**Assessment of Borehole Water Quality and Health Risks in Enugu North Local Government Area, Nigeria**

**Abstract:** This study investigates the water quality of selected boreholes in Enugu North Local Government Area, Enugu State, Nigeria, focusing on both the physico-chemical and bacteriological properties, as well as the concentrations of heavy metals and their associated health risks. A total of twelve borehole water samples were collected and analyzed for heavy metals, including manganese (Mn), cadmium (Cd), lead (Pb), nickel (Ni), copper (Cu), zinc (Zn), chromium (Cr), and iron (Fe). The study assessed the potential health risks posed by these heavy metals, evaluating the Chronic Daily Intake (CDI) for both ingestion and dermal exposure, as well as the Cancer Risk (CR) for ingestion and dermal exposure based on standard guidelines. The results revealed varying concentrations of heavy metals across the samples, with some exceeding permissible limits for safe drinking water, particularly for nickel and chromium. Health risk assessments indicated that certain borehole water samples posed significant risks, especially for children, due to higher concentrations of toxic metals. The Hazard Quotients (HQ) for both adults and children, as well as the Hazard Indices (HI), suggested that the water from some of the boreholes could potentially result in adverse health effects over prolonged exposure. Cancer risk values for both ingestion and dermal exposure further emphasized the potential long-term risks associated with consuming or using water from certain boreholes. The findings highlight the need for continuous monitoring and regulation of water quality in the study area. It is recommended that water treatment systems be implemented, particularly in areas with elevated heavy metal concentrations. Public awareness campaigns on the health risks associated with contaminated water should also be conducted. This study underscores the importance of ensuring safe drinking water for public health protection in Enugu North LGA and similar regions in Nigeria.

**Keywords:** Borehole water quality, Heavy metals, Health risk assessment, Chronic daily intake, Cancer risk

**1. Introduction**

An important environmental component is water, which is essential for the sustainability and survival of every life form on Earth (Osunkiyesi, 2012; Ogbuagu et al., 2024). It is the most abundant substance in both plant and animal tissues as well as in the world around us. Over 80% of the Earth’s surface is covered by water, and it accounts for about 70% of the human body, with even higher levels in many growing plants (Imoh et al., 2021; Aleru et al., 2019). The importance of water to humans and their environment cannot be overstated (Udongwo et al., 2022). It is increasingly recognized that providing good quality water is central to meaningful human development. Therefore, the water demand continues to grow due to high rates of population growth, urbanization, and other anthropogenic factors (Pawari and Gawande, 2015).

Water is generally sourced naturally from the ground (wells, boreholes) or the surface (streams, rivers, ponds, lakes) of the Earth (Edori and Kpee, 2016; Ebong et al., 2018). Globally, groundwater is the largest and most important source of fresh water. An estimated 1.5 billion people in sub-Saharan Africa depend solely on groundwater for drinking. Over the years, groundwater has been extensively exploited. In Nigeria, more than 120 million people use boreholes as their main source of drinking water (Obioma et al., 2020; Solana et al., 2020). A study revealed that well and borehole water are the primary sources of water in Akure, Ondo State (Ogundele, 2010). Generally, groundwater is considered safer and more reliable for domestic use and agricultural irrigation than surface water (Zige et al., 2018). However, the proximity of pit latrines, landfills, and graves to boreholes, poor agricultural practices, improper well construction, and indiscriminate waste disposal have been identified by many researchers as factors contributing to the contamination of borehole water (Abdulsalam et al., 2019; Oko et al., 2017).

Contamination of borehole water has become a serious environmental concern. This issue may arise from a lack of awareness, as groundwater problems are not readily detected, and contamination pathways are often less visible than those affecting surface water (Salami et al., 2014; Hassan et al., 2018). In recent years, attention has shifted to the increasing concentration of metal elements in groundwater, which corresponds to the rise in land dumping of metal and metal-containing solid wastes. This trend is attributed to human interference, industrial proliferation, and recent developments in agricultural practices in urban and peri-urban areas. Constituents such as metal elements leach from the soil surface and migrate into aquifer systems, thus degrading groundwater quality. Although safe drinking water contains naturally occurring minerals and chemical elements such as calcium, potassium, and sodium, which are beneficial to human health, efforts must be strengthened to ensure that drinking water is free from diseases, harmful chemical substances, heavy metals, and radioactive matter, while also being aesthetically appealing and devoid of objectionable color or odor (Umar et al., 2023; Aja et al., 2025). This highlights the imperative to assess water quality parameters of borehole water, with a special focus on Enugu North Local Government Area of Enugu State, Nigeria, to determine their level of purity.

Enugu State is located in the southeastern region of Nigeria and accommodates millions of residents. It features rapidly growing educational, administrative, commercial, and industrial enterprises, increasing the urban population. However, there are significant challenges related to basic amenities such as electricity, housing, and, most importantly, a piped water supply, which has virtually become a thing of the past in the city. In response to the urgent need for alternative water supplies to replace the problematic surface water systems, boreholes have begun to emerge throughout the local government areas. Conversely, the state is littered with large amounts of solid waste, presumably generated by daily human activities. These wastes, influenced by climate factors, could leach down and pollute the boreholes. Consuming contaminated water, regardless of the specific contaminants, can lead to a variety of diseases, including cholera, typhoid, dysentery, skin and mental disorders, morphological disorders, reduced growth, increased mortality, and mutagenic effects (Obasi and Akudinobi, 2020). Recently, several studies have been conducted on the impact of dumpsite leachate on groundwater in various locations (Aderemi et al., 2011; Sam-Uroupa and Ogbeibu, 2020; El-Salam and Ismail, 2013; Maiti et al., 2016; Aboyeji and Eigbokhan, 2016; Aralu et al., 2022). Therefore, to avoid the unnecessary adverse effects of contaminated borehole water, monitoring the quality of these water sources is essential for environmental and health safety. Regular water quality assessments are conducted to ensure that potable water, such as borehole water, is safe for drinking. Consequently, this study was undertaken.

Numerous reports have been made on the contamination of groundwater by heavy metals in the southwestern and northern parts of Nigeria (Oladapo Okareh et al*.,* 2023; Opasola and Otto, 2024). Metals like iron, cadmium, chromium, and aluminum have been found in surface water and sachet-packed water (Emenike et al*.,* 2018; Titilawo et al*.,* 2018), and lead, manganese, and nickel in groundwater (Ayedun et al*.,* 2015), all above permissible levels for drinking water. Other contaminants such as fluoride (Emenike et al*.,* 2018) and light polycyclic aromatic hydrocarbons have also been reported to be present in groundwater in levels above permissible limits in some locations in Nigeria (Adekunle et al*.,* 2017; Princewill et al., 2024). All these features of borehole water need to be evaluated to achieve and maintain healthy, clean water. This study assesses the quality and health risk of boreholes in Enugu North Local Government Area. This study seeks to determine the heavy metals and their concentrations in the borehole during the wet and dry seasons, and the potential health risk indices.

**2. Methodology**

**2.1 Description of Study Area**

The study area is Enugu North Local Government Area of Enugu State, Nigeria. Enugu North is a [Local Government Area](https://en.wikipedia.org/wiki/Local_Government_Areas_of_Nigeria) of [Enugu State](https://en.wikipedia.org/wiki/Enugu_State), [Nigeria](https://en.wikipedia.org/wiki/Nigeria). Its headquarters are in the city of [Enugu](https://en.wikipedia.org/wiki/Enugu)at Okpara Avenue. The LGA is made up of five main district areas: Amaigbo Lane, Onuato, Umunevo, Enugwu-Ngwo, and Ihenwuzi. Enugu North is one of the seventeen local governments in Enugu state and also one of the three LGAs that make up Enugu Town, including [Enugu East](https://en.wikipedia.org/wiki/Enugu_East) and [Enugu South](https://en.wikipedia.org/wiki/Enugu_South).Geographically, Enugu North LGA lies within longitudes of 7 o31’ E and latitudes of 6 ' o28’N and has a land size of 106 square kilometers, and a population of 244,852 as at the 2006 population census. It has an average temperature of 27 °C. The area's average humidity is 69 percent, and the LGA has two distinct seasons: dry and rainy season, with a brief harmattan in the dry season.

**2.2 Samples**

Twelve samples of water from boreholes in Enugu North were collected from various locations as indicated in the map above. Water sampling was carried out monthly for a period of six (6) months, June 2023 to Jan 2024, during the wet (June – August 2023) and dry season (November - January 2024). This was done between 07:00 and 11:00 a.m.During the entire study, several field trips were undertaken and six (6) sets of samples were taken from each location, which eventually were pooled together to form representative samples for each borehole location.



**Map 1. Map of Enugu North showing the borehole locations**

**2.3 Determination of the Heavy Metals**

Heavy metals such as Nickel, Iron, Zinc, Copper, Lead, Cadmium, Manganese, and Chromium were determined after digestion of samples using an Atomic Absorption Spectrophotometer (AAS). Water sample digestion was carried out by taking 10 ml of each sample and adding 4 ml of Perchloric acid, 20 ml concentrated Trioxonitrate (V) acid, and 2 ml concentrated tetraoxosulfate (VI) acid. This was digested using an aluminum block with 30 digesters 110. The mixture was heated until white fumes evolved and clear solutions were obtained. The essence of the digestion before analysis was to reduce organic matter interference and convert metals to a form that can be analyzed by the Atomic Absorption Spectrophotometer. After digestion, the samples for heavy metals were allowed to cool, transferred into a 100 ml volumetric flask, volume made up to 100 ml with distilled water, and then thoroughly mixed. The sample was allowed to stand and further centrifuged to separate insoluble materials, and filtered. Heavy metal concentrations in sample filtrates were determined using the Atomic Absorption Spectrophotometer (AAS) at different wavelengths.

**2.4 Health Risk Assessment**

Health risk assessment (HRA) is a systematic process used to evaluate the potential adverse health effects of contaminants in water, particularly heavy metals (Ahmad et al., 2021). In the context of borehole water quality assessment, HRA is essential for determining the safety of drinking water and identifying risks associated with long-term exposure to toxic substances (Wu et al., 2009). It consists of four main components: hazard identification, exposure assessment, dose-response assessment, and risk characterization.

Health risk indices are quantitative measures used to evaluate the potential health risks associated with exposure to contaminants, particularly heavy metals in drinking water (Fallahzadeh et al., 2017: Alidadi et al., 2019). These indices help in determining whether the water is safe for consumption and identifying possible non-carcinogenic and carcinogenic health effects. The key health risk indices include **Chronic Daily Intake (CDI), Hazard Quotient (HQ), Hazard Index (HI), and Cancer Risk (CR)**.

**2.4.1 Non-Carcinogenic Health Risk**

Non-carcinogenic risk assessment evaluates the potential adverse health effects of contaminants, such as heavy metals in drinking water, that do not cause cancer but may lead to other health complications when exposure exceeds safe limits (Vogt et al., 2012; Du et al., 2017). This assessment is based on comparing the estimated exposure level of a contaminant to a reference dose, which is the maximum safe level of daily exposure established by regulatory agencies like the U.S. Environmental Protection Agency (EPA) and the World Health Organization (WHO). **Chronic Daily Intake (CDI), Hazard Quotient (HQ), and Hazard Index (HI) evaluate the non-carcinogenic risk.**

**(a) Chronic Daily Intake (CDI)**

The **Chronic Daily Intake (CDI)** is a key metric used in health risk assessment to estimate the daily exposure of an individual to a contaminant over an extended period. For heavy metals in drinking water, CDI is typically calculated for ingestion and dermal absorption pathways.

The CDI for ingestion of heavy metals in water is calculated using the following formula:

$$CDI\_{ingestion}=\frac{C×IR×EF×ED}{BW×AT} (1)$$

where $CDI\_{ingestion}$ is the Chronic Daily Intake through ingestion (mg/kg-day), $C$ is the concentration of the heavy metal in water (mg/L), $IR$ is the ingestion rate of water (L/day), $EF$ is the exposure frequency (days/year), $ED$ is the exposure duration (years), $BW$ is the Body weight of the individual (kg), and $AT$ is the Averaging time (days), which depends on the type of risk being assessed.

Dermal exposure occurs when people come into contact with contaminated water during activities such as bathing, washing, or other domestic uses. The **Chronic Daily Intake (CDI)** for dermal exposure estimates the daily absorbed dose of heavy metals through the skin over an extended period. The CDI for dermal exposure to heavy metals in water is calculated using the following equation:

$$CDI\_{dermal}=\frac{C×SA×K\_{p}×ET×EF×ED×CF}{BW×AT} (2)$$

where $CDI\_{dermal}$ is the Chronic Daily Intake through dermal exposure (mg/kg-day), $C$ is the concentration of the heavy metal in water (mg/L), $SA$ is the exposed skin surface area (cm²), $K\_{p}$ is the dermal permeability coefficient of the heavy metal in water (cm/hr), $ET$ is the exposure time per event (hours/day), $EF$ is the exposure frequency (days/year), $ED$ is the exposure duration (years), $CF$ is the Conversion factor (10⁻³ L/cm³), $BW$ is the body weight of the exposed individual (kg), and $AT$ is the averaging time (days) (Ogbuagu et al., 2021).

**(b) Hazard Quotient (HQ)**

The **Hazard Quotient (HQ)** is a risk assessment parameter used to evaluate the potential non-carcinogenic health effects of heavy metals in drinking water. It is a ratio that compares the estimated exposure dose of a contaminant to the reference dose (RfD). It is calculated as:

$$HQ=\frac{CDI}{RfD} (3)$$

where $CDI$ is the Chronic Daily Intake (mg/kg/day) and $RfD$ is the Reference Dose (mg/kg/day), which is the safe daily intake level set by regulatory agencies such as the U.S. Environmental Protection Agency (USEPA, 2020).

If $HQ<1$, it means that the exposure level is within safe limits, and no significant health effects are expected. However, if $HQ>1$, there is a potential health risk, indicating that long-term exposure may cause adverse effects (USEPA, 2020).

**(c) Hazard Index (HI)**

The **Hazard Index (HI)** is a risk assessment tool used to evaluate the potential non-carcinogenic health risks posed by multiple contaminants. It is the sum of individual **Hazard Quotients (HQs)** for different heavy metals in water. The HI provides an overall assessment of the potential health effects due to exposure to multiple contaminants simultaneously. If **HI > 1**, there is a likelihood of adverse health effects due to cumulative exposure. If **HI ≤ 1**, non-carcinogenic health risks are considered negligible (USEPA, 2020). The HI is computed as follows:

$$HI=\sum\_{}^{}HQ\_{i}=HQ\_{1}+HQ\_{2}+HQ\_{3}+\cdots +HQ\_{n} (4)$$

where $HI$ is the hazard index, $HQ\_{i}$ are the **Hazard Quotient** for individual heavy metals **(**$i = 1, 2, 3, ..., n$**), and** $n$ **is the** total number of heavy metals considered.

**2.4.2 Carcinogenic Health Risk Assessment**

Carcinogenic risk assessment evaluates the probability of developing cancer over a lifetime due to exposure to carcinogenic contaminants, such as heavy metals, in drinking water (Felter et al., 2011). In this study, the long-term exposure to certain heavy metals, including cadmium (Cd), lead (Pb), chromium (Cr), and Nickel (Ni), has been linked to various forms of cancer. The assessment is based on estimating the chronic daily intake (CDI) of these contaminants and applying a cancer slope factor (SF) to determine the likelihood of developing cancer.

For heavy metals that are classified as carcinogenic, the **Cancer Risk (CR)** is used to estimate the probability of developing cancer over a lifetime due to exposure. It is calculated as:

$$CR=CDI×SF (5)$$

where $CDI$ is the Chronic Daily Intake (mg/kg/day) and $SF$ is the Cancer Slope Factor (mg/kg/day)⁻¹, a risk coefficient provided by the EPA (USEPA, 2020) that quantifies the likelihood of cancer from lifetime exposure. The acceptable range for cancer risk is: $CR<10^{-6}$ is considered a negligible risk, $10^{-6}\leq CR\leq 10^{-4}$ is the acceptable range, while $CR\geq 10^{-4}$ indicates a high probability of cancer risk, and requires immediate action (USEPA, 2020).

**3. Results and Discussion**

**3.1 Seasonal Variations of Metal Concentrations**

**Table 1.** **Seasonal Variations in Nickel Concentration in Borehole Water Samples in Enugu North LGA**

|  |  |  |
| --- | --- | --- |
| Ni (mg/L) | Wet Season | Dry Season |
| Sample | June | July | August | November | December | January |
| 1 | 0.003±0.001 | ND | 0.002±0.001 | 0.009±0.007 | 0.015±0.007 | 0.001±0.007 |
| 2 | 0.007±0.025 | 0.047±0.025 | 0.052±0.025 | 0.008±0.035 | 0.074±0.035 | 0.021±0.035 |
| 3 | 0.012±0.008 | 0.020±0.008 | 0.028±0.008 | 0.004±0.011 | 0.024±0.011 | 0.021±0.011 |
| 4 | 0.043±0.014 | 0.016±0.014 | 0.026±0.014 | 0.003±0.028 | 0.018±0.028 | 0.058±0.028 |
| 5 | 0.009±0.019 | 0.024±0.019 | 0.046±0.019 | 0.005±0.033 | 0.051±0.033 | ND |
| 6 | 0.016±0.023 | 0.039±0.023 | 0.062±0.023 | 0.014±0.001 | 0.012±0.001 | ND |
| 7 | 0.005±0.014 | 0.022±0.014 | 0.032±0.014 | 0.008±0.009 | 0.019±0.009 | 0.001±0.009 |
| 8 | 0.008±0.012 | 0.021±0.012 | 0.032±0.012 | 0.009±0.009 | 0.009±0.009 | 0.025±0.009 |
| 9 | 0.025±0.013 | 0.005±0.013 | 0.001±0.013 | 0.010±0.015 | ND | 0.031±0.015 |
| 10 | 0.014±0.008 | 0.001±0.008 | 0.015±0.008 | 0.005±0.029 | 0.021±0.029 | 0.062±0.029 |
| 11 | 0.005±0.001 | 0.005±0.001 | 0.006±0.001 | 0.005±0.030 | 0.007±0.030 | 0.058±0.030 |
| 12 | ND | 0.021 | ND | 0.001±0.036 | 0.019±0.036 | 0.070±0.036 |

ND means not detected.

**Table 2.** **Paired sample t-test Results Comparing Nickel Concentration in Borehole Water between Wet and Dry Seasons**

|  |  |  |  |
| --- | --- | --- | --- |
| T value  | Mean difference | 95% confidence interval of mean difference | p-value |
| Lower bound | Upper bound |
| -0.34454 | -0.00125 | -0.0092351 | 0.0067351 | 0.7369 |

Table 1 presents the seasonal variations in nickel (Ni) concentrations across borehole samples in Enugu North Local Government Area, visualized in Figure 1. The nickel concentration in borehole water samples fluctuated between different months in both the wet and dry seasons. During the wet season, concentrations of nickel varied from non-detectable levels (ND) to 0.043 mg/L across the samples. Notably, samples 1, 5, and 9 had ND values for certain months, indicating that nickel was not detected in these samples in specific months. However, other samples, such as 2, 3, and 6, showed relatively higher concentrations of 0.007 mg/L, 0.012 mg/L, and 0.016 mg/L, respectively, suggesting varying levels of contamination or natural variability in the borehole water.

In the dry season, nickel concentrations exhibited a wider range. Some samples showed elevated nickel levels, such as sample 2 (0.074 mg/L in December) and sample 6 (0.062 mg/L in January), while others displayed lower concentrations. Sample 7, for instance, had a very low concentration of 0.001 mg/L in January. This variation in nickel concentration between the seasons might be attributed to changes in rainfall, dilution effects, and runoff of contaminants during the wet season. Regardless of the season, the observed nickel concentrations are notably lower than the World Health Organization's (WHO) permissible limit for drinking water, which is 0.07 mg/L. This indicates that nickel levels in the borehole water samples are within acceptable limits and do not pose a health risk during either season.

Table 2 presents the results of the paired sample t-test. The t-value of -0.34454 and a mean difference of -0.00125 mg/L suggest a negligible average variation between the wet and dry seasons. The p-value of 0.7369, being far greater than the significance threshold of 0.05, supports the null hypothesis that there is no significant seasonal variation in nickel concentrations in borehole water.



**Figure 1. Nickel Concentration in Borehole Water Samples in Enugu North LGA**

**Table 3.** **Seasonal Variations in Iron Concentration in Borehole Water Samples in Enugu North LGA**

|  |  |  |
| --- | --- | --- |
| Fe (mg/l) | Wet Season | Dry Season |
| Sample | June | July | August | November | December | January |
| 1 | 0.109±0.018 | 0.094±0.018 | 0.074±0.018 | 0.39±0.151 | 0.127±0.151 | 0.129±0.151 |
| 2 | 0.078±0.032 | 0.112±0.032 | 0.142±0.032 | 0.18±0.046 | 0.144±0.046 | 0.088±0.046 |
| 3 | 0.045±0.044 | 0.089±0.044 | 0.133±0.044 | 0.13±0.013 | 0.135±0.013 | 0.155±0.013 |
| 4 | 0.941±0.436 | 0.305±0.436 | 0.106±0.436 | 0.29±0.077 | 0.138±0.077 | 0.197±0.077 |
| 5 | 0.417±0.218 | 0.024±0.218 | 0.056±0.218 | 0.281±0.081 | 0.164±0.081 | 0.126±0.081 |
| 6 | 0.049±0.05 | 0.101±0.05 | 0.149±0.05 | 0.156±0.039 | 0.106±0.039 | 0.08±0.039 |
| 7 | 1.156±0.626 | 0.004±0.626 | 0.154±0.626 | 0.12±0.026 | 0.068±0.026 | 0.1±0.026 |
| 8 | 0.06±0.071 | 0.146±0.071 | 0.201±0.071 | 0.13±0.012 | 0.141±0.012 | 0.154±0.012 |
| 9 | 1.374±0.643 | 0.52±0.643 | 0.115±0.643 | 0.113±0.054 | 0.119±0.054 | 0.21±0.054 |
| 10 | 1.077±0.545 | 0.07±0.545 | 0.21±0.545 | 0.147±0.06 | 0.111±0.06 | 0.029±0.06 |
| 11 | 0.701±0.339 | 0.298±0.339 | 0.028±0.339 | 0.211±0.037 | 0.15±0.037 | 0.216±0.037 |
| 12 | 0.012±0.018 | 0.026±0.018 | 0.047±0.018 | 0.258±0.065 | 0.13±0.065 | 0.18±0.065 |

**Table 4.** **Paired sample t-test Results Comparing Iron Concentration in Borehole Water between Wet and Dry Seasons**

|  |  |  |  |
| --- | --- | --- | --- |
| T value  | Mean difference | 95% confidence interval of mean difference | p-value |
| Lower bound | Upper bound |
| 1.5989 | 0.100556 | -0.0378681 | 0.238979 | 0.1382 |

**Table 3** and Figure 2 provide insights into the seasonal variations in iron (Fe) concentration in borehole water samples from Enugu North LGA. In the wet season, the iron concentrations varied significantly across the different months and samples. The concentration ranged from as low as 0.012 mg/L in June (sample 12) to as high as 1.374 mg/L in June (sample 9). Several samples, such as sample 4 and sample 7, showed notably high concentrations, especially during the wet months, with sample 7 having an exceptionally high value of 1.156 mg/L in June and sample 9 recording 1.374 mg/L in June. This variation suggests that environmental factors, such as rainfall and runoff, may lead to increased concentrations of iron in the water, potentially due to the leaching of iron from soils and sediments during the wet season.

In the dry season, the concentration of iron showed a noticeable decrease compared to the wet season for most samples. For instance, sample 4, which had 0.941 mg/L in June during the wet season, dropped to 0.138 mg/L in December. Similarly, sample 7 decreased from 1.156 mg/L in June to 0.068 mg/L in December. However, some samples still exhibited relatively higher concentrations, such as sample 3 (0.155 mg/L in January) and sample 12 (0.18 mg/L in January), indicating that certain boreholes might be more prone to iron contamination regardless of the season. The overall decrease in concentrations in the dry season is attributed to reduced rainfall, lower water table levels, and dilution effects. The elevated iron concentrations observed in some samples exceed the World Health Organization (WHO) permissible limit of 0.3 mg/L for drinking water.

The t-value of 1.5989 in Table 4, with a mean difference of 0.100556 mg/L between the wet and dry seasons, indicates a higher average concentration during the wet season. The p-value of 0.1382 exceeds the standard threshold of 0.05, implying that the difference in iron concentrations between the wet and dry seasons is not statistically significant.



**Figure 2. Iron Concentrations in Borehole Water Samples in Enugu North LGA**

**Table 5.** **Seasonal Variations in Zinc Concentration in Borehole Water Samples in Enugu North LGA**

|  |  |  |
| --- | --- | --- |
| Zn (mg/L) | Wet Season | Dry Season |
| Sample | June | July | August | November | December | January |
| 1 | 0.047±0.511 | 1.066±0.511 | 0.483±0.511 | 0.240±0.486 | 0.512±0.486 | 0.903±0.486 |
| 2 | 0.142±0.298 | 0.130±0.298 | 0.118±0.298 | 0.530±0.551 | 0.530±0.551 | 0.445±0.551 |
| 3 | 0.152±0.229 | 0.291±0.229 | 0.561±0.229 | 0.061±0.343 | 0.820±0.343 | 0.514±0.343 |
| 4 | 0.200±0.045 | 0.026±0.045 | 0.047±0.045 | 0.280±0.235 | 0.390±0.235 | 1.720±0.235 |
| 5 | 0.190±0.543 | 0.116±0.543 | 0.150±0.543 | 0.460±0.802 | 0.650±0.802 | 0.183±0.802 |
| 6 | 0.146±0.229 | 0.133±0.229 | 0.111±0.229 | 0.510±0.343 | 0.720±0.343 | 0.398±0.343 |
| 7 | 0.106±0.045 | 0.091±0.045 | 0.021±0.045 | 0.340±0.235 | 1.020±0.235 | 0.961±0.235 |
| 8 | 0.446±0.543 | 0.120±0.543 | 1.180±0.543 | 0.430±0.802 | 0.890±0.802 | 1.008±0.802 |
| 9 | 0.418±0.229 | 0.014±0.229 | 0.028±0.229 | 0.330±0.343 | 0.780±0.343 | 0.745±0.343 |
| 10 | 0.107±0.298 | 0.102±0.298 | 0.220±0.298 | 0.470±0.551 | 1.211±0.551 | 1.548±0.551 |
| 11 | 0.589±0.298 | 0.662±0.298 | 0.113±0.298 | 0.220±0.486 | 0.460±0.486 | 0.897±0.486 |
| 12 | 0.114±0.229 | 0.698±0.229 | 0.128±0.229 | 0.160±0.343 | 0.711±0.343 | 1.130±0.343 |

**Table 6.** **Paired Sample t-test Results Comparing Zinc Concentration in Borehole Water between Wet and Dry Seasons**

|  |  |  |  |
| --- | --- | --- | --- |
| T value  | Mean difference | 95% confidence interval of mean difference | p-value |
| Lower bound | Upper bound |
| -4.7977 | -0.38642 | -0.56369 | -0.20914 | 0.0005554 |

The results presented in **Table 5** and visualized in Figure 3 provide a detailed examination of seasonal variations in zinc (Zn) concentration in borehole water samples from Enugu North LGA. In the wet season, zinc concentrations varied across the samples, with some samples showing higher concentrations, such as sample 1, which had 1.066 mg/L in July, and sample 8, with 0.446 mg/L in June. Conversely, other samples, like sample 7, displayed lower concentrations, such as 0.106 mg/L in June. Interestingly, sample 4 had a relatively high concentration of 0.200 mg/L in June but dropped significantly in subsequent months, indicating a transient peak in the wet season, which might be related to rainwater runoff.

In the dry season, zinc concentrations showed a general tendency toward higher levels compared to the wet season, particularly in samples like 4 (1.720 mg/L in January), 10 (1.548 mg/L in January), and 7 (1.020 mg/L in December). This trend might suggest a seasonal accumulation of zinc in the water due to reduced dilution from rainfall and runoff during the dry season. Zinc concentrations in the borehole water samples were generally below the World Health Organization (WHO) permissible limit of 3 mg/L for drinking water.

Table 6 provides a statistical evaluation of the observed seasonal differences, with a t-value of -4.7977 and a mean difference of -0.38642 mg/L, and a corresponding p-value of 0.0005554, indicating that zinc concentrations were significantly higher during the dry season compared to the wet season.



**Figure 3. Zinc Concentration in Borehole Water Samples in Enugu North LGA**

**Table 7.** **Seasonal Variations in Copper Concentration in Borehole Water Samples in Enugu North LGA**

|  |  |  |
| --- | --- | --- |
| Cu (mg/L) | Wet Season | Dry Season |
| Sample | June | July | August | November | December | January |
| 1 | 0.006±0.006 | 0.011±0.006 | 0.018±0.006 | 0.036±0.286 | 0.065±0.286 | 0.590±0.286 |
| 2 | 0.003±0.002 | ND | 0.003±0.002 | 0.051±0.275 | 0.580±0.275 | 0.072±0.275 |
| 3 | 0.002±0.002 | 0.004±0.002 | 0.006±0.002 | 0.041±0.163 | 0.077±0.163 | 0.360±0.163 |
| 4 | 0.006±0.001 | 0.006±0.001 | 0.007±0.001 | 0.050±0.321 | 0.640±0.321 | 0.132±0.321 |
| 5 | ND | ND | ND | 0.210±0.090 | 0.071±0.090 | 0.040±0.090 |
| 6 | 0.004±0.001 | ND | 0.005±0.001 | 0.180±0.089 | 0.054±0.089 | 0.009±0.089 |
| 7 | 0.002±0.001 | 0.001±0.001 | 0.001±0.001 | 0.250±0.263 | 0.098±0.263 | 0.614±0.263 |
| 8 | 0.001±0.001 | ND | 0.002±0.001 | 0.022±0.032 | 0.068±0.032 | 0.087±0.032 |
| 9 | 0.007±0.003 | 0.009±0.003 | 0.012±0.003 | 0.016±0.221 | 0.102±0.221 | 0.440±0.221 |
| 10 | 0.013±0.008 | 0.002±0.008 | 0.017±0.008 | 0.310±0.147 | 0.117±0.147 | 0.045±0.147 |
| 11 | 0.007±0.002 | 0.005±0.002 | 0.002±0.002 | 0.029±0.280 | 0.011±0.280 | 0.550±0.280 |
| 12 | 0.009±0.003 | 0.004±0.003 | 0.008±0.003 | 0.019±0.027 | 0.047±0.027 | 0.085±0.027 |

ND denotes not detected.

**Table 8.** **Paired sample t-test Results Comparing Copper Concentration in Borehole Water between Wet and Dry Seasons**

|  |  |  |  |
| --- | --- | --- | --- |
| T value  | Mean difference | 95% confidence interval of mean difference | p-value |
| Lower bound | Upper bound |
| -6.4904 | -0.171364 | -0.230192 | -0.112535 | 6.98e-05 |

Table 7 presents the seasonal variations in copper (Cu) concentrations in borehole water samples from Enugu North LGA, visualized in Figure 4. In the wet season, copper concentrations were generally low across most samples, with several samples exhibiting concentrations near the detection limit, such as sample 1, which recorded values of 0.006 mg/L in June, increasing slightly in subsequent months. Other samples, such as sample 7, recorded values close to 0.002 mg/L. This suggests that during the wet season, copper levels were relatively stable and at low concentrations across most of the borehole water samples.

However, in the dry season, copper concentrations showed a noticeable increase in several samples. For example, sample 1 recorded a sharp increase to 0.590 mg/L in January, and sample 3 showed an increase from 0.006 mg/L in August to 0.360 mg/L in January. Sample 7 exhibited a similar rise, from 0.002 mg/L in June to 0.614 mg/L in January. This significant increase in copper concentrations during the dry season is due to reduced dilution from rainfall, increased evaporation. Although all fall below the permissible limit of 2.0mg/L set by WHO, however, prolonged exposure to high copper levels can lead to health issues.

The paired sample t-test results in Table 8 provide statistical evidence of significant seasonal differences in copper concentrations. The t-value of -6.4904, with a mean difference of -0.171364 mg/L between the wet and dry seasons, and an extremely low p-value of 6.98e-05, indicating a strong statistical seasonal difference between the wet and dry seasons.



**Figure 4. Copper concentration in Borehole Water Samples in Enugu North LGA**

**Table 9.** **Seasonal Variations in Lead Concentration in Borehole Water Samples in Enugu North LGA**

|  |  |  |
| --- | --- | --- |
| Pb (mg/l) | Wet Season | Dry Season |
| Sample | June | July | August | November | December | January |
| 1 | 0.004±0.002 | 0.007±0.002 | 0.008±0.002 | 0.001±0.004 | 0.005±0.004 | 0.010±0.004 |
| 2 | 0.001±0.005 | ND | 0.010±0.005 | 0.003±0.019 | 0.001±0.019 | 0.040±0.019 |
| 3 | 0.008±0.003 | ND | 0.003±0.003 | 0.006±0.002 | 0.002±0.002 | 0.006±0.002 |
| 4 | 0.010±0.007 | ND | ND | 0.001±0.005 | 0.009±0.005 | 0.001±0.005 |
| 5 | 0.020±0.008 | 0.006±0.008 | 0.004±0.008 | 0.004±0.002 | 0.005±0.002 | 0.008±0.002 |
| 6 | ND | 0.010±0.005 | 0.001±0.005 | 0.010±0.016 | 0.040±0.016 | 0.020±0.016 |
| 7 | 0.005±0.003 | ND | 0.006±0.003 | ND | ND | ND |
| 8 | 0.001±0.001 | ND | ND | ND | 0.003±0.001 | ND |
| 9 | 0.004±0.002 | ND | ND | 0.008±0.003 | 0.002±0.003 | 0.002±0.003 |
| 10 | ND | 0.050±0.010 | 0.030±0.010 | 0.030±0.013 | 0.006±0.013 | 0.005±0.013 |
| 11 | 0.010±0.011 | 0.030±0.011 | 0.009±0.011 | 0.003±0.001 | ND | 0.001±0.001 |
| 12 | 0.030±0.014 | 0.004±0.014 | 0.005±0.014 | 0.007±0.005 | ND | 0.010±0.005 |

ND stands for not detected

**Table 10.** **Paired Sample t-test Results Comparing Lead Concentration in Borehole Water between Wet and Dry Seasons**

|  |  |  |  |
| --- | --- | --- | --- |
| T value  | Mean difference | 95% confidence interval of mean difference | p-value |
| Lower bound | Upper bound |
| 0.75486 | 0.002606 | -0.005086 | 0.010298 | 0.4677 |

The analysis of lead concentrations in borehole water samples from Enugu North Local Government Area reveals varying levels of contamination across wet and dry seasons, as detailed in Table 9, and visualized in Figure 5.

In the wet season, lead concentrations across the samples were relatively low, with many samples exhibiting values close to or below the detection limit. For example, samples 2, 3, 7, and 8 recorded concentrations of ND (not detected) during most of the wet season months, emphasizing the absence or minimal presence of lead in these samples. For those that did show lead concentrations, the values remained within the range of 0.001 to 0.020 mg/L, with sample 12 recording the highest concentration of 0.030 mg/L in June.

During the dry season, lead concentrations showed more variability. Several samples showed higher values compared to the wet season, with sample 10 exhibiting a significant increase in January, reaching 0.050 mg/L, as well as sample 2, which increased to 0.040 mg/L in January. Other samples, such as sample 1, also showed increased concentrations from 0.004 mg/L in June to 0.010 mg/L in January. Despite these seasonal increases, lead concentrations in many samples remained low throughout both seasons, suggesting that the borehole water in this area may not be severely contaminated by lead.

The paired sample t-test results presented in Table 10 indicate no statistically significant difference between wet and dry seasons. The t-value of 0.75486, coupled with a mean difference of 0.002606 mg/l and a p-value of 0.4677, suggests that variations in lead levels are not significant at conventional confidence levels.



**Figure 5. Lead concentration in Borehole Water Samples in Enugu North LGA**

**Table 11.** **Seasonal Variations in Cadmium Concentration in Borehole Water Samples in Enugu North LGA**

|  |  |  |
| --- | --- | --- |
| Cd (mg/l) | Wet Season | Dry Season |
| Sample | June | July | August | November | December | January |
| 1 | 0.002±0.000 | ND | 0.002±0.000 | 0.003±0.005 | 0.010±0.005 | 0.001±0.005 |
| 2 | 0.005±0.010 | 0.015±0.010 | 0.025±0.010 | 0.006±0.002 | 0.008±0.002 | 0.005±0.002 |
| 3 | 0.007±0.005 | 0.011±0.005 | 0.016±0.005 | 0.008±0.004 | 0.002±0.004 | 0.009±0.004 |
| 4 | 0.002±0.013 | 0.011±0.013 | 0.027±0.013 | 0.001±0.005 | 0.009±0.005 | 0.010±0.005 |
| 5 | 0.005±0.011 | 0.014±0.011 | 0.027±0.011 | 0.002±0.007 | ND | 0.012±0.007 |
| 6 | 0.007±0.008 | 0.015±0.008 | 0.022±0.008 | 0.004±0.002 | ND | 0.007±0.002 |
| 7 | 0.010±0.002 | 0.010±0.002 | 0.013±0.002 | 0.004±0.008 | 0.005±0.008 | 0.018±0.008 |
| 8 | 0.007±0.009 | 0.015±0.009 | 0.024±0.009 | 0.005±0.000 | 0.005±0.000 | ND |
| 9 | 0.005±0.012 | 0.014±0.012 | 0.029±0.012 | 0.004±0.006 | 0.003±0.006 | 0.013±0.006 |
| 10 | 0.004±0.012 | 0.017±0.012 | 0.028±0.012 | 0.002±0.008 | 0.009±0.008 | 0.017±0.008 |
| 11 | 0.008±0.011 | 0.014±0.011 | 0.029±0.011 | 0.001±0.005 | ND | 0.008±0.005 |
| 12 | 0.010±0.009 | 0.014±0.009 | 0.027±0.009 | ND | 0.001±0.000 | 0.001±0.000 |

ND stands for not detected

**Table 12.** **Paired sample t-test Results Comparing Cadmium Concentration in Borehole Water between Wet and Dry Seasons**

|  |  |  |  |
| --- | --- | --- | --- |
| T value  | Mean difference | 95% confidence interval of mean difference | p-value |
| Lower bound | Upper bound |
| 5.5488 | 0.007694 | 0.0046424 | 0.0107465 | 0.0001731 |

The evaluation of cadmium concentrations in borehole water samples from Enugu North Local Government Area highlights significant seasonal variations, as presented in Table 11 and visualized in Figure 6. During the wet season, cadmium concentrations were generally low across most of the samples. Several samples, such as sample 1, recorded cadmium concentrations as low as ND (not detected) in months like July and December, with only slight concentrations observed in June and August. The highest concentration in the wet season was seen in sample 7, with a value of 0.010 mg/L in June.

In the dry season, there was a noticeable increase in cadmium concentrations compared to the wet season. The concentrations in some samples rose, with sample 2 showing a consistent presence of cadmium across the dry season months, peaking at 0.025 mg/L in August. Similarly, sample 6 exhibited a noticeable increase from 0.007 mg/L in January to 0.015 mg/L in July. Other samples, such as sample 7, which had a value of 0.018 mg/L in January, also demonstrated an increase in cadmium levels in the dry season.

The paired sample t-test results in Table 12 provide a quantitative assessment of the seasonal variations in cadmium concentrations. The t-value of 5.5488 and a highly significant p-value of 0.0001731 indicate a statistically significant difference between wet- and dry-season cadmium concentrations.



**Figure 6. Cadmium Concentrations in Borehole Water Samples in Enugu North LGA**

**Table 13.** **Seasonal Variations in Manganese Concentration in Borehole Water Samples in Enugu North LGA**

|  |  |  |
| --- | --- | --- |
| Mn (mg/l) | Wet Season | Dry Season |
| Sample | June | July | August | November | December | January |
| 1 | 0.018±0.006 | 0.024±0.006 | 0.030±0.006 | 0.018±0.069 | 0.150±0.069 | 0.051±0.069 |
| 2 | 0.119±0.041 | 0.082±0.041 | 0.037±0.041 | ND | 0.210±0.132 | 0.023±0.132 |
| 3 | 0.029±0.014 | 0.001±0.014 | 0.010±0.014 | 0.034±0.165 | 0.311±0.165 | 0.017±0.165 |
| 4 | 0.210±0.096 | 0.087±0.096 | 0.021±0.096 | 0.230±0.155 | 0.388±0.155 | 0.078±0.155 |
| 5 | 0.043±0.016 | 0.011±0.016 | 0.023±0.016 | 0.040±0.046 | 0.120±0.046 | 0.120±0.046 |
| 6 | 0.064±0.022 | 0.044±0.022 | 0.088±0.022 | 0.020±0.038 | 0.027±0.038 | 0.089±0.038 |
| 7 | 0.055±0.020 | 0.073±0.020 | 0.095±0.020 | 0.340±0.205 | 0.025±0.205 | 0.411±0.205 |
| 8 | 0.245±0.125 | 0.047±0.125 | 0.013±0.125 | 0.460±0.204 | 0.118±0.204 | 0.095±0.204 |
| 9 | 0.360±0.177 | 0.116±0.177 | 0.017±0.177 | 0.250±0.072 | 0.134±0.072 | 0.118±0.072 |
| 10 | 0.240±0.104 | 0.058±0.104 | 0.062±0.104 | 0.740±0.387 | 0.090±0.387 | 0.050±0.387 |
| 11 | 0.196±0.088 | 0.055±0.088 | 0.035±0.088 | 1.250±0.697 | 0.044±0.697 | 0.041±0.697 |
| 12 | 0.151±0.058 | 0.056±0.058 | 0.047±0.058 | 1.090±0.610 | 0.031±0.610 | 0.036±0.610 |

**Table 14.** **Paired sample t-test Results Comparing Manganese Concentration in Borehole Water between Wet and Dry Seasons**

|  |  |  |  |
| --- | --- | --- | --- |
| T value  | Mean difference | 95% confidence interval of mean difference | p-value |
| Lower bound | Upper bound |
| -3.8369 | -0.1250972 | -0.1968567 | -0.0533378 | 0.002761 |

Table 13 shows that manganese concentrations varied both across seasons and between samples, with some general patterns and notable anomalies, this is presented in Figure 7. During the wet season, manganese concentrations varied significantly across the samples. Some samples, such as sample 1, showed relatively consistent concentrations throughout the wet season, with values ranging from 0.018 mg/L in June to 0.030 mg/L in August. Other samples, such as sample 2, demonstrated more variability, with concentrations ranging from 0.119 mg/L in June to 0.037 mg/L in August, and then dropping to ND (not detected) in November. Sample 7 had a marked increase from 0.055 mg/L in June to 0.095 mg/L in August.

In the dry season, there was a noticeable increase in manganese concentrations in several samples. For example, sample 1 showed a sharp increase from 0.030 mg/L in August to 0.150 mg/L in December. Similarly, sample 4 exhibited a significant rise from 0.021 mg/L in August to 0.388 mg/L in December, followed by a slight decrease to 0.078 mg/L in January. Sample 6 showed a fluctuation, with a decrease from 0.088 mg/L in August to 0.027 mg/L in December but then rising again to 0.089 mg/L in January. Sample 11 demonstrated a considerable peak, from 1.250 mg/L in November to 0.044 mg/L in December and 0.041 mg/L in January.

The paired sample t-test results in Table 14 provide a statistical perspective on the seasonal variations. The t-value of -3.8369 and the highly significant p-value of 0.002761 indicate a statistically significant difference in manganese concentrations between the wet and dry seasons.



**Figure 7. Manganese Concentrations in Borehole Water Samples in Enugu North LGA**

**Table 15.** **Seasonal Variations in Chromium Concentration in Borehole Water Samples in Enugu North LGA**

|  |  |  |
| --- | --- | --- |
| Cr (mg/l) | Wet Season | Dry Season |
| Sample | June | July | August | November | December | January |
| 1 | 0.005±0.020 | 0.011±0.020 | 0.042±0.020 | 0.020±0.003 | 0.021±0.003 | 0.025±0.003 |
| 2 | ND | 0.015±0.020 | 0.043±0.020 | 0.012±0.019 | 0.047±0.019 | 0.018±0.019 |
| 3 | 0.004±0.012 | 0.026±0.012 | 0.024±0.012 | 0.040±0.013 | 0.030±0.013 | 0.014±0.013 |
| 4 | 0.018±0.019 | 0.024±0.019 | 0.054±0.019 | 0.010±0.020 | 0.049±0.020 | 0.036±0.020 |
| 5 | 0.018±0.021 | 0.043±0.021 | 0.002±0.021 | 0.010±0.030 | 0.060±0.030 | 0.007±0.030 |
| 6 | 0.019 | ND | ND | 0.010±0.011 | 0.032±0.011 | 0.019±0.011 |
| 7 | 0.018±0.008 | 0.014±0.008 | 0.002±0.008 | 0.130±0.064 | 0.018±0.064 | 0.020±0.064 |
| 8 | 0.044±0.018 | 0.032±0.018 | 0.008±0.018 | 0.020±0.025 | ND | 0.055±0.025 |
| 9 | 0.010±0.010 | 0.015±0.010 | 0.030±0.010 | 0.010±0.023 | 0.051±0.023 | 0.047±0.023 |
| 10 | 0.003±0.011 | 0.021±0.011 | 0.023±0.011 | 0.020±0.007 | 0.033±0.007 | 0.022±0.007 |
| 11 | 0.013±0.008 | 0.026±0.008 | 0.011±0.008 | ND | 0.008±0.030 | 0.050±0.030 |
| 12 | 0.007±0.011 | 0.017±0.011 | 0.028±0.011 | ND | 0.041±0.021 | 0.011±0.021 |

**Table 16.** **Paired sample t-test Results Comparing Manganese Concentration in Borehole Water between Wet and Dry Seasons**

|  |  |  |  |
| --- | --- | --- | --- |
| T value  | Mean difference | 95% confidence interval of mean difference | p-value |
| Lower bound | Upper bound |
| -2.713 | -0.009764 | -0.017685 | -0.001843 | 0.02018 |

Table 15 presents the Chromium concentrations in borehole water samples, while Figure 8 depicts the visualization. In the wet season, chromium concentrations varied across the samples, with some showing relatively low levels and others exhibiting higher concentrations. For example, sample 1 exhibited chromium concentrations ranging from 0.005 mg/L in June to 0.042 mg/L in August, indicating some variability within the wet season. Similarly, sample 4 showed an increase from 0.018 mg/L in June to 0.054 mg/L in August, before slightly decreasing in the dry season.

In the dry season, there was a noticeable fluctuation in chromium concentrations across the samples. For example, sample 1 showed concentrations ranging from 0.021 mg/L in December to 0.025 mg/L in January, which represents a relatively stable trend. However, some samples, such as sample 2, exhibited higher values in the dry season. Sample 2 showed 0.047 mg/L in December, compared to a low concentration of ND (not detected) in June and 0.015 mg/L in July. Sample 8 exhibited a sharp decrease in December (ND) compared to 0.044 mg/L in June and 0.032 mg/L in July, before rising to 0.055 mg/L in January.

The paired sample t-test results in Table 16 further validate the observed seasonal differences in chromium concentrations. The t-value of -2.713 and a p-value of 0.02018 indicate a statistically significant difference between wet and dry season chromium levels.



**Figure 8. Chromium Concentrations in Borehole Water Samples in Enugu North LGA**

**3.2 Health Risk Assessment**

**Table 17. Chronic Daily Intake (CDI)** **for Ingestion (mg/kg/day)**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Sample | Mn | Cd | Pb | Ni | Cu | Zn | Cr | Fe |
| 1 | 8.314E-03 | 1.429E-04 | 1.449E-04 | 3.429E-04 | 1.286E-03 | 9.143E-03 | 4.422E-04 | 1.457E-02 |
| 2 | 1.346E-02 | 2.286E-04 | 2.216E-04 | 5.143E-04 | 1.714E-03 | 8.000E-03 | 5.188E-04 | 1.286E-02 |
| 3 | 1.149E-02 | 1.714E-04 | 1.609E-04 | 4.286E-04 | 1.429E-03 | 8.857E-03 | 4.288E-04 | 1.429E-02 |
| 4 | 2.897E-02 | 2.857E-04 | 3.854E-04 | 6.286E-04 | 2.286E-03 | 1.143E-02 | 5.281E-04 | 2.000E-02 |
| 5 | 1.020E-02 | 1.143E-04 | 1.104E-04 | 2.857E-04 | 1.000E-03 | 7.714E-03 | 2.808E-04 | 1.229E-02 |
| 6 | 9.486E-03 | 2.000E-04 | 2.154E-04 | 4.000E-04 | 1.371E-03 | 8.571E-03 | 4.043E-04 | 1.371E-02 |
| 7 | 2.854E-02 | 2.571E-04 | 2.675E-04 | 5.714E-04 | 2.000E-03 | 1.086E-02 | 5.654E-04 | 1.857E-02 |
| 8 | 2.794E-02 | 2.000E-04 | 2.087E-04 | 4.571E-04 | 1.571E-03 | 9.429E-03 | 4.578E-04 | 1.686E-02 |
| 9 | 2.843E-02 | 1.714E-04 | 1.714E-04 | 4.857E-04 | 1.857E-03 | 1.000E-02 | 4.610E-04 | 1.771E-02 |
| 10 | 1.149E-02 | 1.714E-04 | 1.718E-04 | 4.286E-04 | 1.429E-03 | 8.857E-03 | 5.286E-04 | 1.429E-02 |
| 11 | 2.897E-02 | 2.857E-04 | 2.866E-04 | 6.286E-04 | 2.286E-03 | 1.143E-02 | 6.241E-04 | 2.000E-02 |
| 12 | 1.020E-02 | 1.143E-04 | 2.148E-04 | 2.857E-04 | 1.000E-03 | 7.714E-03 | 2.650E-04 | 1.229E-02 |

Table 17 reveals that the Chronic Daily Intake (CDI) values for ingestion of heavy metals in the borehole water samples reveal varying levels of potential exposure risks. Among the assessed metals, iron (Fe) exhibited the highest CDI values across all samples, ranging from **1.229E-02 to 2.000E-02 mg/kg/day**, suggesting a significant presence in borehole water. Manganese (Mn) also displayed relatively high CDI values, particularly in samples **4, 7, 8, 9, and 11**, where it exceeded **2.794E-02 mg/kg/day**, indicating that some boreholes may have elevated Mn levels that require further scrutiny due to its potential neurological effects at high exposure levels.

Cadmium (Cd), lead (Pb), and nickel (Ni) presented considerably lower CDI values compared to Mn and Fe. However, their presence in drinking water is concerning due to their toxic and non-essential nature. The highest Cd ingestion was observed in **samples 4 and 11 (2.857E-04 mg/kg/day)**, while Pb concentrations peaked in **sample 4 (3.854E-04 mg/kg/day)**. Copper (Cu) and zinc (Zn) are essential trace elements, but their intake should remain within safe limits. The CDI values for Cu ranged from **1.000E-03 to 2.286E-03 mg/kg/day**, while Zn varied from **7.714E-03 to 1.143E-02 mg/kg/day**. These values are within expected ranges for drinking water, but prolonged exposure beyond permissible limits could pose health risks. Chromium (Cr) concentrations also showed fluctuations, with **samples 7 and 11** having the highest CDI values (**5.654E-04 and 6.241E-04 mg/kg/day**, respectively), which warrants further risk evaluation due to its potential carcinogenicity.

**Table 18. Chronic Daily Intake (CDI)** **for Dermal Exposure (mg/kg/day)**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Sample | Mn | Cd | Pb | Ni | Cu | Cr | Zn | Fe |
| 1 | 7.483E-05 | 1.286E-06 | 3.118E-06 | 3.086E-06 | 1.157E-05 | 4.286E-06 | 8.229E-05 | 1.311E-04 |
| 2 | 1.211E-04 | 2.057E-06 | 4.611E-06 | 4.629E-06 | 1.543E-05 | 2.044E-06 | 7.200E-05 | 1.157E-04 |
| 3 | 1.034E-04 | 1.543E-06 | 3.809E-06 | 3.857E-06 | 1.286E-05 | 2.548E-06 | 7.971E-05 | 1.286E-04 |
| 4 | 2.607E-04 | 2.571E-06 | 5.142E-06 | 5.657E-06 | 2.057E-05 | 2.451E-06 | 1.029E-04 | 1.800E-04 |
| 5 | 9.180E-05 | 1.029E-06 | 2.565E-06 | 2.571E-06 | 9.000E-06 | 4.045E-06 | 6.943E-05 | 1.106E-04 |
| 6 | 8.537E-05 | 1.800E-06 | 4.165E-06 | 3.600E-06 | 1.234E-05 | 4.787E-06 | 7.714E-05 | 1.234E-04 |
| 7 | 2.569E-04 | 2.314E-06 | 5.648E-06 | 5.143E-06 | 1.800E-05 | 2.314E-06 | 9.771E-05 | 1.671E-04 |
| 8 | 2.515E-04 | 1.800E-06 | 4.654E-06 | 4.114E-06 | 1.414E-05 | 3.832E-06 | 8.486E-05 | 1.517E-04 |
| 9 | 2.559E-04 | 1.543E-06 | 6.654E-06 | 4.371E-06 | 1.671E-05 | 4.548E-06 | 9.000E-05 | 1.594E-04 |
| 10 | 1.211E-04 | 2.057E-06 | 5.644E-06 | 4.629E-06 | 1.543E-05 | 2.557E-06 | 7.200E-05 | 1.157E-04 |
| 11 | 1.034E-04 | 1.543E-06 | 3.822E-06 | 3.857E-06 | 1.286E-05 | 4.656E-06 | 7.971E-05 | 1.286E-04 |
| 12 | 2.607E-04 | 2.571E-06 | 6.484E-06 | 5.657E-06 | 2.057E-05 | 2.566E-06 | 1.029E-04 | 1.800E-04 |

Table 19 presents the Chronic Daily Intake (CDI) values for dermal exposure to heavy metals across the borehole water samples. Manganese (Mn) exhibited the highest CDI values among the metals, particularly in samples 4, 7, 8, 9, and 12, where it exceeded 2.500E-04 mg/kg/day. Similarly, iron (Fe) demonstrated consistently high CDI values across all samples, with the highest recorded in samples 4 and 12 (1.800E-04 mg/kg/day). Lead (Pb), cadmium (Cd), and nickel (Ni) exhibited lower CDI values compared to Mn and Fe. However, Pb concentrations reached their peak in sample 9 (6.654E-06 mg/kg/day), while Cd and Ni showed relatively low but notable values across all samples. Chromium (Cr) concentrations fluctuated across the samples, with sample6 (4.787E-06 mg/kg/day) having the highest recorded value. Copper (Cu) and zinc (Zn) are essential micronutrients, but their dermal exposure should remain within safe limits. Cu values ranged from 9.000E-06 to 2.057E-05 mg/kg/day, while Zn exhibited slightly higher values, peaking at 1.029E-04 mg/kg/day (samples 4 and 12).

**Table 20 Cumulative Hazard Quotient (HQ) and Hazard Indices for Heavy metals in Water Samples**

|  |  |  |
| --- | --- | --- |
| Sample | HQ (Adults) | HQ (Children) |
| 1 | 0.0417 | 0.0972 |
| 2 | 0.0655 | 0.1528 |
| 3 | 0.0298 | 0.0694 |
| 4 | 0.0250 | 0.0583 |
| 5 | 0.0560 | 0.1306 |
| 6 | 0.0964 | 0.2250 |
| 7 | 0.0131 | 0.0306 |
| 8 | 0.0048 | 0.0111 |
| 9 | 0.0190 | 0.0444 |
| 10 | 0.1440 | 0.3361 |
| 11 | 0.0631 | 0.1472 |
| 12 | 0.0667 | 0.1556 |
| Hazard Indices (HI) | 0.6251 | 1.4580 |

The results presented in Table 20 provide a comprehensive assessment of the potential non-carcinogenic health risks associated with heavy metal exposure through water consumption. The HQ values for children are consistently higher than those for adults across all borehole samples. This pattern is expected, as children are more vulnerable to contaminants due to their higher water intake per unit body weight and developing physiological systems. Among the samples, Sample 10 exhibits the highest HQ values for both adults (0.1440) and children (0.3361), indicating a relatively higher risk compared to other locations. Conversely, Sample 8 has the lowest HQ values (0.0048 for adults and 0.0111 for children), suggesting minimal health risks from heavy metal exposure at this site. The cumulative Hazard Index (HI), which aggregates the HQ values for all samples, is 0.6251 for adults and 1.4580 for children. While the HI for adults remains below the safety threshold of 1, implying that heavy metal exposure is unlikely to cause adverse health effects, the HI for children exceeds this limit. This finding raises concerns about potential health risks for children consuming water from these boreholes over prolonged periods.

**Table 21. Slope Factors of Heavy Metals in Drinking Water, adapted from USEPA**

|  |  |  |
| --- | --- | --- |
| Metal  | $$SF\_{ingestion}$$ | $$SF\_{dermal}$$ |
| Chromium (Cr) | 0.5 | 20 |
| Lead (Pb) | 0.0085 | 1.5 |
| Cadmium (Cd) | 0.38 | 6.1 |
| Nickel (Ni) | 1.7 | 42.5 |

Table 21 presents the slope factors of the heavy metals in borehole water, adapted from USEPA, and used for the computation of the cancer risk for both ingestion and dermal exposure of heavy metals.

**Table 22. Cancer Risk (CR) for Ingestion of Heavy Metals from Drinking Water**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Sample | Cd | Pb | Ni | Cr |
| 1 | 5.4302E-05 | 1.23165e-06 | 5.8293E-04 | 2.2110E-04 |
| 2 | 8.6868E-05 | 1.88360e-06 | 8.7431E-04 | 2.5940E-04 |
| 3 | 6.5132E-05 | 1.36765e-06 | 7.2862E-04 | 2.1440E-04 |
| 4 | 1.0857E-04 | 3.27590e-06 | 1.0686E-03 | 2.6405E-04 |
| 5 | 4.3434E-05 | 9.38400e-07 | 4.8569E-04 | 1.4040E-04 |
| 6 | 7.6000E-05 | 1.83090e-06 | 6.8000E-04 | 2.0215E-04 |
| 7 | 9.7698E-05 | 2.27375e-06 | 9.7138E-04 | 2.8270E-04 |
| 8 | 7.6000E-05 | 1.77395e-06 | 7.7707E-04 | 2.2890E-04 |
| 9 | 6.5132E-05 | 1.45690e-06 | 8.2569E-04 | 2.3050E-04 |
| 10 | 6.5132E-05 | 1.46030e-06 | 7.2862E-04 | 2.6430E-04 |
| 11 | 1.0857E-04 | 2.43610e-06 | 1.0686E-03 | 3.1205E-04 |
| 12 | 4.3434E-05 | 1.82580e-06 | 4.8569E-04 | 1.3250E-04 |

The cancer risk (CR) assessment for ingestion of heavy metals from drinking water is presented in Table 22. Among the metals evaluated, nickel (Ni) exhibited the highest cancer risk across all samples, with values ranging from 4.8569E-04 to 1.0686E-03. This indicates a significant potential health threat, as prolonged exposure to Ni is known to contribute to carcinogenic effects. Chromium (Cr) also showed relatively high CR values, ranging between 1.3250E-04 and 3.1205E-04, suggesting that its presence in drinking water poses a notable risk, especially in samples 4, 7, 10, and 11, where the values exceeded 2.5E-04.

Cadmium (Cd) and lead (Pb), while exhibiting lower cancer risk values, still contribute to the cumulative carcinogenic burden. The CR values for Cd ranged from 4.3434E-05 to 1.0857E-04, with the highest risks observed in samples 4 and 11. Lead (Pb) presented the lowest CR values, ranging from 9.38400E-07 to 3.27590E-06, which, although lower compared to other metals, should not be overlooked due to lead’s cumulative toxic effects on human health.

**Table 23 Cancer Risk (CR) for Dermal Exposure of Heavy Metals in Drinking Water**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Sample | Cd | Pb | Ni | Cr |
| 1 | 7.84460e-06 | 4.6770e-06 | 1.311550E-04 | 8.572e-05 |
| 2 | 1.25477e-05 | 6.9165e-06 | 1.967325E-04 | 4.088e-05 |
| 3 | 9.41230e-06 | 5.7135e-06 | 1.639225E-04 | 5.096e-05 |
| 4 | 1.56831e-05 | 7.7130e-06 | 2.404225E-04 | 4.902e-05 |
| 5 | 6.27690e-06 | 3.8475e-06 | 1.092675E-04 | 8.090e-05 |
| 6 | 1.09800e-05 | 6.2475e-06 | 1.530000E-04 | 9.574e-05 |
| 7 | 1.41154e-05 | 8.4720e-06 | 2.185775E-04 | 4.628e-05 |
| 8 | 1.09800e-05 | 6.9810e-06 | 1.748450E-04 | 7.664e-05 |
| 9 | 9.41230e-06 | 9.9810e-06 | 1.857675E-04 | 9.096e-05 |
| 10 | 1.25477e-05 | 8.4660e-06 | 1.967325E-04 | 5.114e-05 |
| 11 | 9.41230e-06 | 5.7330e-06 | 1.639225E-04 | 9.312e-05 |
| 12 | 1.56831e-05 | 9.7260e-06 | 2.404225E-04 | 5.132e-05 |

The cancer risk (CR) assessment for dermal exposure to heavy metals in drinking water is shown in Table 23. Among these metals, nickel (Ni) exhibited the highest CR values, ranging from 1.092675E-04 to 2.404225E-04, indicating a significant potential health risk from dermal absorption. Borehole samples 4 and 12 recorded the highest CR values for Ni, suggesting that individuals exposed to water from these sources may be at greater risk of developing long-term health complications due to Ni exposure.

Chromium (Cr) also showed relatively high cancer risk values, ranging from 4.088E-05 to 9.574E-05. The highest CR values for Cr were observed in samples 6, 9, and 11, reinforcing the concern over its potential adverse health effects. Although Cr levels in dermal exposure were lower than those reported for ingestion (Table 22), they remain substantial, especially in samples where values approached 1.0E-04, which is the upper threshold of the acceptable cancer risk level recommended by the U.S. Environmental Protection Agency (USEPA).

Cadmium (Cd) and lead (Pb) presented relatively lower CR values in comparison to Ni and Cr, with Cd ranging from 6.27690E-06 to 1.56831E-05 and Pb ranging from 3.8475E-06 to 9.9810E-06. While these values fall below the high-risk threshold, their cumulative effect, particularly in conjunction with ingestion exposure, could still pose a long-term health risk. The highest CR values for Cd were recorded in samples 4 and 12, while Pb exhibited the highest risk in sample 9, highlighting variations in contamination levels across different boreholes.

**4. Conclusion**

This study assessed the water quality of selected boreholes in Enugu North Local Government Area, Enugu State, Nigeria, by evaluating both the physico-chemical and bacteriological properties, as well as the concentrations of heavy metals (Mn, Cd, Pb, Ni, Cu, Zn, Cr, Fe) and their associated health risks. The findings underscore the presence of several heavy metals at varying concentrations, some of which pose significant health risks to both adults and children through ingestion and dermal exposure.

The Chronic Daily Intake (CDI) values for heavy metals suggest that ingestion of contaminated water from certain samples could lead to potential health concerns, particularly for children, who are more susceptible to the toxic effects of these metals. In addition, the Hazard Quotient (HQ) values and the Hazard Indices (HI) indicate that, while the overall risk from the water samples may not always exceed the safety thresholds, some boreholes have higher risks, especially with elevated levels of nickel and chromium, which are known carcinogens. Furthermore, the **Cancer Risk (CR)** values for ingestion and dermal exposure provide additional evidence of the potential long-term cancer risk associated with prolonged exposure to specific heavy metals, particularly in areas where concentrations surpass the acceptable limits.

However, while many of the boreholes in Enugu North Local Government Area may provide water that meets basic drinking water standards, a substantial portion of the samples indicate concerning levels of heavy metals that require attention. Given the potential health risks, especially for vulnerable populations, it is recommended that water quality monitoring and regular testing be conducted to ensure safe drinking water. The implementation of effective water treatment systems and public awareness programs about the risks of water contamination are essential steps toward safeguarding public health. Additionally, further research should focus on identifying the sources of contamination and exploring cost-effective methods for water remediation in the affected areas.

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