.

Lower DO levels, as observed in some parts of Obi LGA, may reduce the capacity of the water to support aerobic microbial degradation of contaminants, potentially leading to the persistence of organic pollutants. Furthermore, low DO levels may also indicate anaerobic conditions, which can mobilize certain metals such as iron and manganese into the water, impacting its taste, color, and usability (Adhikari et al., 2020; Adepoju-Bello et al., 2009). In agricultural areas, DO depletion may result from fertilizer and pesticide runoff, which introduces nutrients that enhance microbial growth and oxygen consumption (Obiakor et al., 2019).

DO is also an important indicator for assessing groundwater suitability for domestic and livestock use. While low DO levels do not pose direct health risks, they can be a proxy for other underlying water quality issues such as bacterial contamination or the presence of chemical reductants. In the context of Obi LGA, the variation in DO levels reflects the diverse land use practices, geological formations, and potential contamination sources within different zones.

Globally, similar ranges of DO in groundwater have been reported in various environmental contexts. For instance, Tiwari and Mishra (2020) documented DO levels of 2.1 to 6.9 mg/L in wells across eastern Uttar Pradesh, India, where agricultural runoff and inadequate sanitation were major influences. In South Africa, [9] observed DO values from 1.8 to 7.4 mg/L in rural groundwater supplies, attributing the variation to differences in well construction, proximity to pollution sources, and aquifer characteristics.

The presence of DO in Obi LGA's groundwater, even at relatively low concentrations, indicates that the aquifers are not entirely anaerobic and may still support beneficial oxidation-reduction processes. However, monitoring DO levels remains crucial as they can rapidly change due to environmental factors or increased anthropogenic pressure. Effective groundwater management strategies should include protecting recharge zones from contamination, regular monitoring of organic pollutant levels, and ensuring proper sanitation practices to prevent further oxygen depletion.

In conclusion, the dissolved oxygen levels observed across the different zones of Obi LGA provide valuable insight into the overall health and status of the aquifers. The findings emphasize the need for continuous surveillance and tailored intervention strategies to safeguard groundwater quality, especially in areas prone to organic contamination or reduced oxygen availability.

Low dissolved oxygen (DO) levels in groundwater sources have significant implications for water quality by influencing geochemical and microbial processes that control the solubility and mobility of contaminants. Anaerobic conditions, created by low DO, foster the dominance of anaerobic microorganisms that utilize alternative electron acceptors such as nitrate, sulfate, and iron (III), triggering a range of geochemical transformations. These shifts in redox potential increase the solubility and mobility of certain metals and pollutants. For instance, iron and manganese oxides in sediments are reduced to their soluble forms (Fe^{2+} and Mn^{2+}), which can elevate their concentrations in groundwater [75]. Elevated iron and manganese levels cause staining of plumbing fixtures and laundry, impart a metallic taste to water, and can pose aesthetic and operational challenges.

Moreover, low DO can mobilize other heavy metals like arsenic, cadmium, and lead from sediments into groundwater, presenting serious health risks [83] , [33]. Globally, research confirms that low DO environments correlate with elevated concentrations of these metals. For example, [75] documented such patterns in the United States, while [83] and [33] similarly linked low DO to increased heavy metal presence and microbial contamination.

Sustainability of groundwater resources depends heavily on maintaining adequate DO levels. Concentrations below 3.0 mg/L tend to increase heavy metal mobilization, favor anaerobic microbial growth, and slow aerobic degradation of organic pollutants, while levels below 2.0 mg/L can be lethal to aerobic organisms [80] , [46] ; Padhan et al., 2021). In the present study, the low DO recorded in the Odobu well water sample (ONS-5) and other sites suggests a potential for elevated concentrations of metals such as iron and manganese and indicates a heightened risk for anaerobic conditions.

Low DO is often associated with elevated organic pollution levels from sewage, agricultural runoff, or industrial effluents, which fuel the proliferation of anaerobic bacteria. These bacteria produce harmful gases like hydrogen sulfide and methane, further degrading water quality and generating unpleasant odors. DO is critical for aerobic bacterial decomposition of organic matter; insufficient oxygen slows this process, causing organic matter accumulation and further deterioration in water quality. Water bodies with low DO levels also lose aesthetic value, becoming less attractive for recreational activities such as swimming and fishing.

Improving DO levels in groundwater sources requires effective land use management and pollution control measures aimed at reducing organic pollution inputs. Strategies include better sanitation infrastructure, controlling agricultural runoff, and limiting industrial discharges. These interventions can help restore aerobic conditions, mitigate metal mobilization, and improve overall water quality.

Biochemical Oxygen Demand (BOD_5)

Biochemical Oxygen Demand over five days (BOD_5) is a critical parameter in evaluating water quality, indicating the amount of oxygen required by aerobic microorganisms to break down organic matter. High BOD_5 values signal substantial organic pollution, often stemming from sewage, agricultural runoff, or industrial effluents.

In this study, BOD_5 values ranged from 0.00 mg/L in approximately 50% of samples to a maximum of 4.02 mg/L in the Akanga well water sample (OWA-1), followed closely by Duglu Nigida well (OND-9) at 4.00 mg/L. These levels are consistent with regional studies in Nasarawa State; for instance, Omoniyi et al. (2013) reported BOD_5 values between 1.0 and 5.5 mg/L in Lafia's surface waters, with higher values linked to agricultural and sewage pollution. Similarly, Adamu and Ujoh (2015) found BOD_5 levels ranging from 0.5 to 4.5 mg/L in Keffi groundwater, attributing elevated values to urbanization and inadequate waste management.

Nationally, [83] recorded BOD_5 values from 0.2 to 6.0 mg/L in Lagos groundwater, with higher values associated with sewage and industrial pollution. Globally, comparable BOD_5 ranges have been observed; [92] found values of 0.5 to 5.5 mg/L in Punjab, India, while [131] reported 0.3 to 6.2 mg/L in China's groundwater, often linked to urban sewage contamination. The US Geological Survey (USGS, 2017) recorded BOD_5 levels between 0.1 and 4.8 mg/L in California groundwater, reflecting impacts from agriculture and industry.

The BOD_5 levels measured in Obi LGA suggest the presence of moderate organic pollution in certain locations, which could contribute to oxygen depletion and subsequent water quality deterioration if not managed. Continuous monitoring and reduction of organic inputs remain essential to preserve groundwater quality and prevent adverse ecological and health outcomes.

Groundwater with elevated BOD_5 levels often requires more advanced treatment to ensure its safety for human consumption. This intensifies both the cost and complexity of water treatment processes, presenting significant challenges for resource-limited communities such as those in Obi LGA. According to [86], BOD_5 values exceeding 3 mg/L are indicative of sewage contamination. This threshold aligns with the elevated BOD_5 levels recorded in the Akanga (OWA-1) and Duglu Nigida (OND-9) well water samples, suggesting probable sewage infiltration into these groundwater sources. Notably, approximately 50% of the boreholes and well water sources analyzed in this study show evidence of contamination by organic pollutants.

The concurrent presence of low dissolved oxygen (DO) and high BOD_5 levels further substantiates the influx of organic pollution within the groundwater systems of Obi Local Government Area. It is important to recognize that while high BOD_5 values are critically important for assessing surface water quality due to more active oxygen-dependent microbial processes, their impact on groundwater is often less immediate. Groundwater environments typically contain lower oxygen levels and slower microbial activity, which can delay the degradation processes. Nonetheless, persistent organic pollution can progressively deteriorate groundwater quality, necessitating long-term monitoring and management interventions.

Statistical analysis of the data revealed no significant differences in the mean values of the physicochemical parameters across the four zones studied ($P > 0.05$), indicating relatively uniform water quality characteristics throughout Obi LGA.

CONCLUSION

The physicochemical analysis of groundwater sources in Obi LGA revealed both safe and concerning trends. While nitrate levels (2.46–24.26 mg/L) and total hardness (0.5–91 mg/L) fell within permissible limits, TDS levels (up to 2313 mg/L) and acidity (up to 82.33 mg/L) exceeded WHO and SON standards in several locations. Elevated TDS may affect taste and usability, while high acidity can cause infrastructure corrosion and signal possible contamination. Variations in dissolved oxygen (2.03–6.23

mg/L) suggest differences in organic matter and recharge across sites. The data underscores the urgent need for regular water quality assessments and localized treatment measures to ensure the safety and sustainability of drinking water supplies in Obi LGA.

Table 1.Physiochemical profile of hand-dug well and borehole water samples for Obi West A zone in Obi LGA

OBI WEST A														
Parameters	Well Water Sources						Borehole Water Sources							
	OWA-1	OWI-1	OWG-1	OWK-1	Mean	Range	OWA-2	OWI-2	OWG-2	OWK-2	Mean	Range	WHO	SON
Cl^-	7.69±0.00^{b}	3.55±0.001^{a}	10.64±0.001^{c}	7.09±0.06^{b}	8.05	3.54 - 14.18	7.69±0.00^{b}	3.55±0.00^{a}	14.19±0.006^{e}	10.64±0.00^{c}	8.5	3.55-14.19	250	250
CO_3^{2}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	NS	NS
HCO_3	3.07±0.03^{a}	2.03±0.03^{c}	3.00±0.06^{ab}	0.03±0.03^{ab}	2.93	2.10 - 6.07	3.37±0.03^{a}	3.07±0.03^{a}	2.93±0.03^{c}	2.07±0.03^{c}	2.43	1.03 - 3.07	NS	NS
NO_3	7.63±0.001^{a}	4.76±0.001^{d}	3.74±0.001^{a}	4.93±0.001^{c}	5.16	3.74 - 7.63	7.63±0.001^{a}	3.87±0.001^{e}	5.62±0.001^{b}	3.87±0.001^{e}	5.23	3.07 - 7.63	50	50
TH	13.70±0.07^{f}	17.10±0.06^{d}	21.67±0.09^{b}	8.57±0.09^{g}	13.34	8.57 - 17.10	13.70±0.058^{f}	18.10±0.06^{c}	27.97±0.03^{a}	15.50±0.06^{e}	17.6	11.67 - 27.97	100-300	150
T.AC	6.00±0.00^{c}	7.67±0.33^{b}	7.67±0.33^{b}	6.33±0.33^{bc}	5.88	2.33 - 11.67	6.00±0.00^{c}	6.33±0.33^{b}	11.00±0.58^{a}	2.67±0.67^{d}	6.33	3.0 - 14.33	150	150
T.Alk	100.33±0.33^{e}	106.00±0.58^{a}	105.33±0.33^{b}	93.00±1.53^{f}	104.29	92.33 - 133.0	100.33±0.33^{e}	141.33±0.33^{d}	84.33±2.33^{g}	104.67±0.33^{c}	101.08	73.00 - 141.33	120	120
Temp.	31.63±0.32^{b}	30.23±0.07^{d}	33.23±0.09^{a}	31.10±0.06^{c}	31.05	30.07 - 33.23	31.63±0.32^{b}	30.37±0.09^{d}	31.10±0.06^{c}	31.07±0.03^{c}	30.7	30.2 - 31.6	32	Ambient
pH	6.03±0.33^{d}	6.03±0.03^{d}	6.07±0.03	6.20±0.06^{c}	6.08	5.63 - 6.53	6.00±0.33^{d}	6.2±0.03^{cd}	6.3±0.03^{c}	6.5±0.03^{b}	6.4	6.0 - 7.7	6.5-8.5	6.5-8.5
TDS	505.00±2.89^{c}	242.33±1.45^{f}	1676.00±3.06^{a}	816.00±3.06^{b}	846.58	222.7 - 1676	505.00±2.89^{c}	82.33±1.45^{g}	362.33±1.45^{d}	341.00±2.08^{e}	248.46	82.33 - 505.0	500	500
TSS	0.93±0.001^{c}	1.27±0.001^{a}	0.73±0.001^{d}	1.024±0.001^{b}	0.96	0.73 - 1.27	0.93±0.001^{c}	0.92±0.001^{c}	0.63±0.03^{e}	1.272±0.001^{a}	0.98	0.63 - 1.27		
EC	1059.33±0.003^{a}	480.67±0.67^{f}	1060.67±0.67^{a}	1039.33±0.67^{b}	839.75	440.7 - 1083.3	1059.33±0.67^{c}	160.67±0.67^{g}	730.67±0.67^{d}	678.000±1.16^{e}	478.6	20.83 - 1059.33	500	1000
DO	6.20±0.003^{a}	2.20±0.003^{c}	6.19±0.007^{a}	0.00±0.00^{d}	3.67	0.00 - 6.20	6.20±0.003^{a}	4.20±0.003^{b}	2.20±0.009^{c}	2.203±0.003^{c}	2.65	0 - 6.20	5.0	5.0
BOD	4.02±0.02^{a}	0.003±0.003^{d}	3.97±0.03^{b}	0.00±0.00^{e}	1.78	0.00 - 4.02	4.02±0.02^{a}	1.97±0.03^{c}	0.00±0.00	0.00±0.00^{e}	1	0 - 4.02	10.00	10.0

All units are expressed in mgL unless otherwise stated, ^{a}Temperature in ^{0}C, $^{b?}$Electrical conductivity as μScm^{-1}; Cl^{-} = Chloride: CO_3^{2-} = Carbonate; HCO_3^- = Hydrogen carbonate; No_3^- = Nitrate; NS: Not Specified;TH=Total Hardness, $^{?}$T.AC=Total Acidity, $^{?}$T.AlK=Total Alkalinity, $^{?}$TDS=Total Dissolved Solids, $^{?}$TSS=Total Suspended Solids, $^{?}$DO = Dissolved Oxygen, $^{?}$BOD = Biochemical Oxygen Demand; Means with same alphabets in a column are not significant; Data are expressed as mean±standard deviation of triplicate determinations; WHO = World Health Organization (2011); SON = Stamdards Organization of Nigeria (2016).

Table 2. Physiochemical profile of hand-dug well and borehole water samples for Obi West B zone in Obi LGA

OBI WEST B														
Parameters	Well Water Sources						Borehole Water Sources							
	OWD-1	OWKP-1	OWAT-1	OWGA-1	Mean	Range	OWD-2	OWKP-2	OWAT-2	OWGA-2	Mean	Range	WHO	SON
Cl^-	3.55 ± 0.00^{a}	3.54 ± 0.001^{a}	14.18 ± 0.003^{d}	14.18 ± 0.003^{d}	8.05	3.54 - 14.18	7.09 ± 0.003^{b}	7.09 ± 0.006^{b}	10.64 ± 0.001^{c}	7.09 ± 0.006^{b}	8.5	3.55 - 14.19	250	250
CO_3^{2-}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	NS	NS
HCO_3	2.03 ± 0.03^{c}	6.07 ± 0.07^{a}	2.10 ± 0.06^{c}	2.10 ± 0.06^{c}	2.93	2.10 - 6.07	1.10 ± 0.06^{d}	3.13 ± 0.067^{b}	1.03 ± 0.03^{b}	3.07 ± 0.03^{b}	2.43	1.03 - 3.07	NS	NS
NO_3	6.37 ± 0.001^{b}	2.46 ± 0.001^{g}	5.68 ± 0.001^{d}	5.68 ± 0.001^{d}	5.16	3.74 - 7.63	6.48 ± 0.002^{a}	3.07 ± 0.0001^{f}	6.30 ± 0.002^{c}	5.01 ± 0.004^{c}	5.23	3.07 - 7.63	50	50
TH	14.33 ± 0.03^{d}	10.70 ± 0.06^{f}	10.33 ± 0.33^{f}	10.33 ± 0.33^{f}	13.34	8.57 - 17.10	11.97 ± 0.03^{c}	25.33 ± 0.33^{d}	16.57 ± 0.03^{c}	11.67 ± 0.33^{c}	17.6	11.67 - 27.97	100-300	150
T.AC	11.67 ± 0.33^{b}	2.33 ± 0.33^{d}	2.67 ± 0.67^{d}	2.67 ± 0.67^{d}	5.88	2.33 - 11.67	14.33 ± 0.88^{a}	3.00 ± 0.58^{d}	3.00 ± 1.00^{d}	4.33 ± 0.33^{c}	6.33	3.0 - 14.33	150	150
T.Alk	133.00 ± 1.53^{b}	112.00 ± 1.16^{a}	92.33 ± 1.45^{f}	92.33 ± 1.45^{f}	104.29	92.33 - 133.0	73.00 ± 1.53^{g}	101.33 ± 0.88^{c}	101.67 ± 1.45^{d}	102.00 ± 1.16^{c}	101.08	73.00 - 14.33	120	120
Temperature	30.07 ± 0.03^{c}	30.10 ± 0.06^{c}	31.03 ± 0.33^{a}	31.03 ± 0.33^{a}	31.05	30.07 - 33.23	30.70 ± 0.12^{b}	30.20 ± 0.06^{c}	30.27 ± 0.03^{c}	30.23 ± 0.9^{c}	30.7	73.00 - 141.33	32	Ambient
pH	6.53 ± 0.03^{b}	6.53 ± 0.03^{b}	5.63 ± 0.03^{f}	5.63 ± 0.03^{f}	6.08	5.63 - 6.53	6.3 ± 0.03^{c}	6.30 ± 0.03^{c}	7.70 ± 0.03^{a}	6.2 ± 0.03^{d}	6.4	30.2 - 31.6	6.5-8.5	6.5-8.5
TDS	284.00 ± 2.08^{d}	222.67 ± 1.45^{c}	1513.33 ± 18.56^{a}	1513.33 ± 18.56^{a}	846.58	222.7 - 1676	422.00 ± 1.16^{c}	82.33 ± 1.45^{f}	90.00 ± 2.89^{f}	102.67 ± 1.45^{f}	248.46	6.0 - 7.7	500	500
TSS	1.03 ± 0.001^{b}	0.88 ± 0.002^{f}	0.92 ± 0.001^{e}	0.92 ± 0.001^{e}	0.96	0.73 - 1.27	$1.22.00\pm1.16^{c}$	0.89 ± 0.001^{f}	0.97 ± 0.007^{d}	1.00 ± 0.00^{c}	0.98	82.33 - 505.0	500	500
EC	470.67 ± 0.67^{d}	440.67 ± 0.67^{d}	1083.33 ± 44.10^{a}	1083.33 ± 44.10^{a}	839.75	440.7-1083.3	839.33 ± 0.67^{c}	160.00 ± 1.16^{c}	180.00 ± 1.16^{c}	20.83 ± 0.44^{f}	478.6	0.63 - 1.27	500	1000
DO	4.20 ± 0.01^{a}	2.19 ± 0.007^{b}	4.19 ± 0.007^{a}	4.19 ± 0.07^{a}	3.67	0.00 - 6.20	2.22 ± 0.02^{b}	0.00	0.00	4.20 ± 0.003^{a}	2.65	20.83 - 1059.33	5.0	5.0
BOD	2.01 ± 0.01^{b}	0.00 ± 0.00^{c}	2.13 ± 0.03^{a}	2.13 ± 0.03^{a}	1.78	0.00 - 4.02	0.00 ± 0.00^{c}	0.00	0.00	2.01 ± 0.007^{b}	1	0 - 6.20	10.0	10.0

All units are expressed in mgL^{-1} unless otherwise stated, ^{a}Temperature in ^{0}C, ^{b}Electrical conductivity as μScm^{-1}; Cl^{-} = Chloride: CO_3^{2-} = Carbonate; HCO_3^{-} = Hydrogen carbonate; No_3^{-} = Nitrate; NS: Not Specified; TH=Total Hardness, T.AC=Total Acidity, T.AlK=Total Alkalinity, TDS=Total Dissolved Solids, ?TSS=Total Suspended Solids, ?DO = Dissolved Oxygen, BOD = Biochemical OxygenDemand; Means with same alphabets in a column are not significant; Data are expressed as mean±standard deviation of triplicate determinations; WHO = World Health Organization (2011); SON = Standards Organization of Nigeria (2016).

Table 3. Physiochemical profile of hand-dug well and borehole water samples for Obi East zone in Obi LGA

OBI EAST										
	Well water Sources				**Borehole Water Sources**					
Parameters*	OEA-1	OEI-1	Mean	Range	OEA-2	OEI-2	Mean	Range	WHO	SON
Cl^{-}	7.69 ± 0.00^{b}	3.55 ± 0.001^{a}	5.62	3.55 - 7.69	3.55 ± 0.00^{b}	10.64 ± 0.00^{d}	7.1	3.55 - 10.64	250	250
CO_3^{2-}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	NS	NS
HCO_3^{-}	3.07 ± 0.03^{a}	2.03 ± 0.03^{c}	2.55	2.03 - 3.07	2.07 ± 0.03^{d}	1.90 ± 0.06^{e}	1.99	1.90 - 2.07	NS	NS
NO_3^{-}	7.63 ± 0.001^{a}	4.76 ± 0.001^{d}	6.2	4.76 - 7.63	4.20 ± 0.00^{f}	3.64 ± 0.002^{h}	3.92	3.64 - 4.20	50	50
TH‡	13.70 ± 0.06^{f}	17.10 ± 0.06^{d}	15.4	13.7 - 17.1	10.77 ± 0.03^{c}	8.10 ± 0.06^{f}	9.44	8.1 - 10.77	100 – 300	150
T. Ac‡	6.00 ± 0.00^{c}	7.67 ± 0.33^{b}	6.84	6 - 7.67	16.67 ± 0.67^{b}	27.33 ± 1.76^{a}	22	16.67 - 27.33		
T. Alk‡	100.33 ± 0.33^{e}	106.00 ± 0.58^{a}	103.17	100.3 - 106	35.00 ± 0.58^{a}	12.00 ± 1.53^{c}	23.5	12.0 - 35.0	120	120
Temperature^{a}	31.63 ± 0.32^{b}	30.23 ± 0.07^{d}	30.93	30.23 - 31.63	31.23 ± 0.15^{b}	31.07 ± 0.07^{b}	31.15	31.07 - 31.23	32	Ambient
pH	6.00 ± 0.33^{d}	6.00 ± 0.03^{d}	6.00		6.60 ± 0.03^{b}	6.20 ± 0.03^{c}	6.40	6.2 - 6.6	6.5 – 8.5	6.5 – 8.5
TDS‡	505.00 ± 2.89^{c}	242.33 ± 1.45^{f}	373.67	242.3 - 505.0	920.33 ± 0.33^{b}	662.33 ± 1.45^{c}	791.33	662.33 - 920.33	500	500
TSS‡	0.93 ± 0.001^{c}	1.27 ± 0.001^{a}	1.1	0.93 - 1.27	0.93 ± 0.001^{e}	0.94 ± 0.003^{d}	0.94	0.93 - 0.94		
EC^{b}‡	1059.33 ± 0.67^{c}	480.67 ± 0.67^{f}	770	480.7 - 1059.3	1840.67 ± 0.67^{b}	1320.33 ± 0.03^{c}	1581	1320.33 - 1840.67	500	1000
DO‡	6.20 ± 0.003^{a}	2.20 ± 0.003^{c}	4.2	2.20 - 6.20	4.19 ± 0.01^{a}	4.21 ± 0.01^{a}	4.2	4.19 - 4.21		
BOD‡										

*All units are expressed in mgL^{-1} unless otherwise stated, ^{a}Temperature in ^{o}C, ^{b}‡Electrical conductivity as μScm^{-1}; Cl^{-} = Chloride; CO_3^{2-} = Carbonate; HCO_3^{-} = Hydrogen carbonate; NO_3^{-} = Nitrate; NS: Not Specified; ‡TH=Total Hardness, ‡T. Ac=Total Acidity, ‡T. Alk = Total Alkalinity, ‡TDS = Total Dissolved Solids, ‡TSS=Total Suspended Solids, ‡DO = Dissolved Oxygen, ‡BOD = Biochemical Oxygen Demand; Means with same alphabets in a column are not significant; Data are expressed as mean±standard deviation of triplicate determinations; WHO = World Health Organization (2011); SON = Standards Organization of Nigeria (2016).

Table 4. Physiochemical profile of hand-dug well and borehole water samples for Obi North A zone in Obi LGA

OBI NORTH A														
Parameters	Well Water Sources						Borehole Water Sources							
	ONS-1	ONS-3	ONS-5	ONT-7	Mean	Range	ONS-2	ONS-4	ONS-6	ONT-8	Mean	Range	WHO	SON
Cl^-	0.00	0.00	7.07±0.01^{c}	7.08±0.01^{c}	4.55	0 - 10.63	0.00±0.00^{a}	3.54±0.001^{b}	3.54±0.001^{b}	3.55±0.00^{b}	1.52	0-3.55	250	250
CO_3^{2-}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	NS	NS
HCO_3	2.27±0.15^{cd}	1.03±0.03^{e}	4.00±0.06^{a}	1.17±0.12^{e}	2.19	1.03 - 4.0	2.33±0.18^{c}	2.03±0.03^{cd}	2.03±0.03^{b}	2.10±0.06^{cd}	2.26	2.03 - 3.10	NS	NS
NO_3	5.26±0.002^{i}	3.68±0.002^{n}	24.26±0.001^{a}	4.07±0.001^{i}	8.76	3.68 - 24.26	5.67±0.002^{h}	3.78±0.002^{m}	23.16±0.01^{b}	2.86±0.002^{0}	8.03	2.86 - 23.16	50	50
TH	14.10±0.06^{e}	0.00±0.00^{j}	20.33±0.03^{b}	17.17±0.09^{c}	11.89	0.00 - 20.33	16.40±0.12^{d}	5.33±0.67^{h}	10.17±0.12^{g}	4.60±0.06^{i}	22.3	4.60 - 91.0	100-300	150
T.AC	3.67±0.88^{fg}	6.33±0.33^{cdc}	82.33±1.20^{a}	4.33±0.33^{efg}	16.14	2.67 - 82.33	8.00±0.00^{c}	3.67±0.33^{fg}	11.00±0.58^{b}	4.67±0.33^{efg}	6.1	3.67 - 11.0	150	150
T.Alk	80.67±0.33^{i}	199.00±2.08^{g}	122.67±1.45^{c}	102.00±1.53^{d}	147.76	80.67 - 272.0	41.67±1.20^{k}	136.67±1.20^{f}	119.67±1.20^{b}	272.33±2.85^{c}	130.57	41.67 - 272.33	120	120
Temperature	30.10±0.06^{hi}	30.13±0.03^{hi}	30.13±0.03^{hi}	31.00±0.06^{bc}	30.4	30 - 31.2	30.23±0.03^{c}	31.10±0.06^{bc}	30.27±0.07^{e}	30.60±0.06^{d}	30.5	30.13 - 31.10	32	Ambient
pH	6.2±0.09^{de}	6.2±0.03^{de}	6.4±0.03^{bc}	6.2±0.03^{de}	6.1	5.5 - 6.4	6.1±0.03^{de}	6.1±0.07^{de}	6.3±0.03^{cd}	6.4±0.03^{bc}	6.3	6.1 - 6.7	6.5-8.5	6.5-8.5
TDS	46.00±1.00^{m}	92.33±1.45^{j}	54.33±2.33^{i}	802.00±1.53^{a}	285.48	46.0 - 802.0	86.67±0.88^{k}	643.67±1.86^{b}	550.00±1.16^{c}	416.00±0.58^{f}	371.1	86.67 - 643.67	500	500
TSS	1.31±0.001^{e}	1.42±0.005^{b}	1.52±0.001^{a}	1.03±0.001^{h}	1.18	0.83 - 1.52	1.20±0.002^{f}	0.74±0.01^{i}	1.33±0.001^{d}	1.12±0.001^{g}	1.11	0.74 - 1.35	500	500
EC	90.33±0.33^{0}	180.33±0.33	111.00±0.58^{a}	1601.00±0.58^{a}	557.62	90.33 - 1601	169.33±0.67^{m}	1380.33±0.33^{b}	1009.67±0.33^{c}	830.33±0.33^{f}	747.33	169.33-1380.33	500	1000
DO	2.20±0.003^{c}	4.20±0.009^{b}	2.03±0.03^{d}	4.16±0.01^{b}	3.6	2.03 - 4.21	4.17±0.03^{b}	4.19±0.01^{b}	2.17±0.03^{c}	2.19±0.01^{c}	3.04	2.16 - 4.19	5.0	5.0
BOD	0.00	2.03±0.03c	0.00	2.13±0.03^{b}	1.47	0 - 4.0	2.07±0.07^{bc}	2.03±0.03^{c}	0.00	0.00	0.88	0 - 2.07	10.0	10.0

All units are expressed in mgL^{-1} unless otherwise stated, [a]Temperature in ^{0}C, [b]Electrical conductivity as μScm^{-1}; Cl^{-} = Chloride: CO_3^{2-} = Carbonate; HCO_3^{-} = Hydrogen carbonate; No_3^{-} = Nitrate; NS: Not Specified; TH=Total Hardness, T.AC=Total Acidity, T.AlK=Total Alkalinity, TDS=Total Dissolved Solids, ?TSS=Total Suspended Solids, ?DO = Dissolved Oxygen, BOD = Biochemical Oxygen Demand; Means with same alphabets in a column are not significant; Data are expressed as mean±standard deviation of triplicate determinations; WHO = World Health Organization (2011); SON = Standards Organization of Nigeria (2016).

Table 5. Physiochemical profile of hand-dug well and borehole water samples for Obi North B zone in Obi LGA

OBI NORTH B												
Parameters	Well Water Sources					Borehole Water Sources						
	ONA-1	OND-9	ONI-11	Mean	Range	ONA-2	OND-10	ONI-12	Mean	Range	WHO	SON
Cl^{-}	3.55±0.00^{b}	10.63±0.001^{d}	3.44±0.00^{b}	4.55	0 - 10.63	0.00	0.00	0.00	1.52	0 - 3.55	250	250
CO_3^{2-}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	NS	NS
HCO_3	2.02±0.03^{cd}	2.83±0.82^{b}	1.97±0.03^{d}	2.19	1.03 - 4.0	3.10±0.06^{b}	2.20±0.12^{cd}	2.03±0.03^{cd}	2.26	2.03 - 3.10	NS	NS
NO_3	8.36±0.001^{f}	11.36±0.001^{d}	4.36±0.001^{k}	8.76	3.68 - 24.26	4.60±0.001^{j}	10.36±0.002^{e}	5.76±0.001^{g}	8.03	2.86 - 23.16	50	50
TH	14.33±0.04^{e}	4.73±0.7^{i}	12.60±0.12^{f}	11.89	0.00 - 20.33	12.37±0.03^{f}	16.20±0.12^{d}	91.00±0.06^{a}	22.3	4.60 - 91.0	100-300	150
T.AC	8.00±0.00^{c}	2.67±0.33^{g}	5.67±0.33^{def}	16.14	2.67 - 82.33	7.00±1.00^{cd}	4.33±0.33^{efg}	4.00±1.16^{fg}	6.1	3.67 - 11.0	150	150
T.Alk	272.00±1.53^{c}	202.67±1.45^{a}	135.33±0.33^{f}	147.76	80.67 - 272.0	86.67±0.88^{h}	201.67±0.88^{d}	55.33±0.33^{j}	130.57	41.67 - 272.33	120	120
Temperature	30.00±0.00^{j}	30.23±0.09^{g}	31.17±0.12^{a}	30.4	30 - 31.2	30.23±0.09^{f}	30.97±0.03^{c}	30.13±0.33^{hi}	30.5	30.13 - 31.10	32	Ambient
pH	5.50±0.60^{g}	6.50±0.03^{b}	6.00±0.03^{f}	6.1	5.5 - 6.4	6.70±0.03^{a}	6.40±0.03^{bc}	6.20±0.00^{d}	6.3	6.1 - 6.7	6.5-8.5	6.5-8.5
TDS	463.67±1.86^{d}	118.33±1.67^{i}	421.67±1.17^{e}	285.48	46.0 - 802.0	174.33±0.33^{h}	4.22±1.16^{e}	305.00±2.89^{g}	371.1	86.67 - 643.67	500	500
TSS	0.83v0.001^{k}	1.01±0.001^{i}	1.12±0.01^{g}	1.18	0.83 - 1.52	1.13±0.002^{g}	1.35±0.001^{c}	0.92±0.002^{j}	1.11	0.74 - 1.35	500	500
EC	830.67±0.67^{f}	239.33±0.67^{j}	850.67±0.67^{d}	557.62	90.33 - 1601	380.00±0.58^{i}	841.00±0.58^{d}	620.67±0.67^{g}	747.33	169.33 - 1380.33	500	1000
DO	4.21±0.01^{bo}	6.20±0.01^{a}	2.19±0.01^{c}	3.6	2.03 - 4.21	2.20±0.003^{c}	4.19±0.007^{b}	2.16±0.03^{c}	3.04	2.16 - 4.19	5.0	5.0
BOD	2.11±0.01^{bo}	4.00±0.06^{a}	0.00	1.47	0.00	0.00	2.03±0.03^{c}	0.00	0.88	0 - 2.07	10.0	10.0

All units are expressed in mgL^{-1} unless otherwise stated, ^{a}Temperature in ^{0}C, ^{b}Electrical conductivity as μScm^{-1}; Cl = Chloride: CO_3^{2-} = Carbonate; HCO_3^- = Hydrogen carbonate; No_3^- = Nitrate; NS: Not Specified; TH=Total Hardness, T.AC=Total Acidity, T.AlK=Total Alkalinity, TDS=Total Dissolved Solids, ?TSS=Total Suspended Solids, ?DO = Dissolved Oxygen, BOD = Biochemical Oxygen Demand; Means with same alphabets in a column are not significant; Data are expressed as mean±standard deviation of triplicate determinations; WHO = World Health Organization (2011); SON = Standards Organization of Nigeria (2016).

Table 6. Physiochemical profile of hand-dug well and borehole water samples for Obi South A zone in Obi LGA

OBI SOUTH A												
Parameters	Well Water Sources					Borehole Water Sources						
	OSAO-1	OSKA-1	OSK-1	Mean	Range	OSAO-2	OSKA-2	OSK-2	Mean	Range	WHO	SON
Cl^-	10.64 ± 1.00^{d}	3.54 ± 0.001^{b}	3.54 ± 0.002^{b}	5.67	0 - 10.64	7.09 ± 0.01^{c}	7.0 ± 0.02^{c}	7.05 ± 0.02^{c}	5.63	3.37-7.09	250	250
CO_3^{2}	1.00 ± 0.00^{c}	0.00	0.02 ± 0.01^{a}	0.21	0 - 1.00	0.00	0.00	0.00	0.00	0.00	NS	NS
HCO_3	5.10 ± 0.06^{a}	1.03 ± 0.03^{f}	1.07 ± 0.07^{b}	2.07	1.03 - 5.10	3.10 ± 0.06^{b}	2.03 ± 0.03^{de}	2.03 ± 0.03^{a}	2.07	1.03 - 3.10	NS	NS
NO_3	8.67 ± 0.001^{a}	4.87 ± 0.001^{e}	5.24 ± 0.01^{e}	7.72	4.87 - 13.46	6.38 ± 0.001^{b}	5.67 ± 0.001^{d}	5.02 ± 0.01^{f}	7.31	5.02 - 13.28	50	50
TH	9.07 ± 0.03^{e}	10.00 ± 0.00^{d}	18.97 ± 0.88^{a}	9.49	0.50 - 10.0	14.67 ± 0.33^{e}	9.10 ± 0.06^{e}	14.10 ± 0.06^{c}	11.23	3.10 - 15.20	100-300	150
T.AC	5.00 ± 0.58^{cd}	30.00±1.16	11.67 ± 0.33^{a}	11.2	3.67 - 30.0	5.00 ± 1.00^{cd}	7.67 ± 0.33^{c}	9.93 ± 0.07^{b}	8.12	5.0 - 11.67		
T.Alk	102.00 ± 1.16^{g}	272.33±2.33	102.33 ± 1.45^{a}	123.4	50.0 - 272.33	174.00 ± 2.08^{c}	202.68±1.45	84.67 ± 0.33^{c}	124.4	75.33 - 202.68	120	120
Temperature	30.17 ± 0.09^{c}	31.27 ± 0.15^{b}	31.03 ± 0.09^{a}	30.53	30.0 - 31.27	31.00 ± 0.06^{b}	33.17 ± 0.03^{a}	30.23 ± 0.15^{b}	30.98	30.20 - 33.17	32	Ambient
pH	6.2 ± 0.03^{c}	6.0 ± 0.03^{d}	6.5 ± 0.09^{b}	6	5.6 - 6.5	6.5 ± 0.03^{b}	6.5 ± 0.03^{b}	6.1 ± 0.06^{c}	6.5	6.1 - 6.7	6.5-8.5	6.5-8.5
TDS	274.33 ± 2.33^{f}	181.33 ± 1.86^{g}	2313.00 ± 1.53^{a}	603.67	35.67 - 274.33	373.00 ± 1.53^{d}	1516.67 ± 16.67^{a}	270.00 ± 2.31^{c}	486.93	132.33 - 1516.67	500	500
TSS	0.43 ± 0.001^{g}	1.13 ± 0.002^{b}	1.27 ± 0.001^{e}	1.12	0.43 - 1.62	1.13 ± 0.001^{b}	1.02 ± 0.001^{c}	1.41±0.001	1.33	1.02 - 1.58	500	500
EC	551.00 ± 1.00^{oe}	371.33 ± 14.35^{f}	1632.67 ± 1.45^{a}	720.93	371.33 - 1632.67	650.33 ± 0.33^{d}	2031.67 ± 0.88^{a}	540.00±1.16	756.4	269.67 - 2031.67	500	1000
DO	2.20 ± 0.00^{b}	2.19 ± 0.07^{b}	2.41 ± 0.01^{c}	3.05	2.19 - 6.23	4.19 ± 0.01^{a}	2.19 ± 0.01^{b}	4.21 ± 0.01^{b}	3.06	2.19 - 4.21	5.0	5.0
BOD	0.00	0.00	1.22 ± 0.01^{c}	1.25	0 - 3.97	2.00 ± 0.06^{a}	0.00	2.02 ± 0.02^{b}	1.05	0 - 2.02	10.0	10.00

All units are expressed in mgL^{-1} unless otherwise stated, ^{a}Temperature in ^{0}C, ^{b}Electrical conductivity as µScm^{-1}; Cl^{-} = Chloride: CO_3^{2-} = Carbonate; HCO_3^{-} = Hydrogen carbonate; No_3^{-} = Nitrate; NS: Not Specified; TH=Total Hardness, T.AC=Total Acidity, T.AlK=Total Alkalinity, TDS=Total Dissolved Solids, $^{?}$TSS=Total Suspended Solids, $^{?}$DO = Dissolved Oxygen, BOD = Biochemical Oxygen Demand; Means with same alphabets in a column are not significant; Data are expressed as mean±standard deviation of triplicate determinations; WHO = World Health Organization (2011); SON = Standards Organization of Nigeria (2016).

Table 7. Physiochemical profile of hand-dug well and borehole water samples for Obi South B zone in Obi LGA

OBI SOUTH B										
Parameters*	**Well water sources**				**Borehole water sources**					
	OSA-1	OSR-1	Mean	Range	OSA-2	OSR-2	Mean	Range	WHO	SON
Cl^{-}	10.63±0.00^{d}	0.00±0.00^{a}	5.67	0 - 10.64	3.54±0.001^{b}	3.37±0.18^{b}	5.63	3.37 - 7.09	250	250
CO_3^{2-}	0.00	0.02±0.01^{a}	0.21	0 - 1.00	0.00	0.00	0.00	0.00	NS	NS
HCO_3^{-}	1.97±0.03^{a}	1.17±0.12^{b}	2.07	1.03 - 5.10	1.03±0.03^{b}	2.17±0.12^{a}	2.07	1.03 - 3.10	NS	NS
NO_3^{-}	13.46±0.00l^{a}	6.38±0.02^{c}	7.72	4.87 - 13.46	13.28±0.001^{b}	6.20±0.001^{d}	7.31	5.02 - 13.28	50	50
TH^{ǂ}	0.50±0.06^{f}	8.90±0.15^{d}	9.49	0.50 - 10.0	15.20±0.12^{b}	3.10±0.06^{e}	11.23	3.10 - 15.20	100 – 300	150
T. Ac^{ǂ}	5.67±0.33^{c}	3.67±0.33^{d}	11.2	3.67 - 30.0	6.33±0.33^{c}	11.67±0.33^{a}	8.12	5.0 - 11.67		
T. Alk^{ǂ}	90.33±0.88^{b}	50.00±1.16^{e}	123.4	50.0 - 272.33	85.33±0.33^{c}	75.33±0.33^{d}	124.4	75.33 - 202.68	120	120
Temperature^{a}	30.20±0.12^{b}	30.00±0.12^{b}	30.53	30.0 - 31.27	30.20±0.06^{b}	30.30±0.12^{b}	30.98	30.20 - 33.17	32	Ambient
pH	5.6±0.03^{d}	5.8±0.09^{d}	6	5.6 - 6.5	6.7±0.07^{ab}	6.7±0.03^{a}	6.5	6.1 - 6.7	6.5 – 8.5	6.5 – 8.5
TDS^{ǂ}	214.00±1.00^{d}	35.67±2.91^{b}	603.67	35.67 - 274.33	132.33±1.45	142.67±1.45^{e}	486.93	132.33 - 1516.67	500	500
TSS^{ǂ}	1.62±0.02	1.16±0.001^{f}	1.12	0.43 - 1.62	1.53±0.002^{c}	1.58±0.01^{b}	1.33	1.02 - 1.58		
EC^{bǂ}	431.33±0.88^{d}	618.33±6.01^{d}	720.93	371.33 - 1632.67	269.67±0.33^{f}	290.33±0.88^{e}	756.4	269.67 - 2031.67	500	1000
DO^{ǂ}	6.23±0.02^{a}	2.22±0.01^{d}	3.05	2.19 - 6.23	2.25±0.03^{d}	2.47±0.12^{c}	3.06	2.19 - 4.21		
BOD^{ǂ}	3.97±0.03^{a}	1.04±0.03^{d}	1.25	0 - 3.97	0.00	1.21±0.01^{c}	1.05	0 - 2.02		

**All units are expressed in mgL^{-1} unless otherwise stated, ^{a}Temperature in ^{o}C, ^{b†}Electrical conductivity as µScm^{-1}; Cl^- = Chloride; CO_3^{2-} = Carbonate; HCO_3^- = Hydrogen carbonate; NO_3^- = Nitrate; NS = Not Specified; †TH=Total Hardness, †T. Ac=Total Acidity, †T. Alk = Total Alkalinity, †TDS = Total Dissolved Solids, †TSS=Total Suspended Solids, †DO = Dissolved Oxygen, †BOD = Biochemical Oxygen Demand; Means with same alphabets in a column are not significant; Data are expressed as mean±standard deviation of triplicate determinations; WHO = World Health Organization (2011); SON = Standards Organization of Nigeria (2016).*

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