WATER QUALITY ASSESSEMENT USING GEOGRAPHIC INFORMATION SYSTEM TECHNIQUES IN UGBOWO CAMPUS, UNIVERSITY OF BENIN, BENIN CITY, EDO STATE.

BY

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CERTIFICATION

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PLAGIARISM

This work **WATER QUALITY ASSESSEMENT USING GEOGRAPHIC INFORMATION SYSTEM TECHNIQUES IN UGBOWO CAMPUS, UNIVERSITY OF BENIN, BENIN CITY, EDO STATE,** by OAIKHENA, Ejiyamemen Edewede, Matriculation Number ENG2002111, of the Department of Civil Engineering, Faculty of Engineering, University of Benin, Benin City, Edo State, Nigeria, has PASSED the PLAGIARISM TEST.

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DEDICATION

This research work is dedicated to the Almighty God, the source of wisdom and strength, whose grace and guidance have sustained me throughout this academic journey.

I dedicate this project work to my loving family, whose unwavering support and encouragement have been my pillars of strength throughout this journey. Your belief in me fuels my aspirations.

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ABSTRACT

The study addressed the critical challenge of ensuring safe and sustainable borehole water quality in the University of Benin, Benin City, Edo Satae, Nigeria, where contamination risks from anthropogenic and environmental factors threaten public health. The study aimed to assess spatial variations in borehole water quality, evaluate compliance with national and international standards such as the NSDWQ and WHO standard and visualize contamination risk zones using GIS techniques.

Geographic coordinates were obtained using a GPS navigation tool called coordinate and water samples for laboratory analysis were collected at three borehole sites: A, B and C and their respective distribution points. Thirty-four physicochemical and microbial parameters were analyzed in accordance with the APHA standard laboratory procedures. The Weighted Arithmetic Water Quality Index (WAWQI) method was applied to compute the WQI for each sampling point. The results were integrated into ArcGIS Pro software, where shapefiles were created and thematic maps generated to show spatial distribution of WQI and individual parameters relative to environmental features such as septic tanks and drainage channels.

The results of the pH, electrical conductivity, turbidity, total dissolved solids, values ranged from 4.8 to 6.0, 110 to 305 µS/cm, 3.48 to 4.04 NTU and 56 to 153 mg/L respectively. Calcium and Magnesium ranged from 2.87 to 7.14 mg/L and 1.61 to 4.00 mg/L respectively corroborating the low hardness values of 13.8 to 37.6 mg/L. Concentrations of iron, manganese, zinc, copper ranged from 0.210 to 0.327 mg/L, 0.045 to 0.070 mg/L, 0.107 to 0.167 mg/L and 0.017 to 0.026 mg/L respectively. Microbiological results revealed that total heterotrophic bacterial counts were present in Borehole B and distribution points A and C at 10×10^3 CFU/mL, all samples tested negative for coliforms and E. coli, indicating the absence of fecal contamination. Boreholes points A and B had WQI values of 61.27 and 57.30, inferring good quality, while Borehole C, distribution points A, B and C exhibited higher WQI values of 73.94, 82.79, 79.64 and 98.80 respectively reflecting post-storage contamination and influence from surrounding activities having a water quality grade of poor in line with the WHO and NSDWQ standards. The study concluded that GIS proved highly effective in visualizing spatial water quality variations and identifying areas at risk of contamination.

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ACRONYMS

AAS – Atomic Absorption Spectroscopy

AHP – Analytical Hierarchy Process

ANN – Artificial Neural Network

APHA – American Public Health Association

AU – African Union

AWWA – American Water Works Association

BOD – Biochemical Oxygen Demand

CFU – Colony Forming Units

COD – Chemical Oxygen Demand

DIP – Digital Image Processing System

DO – Dissolved Oxygen

DRASTIC – Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, and hydraulic Conductivity

EBK – Empirical Bayesian Kriging

EC – Electrical Conductivity

EDTA – Ethylenediaminetetraacetic Acid

EMB – Eosin Methylene Blue

FAS – Ferrous Ammonium Sulfate

GC– MS – Gas Chromatography– Mass Spectrometry

GIS – Geographic Information System

GLDAS – Global Land Data Assimilation System

GNSS – Global Navigation Satellite System

HU – Hazen Units

IDW – Inverse Distance Weighting

KCl – Potassium Chloride

MPN – Most Probable Number

MSE – Mean Square Error

NASA – National Aeronautics and Space Administration

NED – Naphthylethylenediamine Dihydrochloride

NSDWQ – Nigerian Standard for Drinking Water Quality

NTU – Nephelometric Turbidity Units

PCU – Platinum Cobalt Units

pH – Potential of Hydrogen ion concentration

QGIS – Quantum Geographic Information System

RMSE – Root Mean Square Error

TCC – Total Coliform Count

TCU – True Colour Units

TDS – Total Dissolved Solids

TS – Total Solids

TSS – Total Suspended Solids

UAV – Unmanned Aerial Vehicle

UNESCO – United Nations Educational, Scientific and Cultural Organization

UNICEF – United Nations International Children's Emergency Fund

USEPA – United States Environmental Protection Agency

WAWQI – Weighted Arithmetic Water Quality Index

WGHM – WaterGAP Global Hydrology Model

WHO – World Health Organization

WQI – Water Quality Index

CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

Access to clean and safe water remains a fundamental human right (AU, 1981) and a core component of sustainable development (UNICEF, 2016). Groundwater, particularly from boreholes, serves as a primary source of freshwater for millions of people, especially in rural and peri– urban areas where municipal water supply systems are inadequate or non–existent (Isa et al., 2013; Onu, 2024). However, despite its perceived purity, borehole water is susceptible to contamination from natural and anthropogenic sources, including industrial discharge, agricultural runoff, improper waste disposal, and poor borehole construction practices (Oboh and Egun, 2017; Udongwo and Sambo, 2022).

The World Health Organization (WHO, 2017) estimates that approximately 80% of all human diseases are waterborne, emphasizing the urgent need for effective water quality monitoring and management. Contaminated borehole water can harbor harmful pathogens, heavy metals (e.g., lead, arsenic) and chemical pollutants, leading to severe health risks such as cholera, dysentery, kidney damage, and even cancer (Edokpayi et al., 2017; Yan et al., 2024).

Traditional water quality assessment methods often rely on periodic laboratory testing, which is time– consuming, costly and lacks real– time spatial analysis (Kanu et al., 2023). The integration of Geographic Information Systems (GIS) into water quality monitoring offers powerful capabilities for data management, spatial analysis and decision– making (Chang, 2016). GIS helps map borehole locations, monitor contamination trends, and plan interventions effectively, providing essential tools for sustainable water resource management (Kufoniyi, 1998; Spellman, 2017).

Despite its potential, the adoption of GIS– based water quality monitoring systems in developing regions like Nigeria remains limited due to high costs, technical expertise gaps and fragmented data management (Daffi et al., 2020). Given the rapid urban expansion in regions like Benin City, the need for reliable, data– driven borehole water management has become increasingly urgent (Onu, 2024). This study seeks to bridge this gap by applying GIS techniques for monitoring borehole water quality in the University of Benin, Nigeria.

1.2 Statement of the Problem

The proliferation of boreholes in Nigeria has not been matched with robust monitoring systems to ensure consistent water quality assessment across locations. Current practices rely heavily on manual testing, which is labor– intensive, error– prone and lacks centralized data management (Oboh and Egun, 2017). This disjointed approach hinders policymakers and public health officials from making evidence– based decisions or enforcing water quality standards effectively (Udongwo and Sambo, 2022).

Poorly managed boreholes pose significant health risks due to potential contamination from pathogens, heavy metals and other pollutants (WHO, 2017). For instance, microbial contamination from nearby pit latrines or industrial activities can lead to outbreaks of waterborne diseases (Edokpayi et al., 2017). Additionally, the absence of real– time monitoring means contamination often goes undetected for extended periods, exacerbating public health and environmental challenges (Daffi et al., 2020). The lack of structured frameworks for routine water quality testing and spatial monitoring compounds these challenges, leading to inefficient management and increased public health risks (Agwaibor, 2024).

This study addresses these gaps by using GIS techniques to streamline borehole water quality monitoring, improve data accuracy and facilitate timely interventions.

1.3 Aim and Objectives

The aim of this research is to apply GIS techniques for borehole water quality assessment in University of Benin, Benin City, Edo State. The objectives are to:

i. assess the spatial variations in borehole water quality in the study area by analyzing key physio-chemical and microbiological parameters.
ii. evaluate the compliance of the borehole water samples with WHO and NSDWQ standards.
iii. compute the Water Quality Index (WQI) for each water sample and interpret the overall water quality status.
iv. develop and analyze spatial and attribute data using georeferenced shapefiles to visualize the spatial distribution of water quality parameters and identify potential contamination zones.

1.4 Scope of the Study

This research focuses on the water quality of three (3) selected borehole water supply systems within the Ugbowo Campus, University of Benin, Benin City, Edo State, Nigeria. Its scope includes:

i. acquisition of geospatial data and attribute data of the three selected boreholes and distribution points within the study area using a Global Positioning System (GPS) tool.
ii. collection of water samples from the borehole sources and their respective distribution points.

iii. laboratory analysis of water samples on water quality indicators such as physical, chemical and microbiological parameters.
iv. use of Water Quality Index (WQI) for assessment and interpretation of overall water quality.
v. application of Geographic Information System (GIS) tool to analyze and visualize the spatial distribution of water quality data.

1.5 Justification of the Study

This study contributes significantly to the body of knowledge in civil engineering by exploring how Geographic Information Systems (GIS) can be effectively applied to the management of groundwater quality. Through its findings, the research highlights the potential of GIS– based tools to enhance borehole water quality governance by enabling more accurate mapping, analysis and visualization of water quality data across different locations leading to better decision– making, promoting efficient allocation of resources for water infrastructure and reinforces efforts aimed at achieving long– term environmental sustainability.

By leveraging Geographic Information Systems (GIS), this research introduces an innovative, cost– effective approach to water quality management, enabling policymakers and environmental agencies to identify pollution hotspots, predict contamination trends, and implement targeted interventions (Balla et al., 2024; Masood et al., 2022). Furthermore, the study aligns with Sustainable Development Goal (SDG) 6 by promoting clean water accessibility and sustainable resource management (UNICEF, 2016). The findings will contribute to evidence– based regulations for borehole construction and maintenance, while also serving as a model for integrating geospatial technology into public health strategies in resource– limited settings (Daffi et al., 2020). Ultimately, this research bridges a critical gap in water safety monitoring, offering scalable solutions that enhance decision– making and safeguard community health.

CHAPTER TWO: LITERATURE REVIEW

2.1 Definition of Water

Water is a transparent, tasteless, odourless and colourless chemical compound made up of two hydrogen atoms and one oxygen atom covalently bounded together, it is chemically represented by its chemical formula (H_2O) and the systematic name dihydrogen monoxide also less commonly referred to as oxidane. The Earth is approximately 71% covered by water with the remaining 29% consisting of land (NASA, 2022). Approximately 97.5% of the Earth's water is saline, primarily oceanic sources while only about 2.5% is freshwater and of this 2.5%, about 68.9% is stored in glaciers and ice caps, 30.8% is groundwater and less than 0.3% is surface water found in lakes, reservoir systems and rivers (UNESCO, 1998). This statement highlights limited availability of freshwater accessibility for human consumption. Groundwater plays a crucial role in supplying freshwater, providing a larger percentage of the Earth's population with fresh water supply by implementing the use of hydraulic structures such as wells, borehole water systems, etc. However, over–exploitation and pollution threaten the sustainability of groundwater resources.

According to the World Health Organization (WHO, 2017) about 80% of all the diseases in human beings are water– borne. Once the groundwater is contaminated, it is difficult to ensure its restoration and proper quality by preventing the pollutants from the source.

2.2 Borehole Water Supply System

A borehole is a narrow, deep well drilled into the earth's surface to access underground water stored in aquifers (Aquafix, 2024). These aquifers are geological formations of layers of permeable rock or soil that hold water and allow it to flow. Boreholes serve as independent, localized water sources that tap into underground aquifers, offering communities a dependable alternative for domestic, agricultural and even industrial water needs (Isa et al., 2013; Onu, 2024). Borehole systems can be either manually operated or mechanized with pumps, and the depth of a borehole often determines the volume and quality of water extracted.

The following are some types of boreholes as regards hydrology, these types are based on the construction methods, depth and purpose of the borehole.

i. Hand– Dug Boreholes are shallow manually excavated boreholes common in rural areas with limited technology and often do not penetrate as deep as the mechanically drilled boreholes.
ii. Mechanically drilled boreholes are deeper wells constructed using rotary or percussion drilling rigs, providing access to confined aquifers.
iii. Exploratory Boreholes are used for hydrogeological investigations to assess groundwater potential.
iv. Dewatering boreholes are temporary installations used at construction sites to lower groundwater levels for safe excavation.

In many rural and peri– urban areas, it represents the most viable source of clean water (Oboh and Egun, 2017). Boreholes are less susceptible to surface contamination compared to rivers and open wells and when properly constructed and maintained, they provide water that is relatively free from biological impurities (WHO, 2017; Edokpayi et al., 2017). This makes them a dependable option for communities that lack access to treated municipal water. Boreholes also offer year– round availability when properly situated, constructed and managed, aiding to alleviate the daily burden of having to fetch and carry water over long distances. Additionally, during times of drought or failure in public water systems, boreholes serve as a critical backup resource, especially in rapidly expanding cities where infrastructure development is unable to keep pace with population growth. Institutions such as schools, hospitals and industries rely on boreholes to ensure a stable water supply and reduce dependence on often unreliable public utilities (Agwaibor, 2024).

2.3 Challenges of Borehole Water Supply

The popularity of boreholes stems from their relative reliability and the perception that groundwater, having passed through layers of soil and rock, is naturally filtered and therefore cleaner than surface water. However, borehole water can be subject to contamination from various sources including nearby latrines, agricultural runoff, industrial waste and poor construction practices. These contaminants, which may alter the characteristics of the water from the source may pose serious health risks when consumed untreated. Chemical pollutants like nitrates, heavy metals (e.g., arsenic and lead), pesticides, hydrocarbons and microbial pathogens can easily infiltrate aquifers through unlined latrines, leaking septic tanks, landfill leachates and surface spills, especially when boreholes are shallow or improperly sealed. While deeper boreholes tend to yield more stable and cleaner water, they are more expensive to construct and maintain. Effective water safety requires appropriate casing, sealing and routine maintenance to prevent contamination and to ensure long– term functionality (Udongwo and Sambo, 2022).

In many communities, boreholes are drilled without adequate hydrogeological studies, environmental impact assessments or regulatory oversight (Oboh and Egun, 2017; Daffi et al., 2020). This has led to a fragmented approach to groundwater resource management, raising concerns about both water quality and sustainability. One major challenge facing borehole systems is the lack of regulation and coordination in their construction and management. Unregulated borehole drilling often results in over– extraction, rapid depletion of aquifers, and interference between closely situated boreholes, especially in densely populated or high– demand areas. Such practices place immense stress on groundwater reserves and can even cause inter– user conflicts. The absence of a coordinated monitoring framework for borehole placement and water extraction threatens the long– term viability of this critical resource (Dan– Hassan, 2017).

In addition to regulatory challenges, cost remains a significant barrier. Drilling boreholes, particularly deep ones require substantial financial investment, making them unaffordable for many low– income households without external support. Furthermore, borehole maintenance is frequently neglected. Faulty pumps, collapsed casings or contamination due to faulty sealing can render boreholes unusable, leading to water scarcity even in communities with substantial borehole infrastructure.

Compounding these issues is the general complacency surrounding groundwater safety. The assumption that it is always pure often results in a lack of routine water quality testing. Borehole water is commonly used directly for drinking and household purposes without prior testing or treatment. This is problematic, as contaminated borehole water while appearing clear and tasteless can harbor pathogens and toxins that result in severe health conditions, including waterborne diseases such as cholera and dysentery and long– term effects like organ damage or reproductive complications due to chemical toxicity (Udongwo and Sambo, 2022).

2.4 Importance of Borehole Water Supply System Monitoring and Management

A well– managed borehole water supply system requires more than just physical infrastructure, it demands a systematic framework for regular water quality testing, continuous monitoring and proper documentation. Unfortunately, many communities lack such frameworks, leaving them vulnerable to water contamination and inefficient resource use. Given the health and environmental risks associated with poorly managed boreholes, there is a pressing need for structured oversight that ensures boreholes are constructed to technical standards, regularly tested for safety and accurately tracked through consistent data records. GIS technology allows for the spatial mapping of borehole locations and the integration of both real– time and periodic water quality data and by combining spatial information with key water quality indicators (attribute data), such as pH levels, turbidity and the presence of contaminants, GIS provides a powerful visual and analytical tool to assess the status of groundwater resources.

Through this spatial visualization, decision– makers can identify trends and patterns in water quality across different areas, helping to detect pollution hotspots early and allocate resources more effectively. GIS also plays a crucial role in supporting regulatory bodies and public health planners by enabling them to prioritize interventions, monitor compliance with environmental standards, and improve communication with the public on water safety risks.

2.5 Water Quality Parameters

Water quality is a measure of the suitability of water for various purpose, in this study focusing on borehole water the main purpose is drinking. Water quality parameters are measurable characteristics of water that determine its quality. These parameters can be categorized as; physical, chemical and microbiological parameters. Other forms of classifications exist such as physiochemical, biochemical and radiological classification.

However, in this study the former classification is adopted and below is a table that summarizes the different water quality parameters into various categories for portable water.

Table 2.1: Classification of Water Quality Parameters

Physical Parameter	Chemical Parameter	Biological Parameter
Color	pH	Bacteria
Electrical Conductivity	Acidity	Algea
Odour	Alkalinity	Viruses
Taste	Calcium and magnesium	Protozoa
Temperature	Iron and manganese	Biological Oxygen Deman (BOD)
Turbidity	Copper	Total Coliform Count (TCC)
Total Solids (TS)	Zinc	
	Chloride	
	Fluoride	
	Nitrogen	
	Sulphate	

	Dissolved Oxygen (DO)	
	Chemical Oxygen Demand (COD)	

Source: (Spellman, 2017)

2.5.1 Physical Parameters

a. Color

Colour in water refers to the visible tint caused by dissolved or suspended substances. It can be caused by dissolved organic matter (humic and fulvic acids), the presence of metals either naturally occurring or as by– products of corrosion and leaching or from industrial effluents contaminating the water source. The source of colour in a drinking water supply should be investigated, particularly if a substantial change has taken place as the presence of colour in portable water reduces aesthetic appeal and by extension trust in the supply.

The presence of colour is measured Hazen units (HU) or True Colour Units (TCU) after filtration to remove suspended particles (APHA, 2017). There is no health– based guideline proposed for colour in portable water; however, majority of people can identify color in a glass of water over 15TCU (WHO, 2017).

Colour can be measured using visual comparison with platinum– cobalt scale, spectrophotometric analysis or colorimetric analysis. In cases of undesirable result, adsorption, filtration or Tannins anion exchange resins can be used as treatment methods.

b. Electrical Conductivity

Electrical Conductivity (EC) is a key water quality parameter that measures the ability of water to conduct an electric current, which reflects the concentration of dissolved ions such as salts, minerals and metals. High EC levels typically result from natural mineral dissolution, agricultural runoff, industrial discharges or seawater intrusion, while low EC may indicate soft water. Elevated EC can lead to undesirable salty taste, corrosion of plumbing systems and harm to aquatic ecosystems, though it is not directly linked to health risks. The World Health Organization (WHO) does not set a strict health– based limit but recommends keeping EC below 400 µS/cm for palatability, while the U.S. EPA considers 500 µS/cm an aesthetic guideline. Treatment methods such as reverse osmosis, distillation, and ion exchange are effective in reducing excessive conductivity.

c. Taste and Odour

Taste and Odour is an organoleptic parameter affecting water acceptability and can be caused by volatile organic or inorganic compounds. Common causes include algal blooms, chlorination byproducts, hydrogen sulfide and metallic ions from corroding pipes. Although unpleasant taste and odour are primarily aesthetic concerns, they can indicate underlying contamination, such as sewage leaks or chemical spills. The WHO emphasizes that drinking water should be free from objectionable taste or odour, while the U.S. EPA sets secondary standards for compounds like hydrogen sulfide (0.05 mg/L) and geosmin (10 ng/L). Treatment options include activated carbon filtration (for organic removal), aeration (to eliminate volatile compounds like H_2S), advanced oxidation (for algal toxin breakdown), and optimized disinfection to minimize chlorinous tastes. Unlike EC, taste and odour often require sensory evaluation or advanced analytical techniques like GC–

MS for precise identification. Both parameters are crucial for ensuring water acceptability and safety, even if their health impacts are generally indirect.

d. Temperature

Temperature refers to the hotness or coolness of a substance, in this case the substance being water. Borehole water temperature is influenced by the ambient subsurface conditions of the groundwater source including geothermal gradient and seasonal temperature variations. The temperature of any water source influences physical, chemical and biological processes and by extension the characteristics of water related to those processes. Temperature is said to be an essential determinant for the survival of most cellular microorganisms as their metabolic activities depend on it (Muhammed et al., 2023). Consequently, high water temperature enhances microbial growth and may influence the colour, odour, tastes and corrosivity of water. Although there are no strict guidelines for temperature limits of portable water by the WHO, cool water is generally more palatable than warm water and according to (SON, 2007) the standard temperature is ambient temperature. In Nigeria, the atmospheric temperature varies from 25°C – 35°C. Temperature of water is measured using a thermometer.

e. Turbidity

Turbidity describes the cloudiness of water caused by suspended particles such as clay and silt, chemical precipitates such as manganese and iron and organic particles such as debris and organisms (APHA et al., 2012). These particles contributing to turbidity provide attachment surfaces and nutrients for microbial organisms resulting in elevated E. coli and Total Coliform Count (TCC) (Oyaro et al., 2018). In essence, promoting microbial contamination of water and reducing the efficacy of water treatment techniques (Sorlini et al., 2018). This visible cloudiness is aesthetically unpleasant to consumers, even if chemically safe, the trust and usage of the public would be affected (WHO, 2017).

Turbidity is measured in Nephelometric Turbidity Units (NTU) and can be visibly observed by the naked human eyes at approximately greater than 4.0 NTU. Large municipal supplies should consistently produce water with no visible turbidity and should be able to always achieve 0.5 NTU before disinfection and average 0.2 NTU or less. According to (WHO, 2017), the acceptable guideline for turbidity limits in portable water is 0– 5 NTU which is also adopted by (SON, 2007).

Turbidity is measured using a turbidimeter or nephelometer, a device that measures that scattering and absorbing effect that suspended particles have on light. In cases where the quality of the tested water sample is not within the guidelines, water treatment techniques such as coagulation and flocculation, sedimentation and filtration can be implemented.

f. Total Solids (TS)

The Total Solids (TS) in water is a composite of the Total Suspended Solids (TSS) and the Total Dissolved Solids (TDS). TDS are the constituents which passes through 2.0 µm or less nominal pore size under specific conditions. Constituents of TSS in any given sample of water are retained by a filter with a 2 µm or less pore size measured by weighing the dried residue left on the filter (APHA, 2017).

The palatability of water with a TDS level of less than 600mg/l is generally considered to be good; drinking water becomes significantly and increasingly unpalatable at TDS levels greater than about 1000mg/l (WHO, 2017)

TS is measured in mg/l i.e., milligram of the solid substance in one liter of water sample. It can be measured using gravimetric analysis which involves the evaporation of a known volume of water.

2.5.2 Chemical Parameters

a. pH

In water quality assessments, pH is a critical variable affecting chemical stability and biological viability. pH is an expression of hydrogen ion concentration in water. Specifically, pH is the negative logarithm of hydrogen ion (H^+) concentration (mol/L) in an aqueous solution: $pH = -\log_{10}(H^+)$. This means one unit change in pH (e.g., a change from 7 to 6) indicates 10 times change in H^+ ion concentration in that solution.

The pH scale measures how acidic or basic a solution is. The scale ranges from 0 to 14. A pH of 7 is neutral, less than 7 is acidic and a pH greater than 7 is basic. Pure water is neutral at 25 degrees Celsius, with a pH of about 7.0, due to the presence of atmospheric carbon dioxide gas, normal rainfall has a pH of roughly 5.6, which is considered moderately acidic. At very high pH, metals tend to precipitate and water tend to have an unpleasant odour and taste while at low pH, solubility of metals tends to be high, chemicals like cyanide and sulfide become more toxic. Acidic waters also corrode metal pipes. Therefore, heavy metals in water with a low pH tend to be more toxic, as they become more soluble and bioavailable (Saalidong et al., 2022). This connotes that the pH of water entering the distribution system must be controlled to minimize corrosion of water mains and pipes in the household as well as for consumer satisfaction.

The optimum pH required will vary in different supplies according to the composition of the water and the nature of the construction materials used in the distribution system, but it is usually in the range 6.5–8.5 (WHO, 2017).

The measurement of pH value can be performed electrochemical methods such as glass electrodes and pH meters or colorimetric methods involving indicators. (Tiwari and Mahalpure, 2025).

b. Alkalinity

Alkalinity is related to the acid– neutralizing capacity (ANC) of a solution (US EPA, 2024). It is primarily due to the presence of bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), and hydroxide (OH^-) ions. Although basic solutions are alkaline, “basicity” and “alkalinity” are not the same. Basicity refers to the ratio of hydrogen and hydroxyl (OH^-) ions in solution and is directly related to pH.

Alkalinity originates from the dissolution of geological minerals (e.g. carbonates) and atmospheric CO_2. Surface or groundwater in limestone areas often exhibit high alkalinity. (Wilson, 2019). This implies that borehole alkalinity is linked to aquifer lithology (e.g. chalk, basalt) and soil interactions. High alkalinity in limestone– rich areas (e.g. Cretaceous chalk aquifers 5) contrasts with low alkalinity in base– poor regions (e.g., silty clay aquifers). Alkalinity buffers pH fluctuations, however excess alkalinity i.e. greater than500 mg/L $CaCO_3$ may cause scaling, reduce disinfection efficiency and alter metal bioavailability.

The determination of alkalinity is necessary to determine the amount of chemical substances (e.g. lime $Ca(OH)_2$) required for water softening. Although WHO does not give a strict limiting value for alkalinity of water, it recommends a value of pH between 6.5–

8.5 for drinking water. Hence high alkalinity, greater than 200mg/L $CaCO_3$) may affect the portability of the water. Alkalinity is determined by titration with a standard acid solution (H_2SO_4 of 0.02N) using indicators such as methyl orange to a pH end point of 4.5 or phenolphthalein to a pH end point of 8.3.

c. Acidity

Acidity refers to the capacity of water to neutralize bases, primarily due to the presence of free hydrogen ions (H^+), dissolved carbon dioxide (CO_2), and hydrolysable salts (e.g. Fe^{3+} and Al^{3+}). While pH measures H^+ activity, acidity assesses the proton– donating capability of water. It influences corrosivity and buffering capacity in borehole water by reflecting anthropogenic and geogenic acid inputs.

Natural acidity in groundwater arises from CO_2 dissolution from soil respiration, organic matter decay and sulfide mineral oxidation (e.g. pyrite) in aquifers. Anthropogenic sources include acid mine drainage, industrial effluents and acid rainfall (i.e. rainwater with pH less than 5.6) infiltrating recharge zones.

Acidic water reduces disinfection efficacy and increases solubility of heavy metals, posing health risks such as kidney damage. WHO recommends a pH range of 6.5–8.5 for drinking water. Acidity should not exceed 50 mg/l $CaCO_3$ to prevent corrosivity while pH is the primary indicator, acidity titration ensures compliance. Standard titration with 0.02N NaOH (strong base) to pH 8.3 (total acidity) or pH 4.5 (mineral acidity) using digital titrators or colorimetric indicators.

d. Cations

i. Calcium and Magnesium

Hardness is the measurement of divalent ions, such as calcium (Ca^{+2}), magnesium (Mg^{+2}), ferrous iron (Fe^{+2}), strontium (Sr^{+2}) and Manganous manganese (Mn^{+2}) (Boyd et al., 2016; Wurts, 2002). The most common causes of water hardness are calcium and magnesium ions. According to (Samie et al. 2013), the most common source of calcium and magnesium in groundwater is through the erosion of rocks, such as limestone and dolomite, and minerals, such as calcite and magnesite. Locally, anthropogenic sources like cement leaching or agricultural lime can raise calcium levels.

There are two types of water hardness: temporary and permanent hardness. Temporary hardness is caused by carbonates and bicarbonates and can be removed by boiling. On the other hand, permanent hardness is as a result of sulfates, chlorides or nitrates of calcium and magnesium. These remain soluble even after boiling and require ion exchange or chemical precipitation for removal.

Total hardness is quantified as the sum of Ca^{2+} and Mg^{2+} concentrations, typically measured by ethylene diamine tetra acid (EDTA) titration or atomic absorption spectroscopy (AAS), and expressed in mg/l of $CaCO_3$ equivalents.

Calcium concentrations up to and exceeding 100 mg/l are common in natural sources of water, particularly groundwater. Magnesium is present in natural groundwater usually at lower concentrations (from negligible to about 50 mg/l and rarely above 100 mg/l), so calcium– based hardness usually predominates groundwater (National Research Council, 1977).

Although the WHO has no strict standard for calcium and magnesium ion concentration, studies suggest that the concentration of Ca^{2+} ions should be within 75 – 200 mg/L as excessive calcium ions may cause kidney stones and reduce soap lathering, but deficiency increases pipe corrosion.

Table 2.2: Classification of Water Hardness

Water Classification	Total Hardness (in mg/L or ppm $CaCO_3$)
Soft	<75
Moderately hard	75– 150
Hard	150– 300
Very Hard	>300

Source: (US EPA, 1986)

ii. Iron and Manganese

Iron (Fe) and Manganese (Mn) are often derived from geological formations like basalt or dolomite in groundwater. Although neither metal is considered a direct health hazard and instead have secondary drinking standard as they cause aesthetic problems that make water undesirable (Penn State Extension, 2023).

Iron also promotes the growth of "iron bacteria", which derive their energy from the oxidation of ferrous iron to ferric iron and in the process deposit a slimy reddish– brown coating on the piping. At levels above 0.3 mg/l, iron stains laundry and plumbing fixtures

(WHO, 2017). There is usually no noticeable taste at iron concentrations below 0.3 mg/l, although turbidity and colour may develop. At levels exceeding 0.1 mg/l, manganese in water supplies may cause an undesirable taste in beverages and stains sanitary ware and laundry. Even at a concentration of 0.2 mg/l, manganese will often form a coating on pipes, which may slough off as a black precipitate. (WHO, 2017).

Both iron and manganese concentration can be measured using Atomic Absorption Spectroscopy (AAS) and colorimetric tests. Treatment strategies such as oxidation using chemical oxidants like chlorine and Potassium Permanganate ($KMnO_4$), filtration, ion exchange and aeration followed by sedimentation can be adopted when iron and manganese concentration are above desired range.

iii. Copper

Copper (Cu^{2+}) is both an essential micronutrient and a potential toxin, entering water systems through natural weathering of copper– bearing rocks (e.g., chalcopyrite) and anthropogenic activities like mining, industrial discharges and corrosion of copper plumbing (Manne et al. 2022; Briffa et al. 2020). High concentrations can interfere with the intended domestic uses of the water. Above 1mg/l, staining of sanitary ware and laundry may occur at copper concentrations and at levels above 5 mg/l, copper also imparts a colour and an undesirable bitter taste to water. Although copper can give rise to taste, it should be acceptable at the health– based guideline value of 2 mg/l (WHO, 2017).

High concentrations of copper (i.e. greater than 2 mg/day) may cause liver damage (Wilson’s disease) and neurotoxicity, while deficiency (i.e. less than 0.9 mg/day) is associated with hematological and skeletal abnormalities (Brewer, 2010). Similar methods of analysis can be used for iron and manganese can be adopted.

iv. Zinc

Zinc (Zn^{2+}) is an essential, trace element that can originate from natural weathering of minerals such as sphalerite and anthropogenic sources like industrial effluents, galvanized pipe corrosion and mining runoff. When boiling, zinc– containing water with concentrations ranging from 3 to 5 mg/l may turn opalescent and form a greasy coating. Despite the fact that zinc concentrations in drinking water are rarely higher than 0.1 mg/l, no health– based recommended value for zinc in drinking water has been established (WHO, 2017). Similar methods of analysis use for iron and manganese can be adopted.

v. Sodium

The main source of sodium (Na^+) in natural waterways is geological weathering (such as the breakdown of halite), seawater intrusion and man– made sources including industrial discharges and road salt. The taste threshold concentration of sodium in water depends on the associated anion and the temperature of the solution. At room temperature, the average taste threshold for sodium is about 200 mg/l. No health– based guideline value has been derived, as the contribution from drinking water to daily intake is small.

e. Anion

i. Chloride

Chloride (Cl^-) is the most prominent anon in natural water. Geological weathering, seawater percolation and anthropogenic activities like sewage and industrial effluents, urban runoff containing de– icing salt are sources of Chloride ion. Depending on the alkalinity of the water, high chloride concentrations cause the water to taste salty and excessively accelerate the rate at which metals in the distribution system corrode. Taste thresholds for the chloride anion depend on the associated cation and are in the range of 200–300 mg/l for sodium, potassium and calcium chloride, there is no health– based guideline value is proposed for chloride in drinking– water (WHO, 2017). However, chloride concentrations more than 250 mg/l can give rise to detectable taste in water.

Ion chromatography, silver nitrate titration and colorimetric methods may be used for the analysis of the concentration of this anion. In the case of excess concentration, Friedel's salt method and advanced oxidation are treatment technologies that have proven to be very effective.

ii. Fluoride

Fluorine (Fl^-) is a common element that is widely distributed in Earth's crust and exists in the form of fluorides in several minerals, such as fluorspar, cryolite and fluorapatite. Traces of fluorides are present in many waters, with higher concentrations often associated with groundwaters. In some countries, fluoride may also be added to drinking water to provide protection against dental caries. The amounts added to drinking water are such that final concentrations are usually between 0.5– 1mg/l. Where the intakes are likely to approach, or be greater than, 6 mg/day, it would be appropriate to consider setting a standard or local guideline at a concentration lower than 1.5 mg/l (WHO, 2017).

Fluoride concentration can be determined by means of an ion– selective electrode, which makes it possible to measure the total amount of free and complex– bound fluoride dissolved in water. The method can detect fluoride concentrations in water well below the guideline value. A range of treatment technologies are available for both large and small supplies, the various methods for small supplies that are favoured in different countries are: bone charcoal, contact precipitation, activated alumina and clay. However, in some areas with high natural fluoride levels in drinking– water, the guideline value may be difficult to achieve in some circumstances with the treatment technology available. Large supplies tend to rely on activated alumina or advanced treatment processes such as reverse osmosis.

iii. Sulfate

Water naturally contains sulfate, a polyatomic anion (SO_4^{2-}) made up of sulfur and oxygen, due to mineral dissolution, atmospheric deposition and microbiological activity. Sulfate has laxative effect in unacclimated infants at concentrations greater than 500mg/l, a bitter tase between 300– 400 mg/l and combines with chloride to accelerate pipe corrosion. Although there is no health– based guideline value for sulfate, at concentrations less than 250 mg/l, taste impairment is typically regarded as being minimal (WHO, 2017).

Reverse osmosis, ion exchange or biological treatment using sulfate reducing bacteria can be implemented as treatment strategies.

iv. Nitrogen

Nitrogen dissolves in water and can exist as ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-) and organic compounds (e.g., amino acids) in wastewaters (Wiesmann, 2005; Liu et al., 2024). The sources of nitrogen can be from atmospheric and organic matter deposition, fossil fuels and anthropogenic sources. Nitrogen in drinking has several impacts when excess in drinking water namely, methemoglobinemia ("blue baby syndrome") from excess nitrate (concentration greater than 10 mg/L) and ammonium toxicity (concentration greater than 1.5mg/l) which results in liver damage. The guidelines for nitrate and nitrite ion are 50mg/l and 3mg/l (WHO, 2017).

Nitrogen has traditionally been removed from wastewater by nitrification and denitrification processes, in which organic carbon has been used as an electron donor during denitrification, advanced methods like partial nitrification and autotrophic denitrification can employed (Kosgey et al., 2022).

f. Dissolved Oxygen

This refers to the concentration of molecular oxygen (O_2) dissolved in water critical for aerobic microbial activity and reduction– oxidation (redox) reactions in groundwater systems. It is measured in milligrams per liter of water (mg/l). Shallow aquifers typically have higher DO ranging from 2– 6 mg/l due to the atmospheric diffusion, while deep confined aquifers may approach 0mg/l. The permeability of the soil influences oxygen infiltration as cohesionless or granular soils are more permeable than cohesive or fine–grained soil. DO solubility decreases by 0.3mg/l per 1°C rise in water temperature.

g. Chemical Oxygen Demand (COD)

This is a measure of the oxygen equivalent required to chemically oxidize organic matter in water using strong oxidants like potassium dichromate ($K_2Cr_2O_7$) or potassium permanganate ($KMnO_4$) (APHA, 2018), It is a critical parameter in quantifying organic pollutants in water, although it is primarily used for wastewater it aids in detecting oxidizable inorganic compounds and organic contamination from natural and anthropogenic sources in drinking water.

Drinking water has low levels of COD, usually lower than 10mg/l as higher values indicate water pollution, as such the WHO does not have any strict guidelines for COD in portable water. High COD increases disinfectant demand.

Dichromate reflux and permanganate oxidation can be used to analyze the COD, alternative methods are spectrophotometry and electrochemical sensors. In a case where COD is too high, advanced oxidation processes or biological treatment involving activated sludge can be adopted as treatment strategies.

h. Biochemical Oxygen Demand (BOD)

This is a measure of the amount of oxygen required by microorganisms in water to fully oxidize the organic matter, usually waste present in a water sample. Time has an influence on BOD, since microorganisms consume more oxygen as time progresses. Five– day Biological Oxygen Demand (BOD_5) is the amount of dissolved oxygen (DO) required by microorganisms to decompose organic matter for a five– day period of time under aerobic conditions at 20°C and it is the water quality parameter tested for.

Drinking water ought to have a BOD_5 level lower than 2mg/l. It can be measured using Winkler method. In cases of high BOD_5, advanced oxidation or activated sludge can be used as treatment strategies.

2.5.3 Microbiological Parameters

a. Escherichia Coli (E. coli)

Naturally, Escherichia coli (E. coli) is a facultative anaerobic bacterium that inhabits the large gastrointestinal tracts of warm– blooded animals and is a major normal flora associated with the human colon (Odonkor and Mahami, 2020). Escherichia coli is considered the most suitable indicator of faecal contamination in water (WHO, 2017). Its presence in borehole water can be as a result of subsurface infiltration of contaminated water, especially during rainy seasons and poor maintenance of borehole water supply system facilities. Approximately 1.7 billion cases of childhood diarrhea occur each year, resulting to the death of approximately 525,000 children below the age of five (Yan et al., 2024). The presence of E. coli can result in diarrhea, urinary tract infections, haemolytic uremic syndrome, etc. According to (WHO, 2017) E. coli should not be detectable in any 100 mL sample of drinking water.

b. Total Coliforms

Total coliform bacteria include a wide range of aerobic and facultatively anaerobic, gram–negative, non– spore– forming bacilli capable of growing in the presence of relatively high concentrations of bile salts with the fermentation of lactose and production of acid or aldehyde within 24 hours at 35–37 °C (WHO, 2017). This broad group is used as a primary screening tool for water safety due to its ease of detection and correlation with sanitary conditions. Its presence can be due to surface water infiltration, leaking septic systems and poor maintenance of borehole water supply systems. Most total coliforms are harmless, their presence however indicates that disease– causing organisms (pathogens) could be in the water system including Salmonella, Giardia, and viruses. Detection of Enterococci is commonly conducted using membrane filtration with counts reported as colony forming units (CFU) per 100 mL or most probable number (MPN) per 100ml (APHA, 2017).

c. Enterococci (Faecal Streptococci)

Enterococci are gram– positive, facultative anaerobic bacteria that are commonly found in the intestines of mammals and birds. The occurrence of Enterococcus species in borehole water is frequently linked to infiltration from nearby pit latrines, animal enclosures, or agricultural activities, particularly where the protective casing of the borehole has been compromised. Although Enterococci themselves are not highly pathogenic, their presence is significant because they indicate faecal contamination and the potential presence of other enteric pathogens such as viruses and protozoa (Edokpayi et al., 2017). Detection of

Enterococci is commonly conducted using membrane filtration with counts reported as colony forming units (CFU) per 100 mL (APHA, 2017).

Table 2.3:Water Quality Standards for Drinking Water

Parameter	Unit	WHO Standard	NSDWQ
Colour	TCU	15	15
EC	µS/cm	400	1000
Temperature	˚C	ambient	ambient
Turbidity	NTU	0-5	5
TDS	mg/L	1000	500
pH	____	6.5-8.5	6.5-8.5
Calcium (Ca^{2+})	mg/L	____	____
Magnesium (Mg^{2+})		____	20
Hardness	mg/L of $CaCO_3$	____	150
Iron (Fe^{2+})	mg/L	0.3	0.3
Manganese (Mn^{2+})		0.1	0.2

Copper (Cu^{2+})	mg/L	2.0	1.0
Zinc (Zn^{2+})		____	3.0
Sodium (Na^{+})		____	200
Chloride (Cl^{-})		____	250
Fluoride (Fl^{-})		1.5	1.5
Sulphate (SO_4^{2-})		____	100
Ammonium (NH_4–N)		____	____
Nitrite (NO_2^{-})		3	0.2
Nitrate (NO_3^{-})		50	50
E. coli	CFU/mL	0	0
Total Coliforms	CFU/100mL	0	0
Total Heterotrophic Bacteria (THB)	CFU/mL	0	0

Source: (WHO, 2017 and SON, 2015)

2.6 Water Quality Index (WQI)

Water Quality Index (WQI) is a numerical tool used to assess and classify water quality by integrating multiple physicochemical and microbial parameters into a single score (APHA et al., 2012). It is a mathematical aggregate of various water quality parameters that provides a single numerical value indicating the overall water quality of any sample, a minimum of nine water quality parameters must be used (Brown et al., 1970). WQI simplifies complex water quality data into an easily interpretable format, typically ranging from 0 (best) to 100 (worst) (WHO, 2017) temperature, pH, turbidity, fecal coliform, dissolved oxygen, biochemical oxygen demand, total phosphates, nitrates and total solids.

The W**eighted Arithmetic WQI** is used in this study as it widely used in Nigeria in assessing groundwater quality as opposed to NSFWQI which is primarily for surface water assessment, the WAWQI method accommodates a broader range of parameters and aligns better with local environmental and hydrogeological conditions.

Table 2.4: Classification of Water Quality Index Using Weighted Arithmetic

WQI	Index Level	Grading	Possible usage
0– 25	Excellent	A	Drinking, irrigation, industrial
26– 50	Good	B	Domestic, irrigation, industrial
51– 75	Moderate	C	Irrigation, industrial

76– 100	Poor	D	Irrigation
>100	Very Poor	E	Proper treatment is required before use of any kind.

Source: (Chatterji and Raziuddin, 2002)

2.7 Geographic Information System (GIS)

Geographic Information System (GIS) is a computer– based system for capturing, storing, analyzing and displaying geospatial data (Chang, 2016). GIS establishes relationships between attribute and spatial data making it a powerful decision– making tool in various fields such as urban planning, environmental management, civil engineering, and public health (Chang, 2016). GIS has a “key index variable” feature that can link previously unconnected datasets thereby establishing a relationship. Locations and extents are typically recorded using coordinates: longitude (x), latitude (y), and elevation (z), as well as time stamps, enabling GIS to handle spatiotemporal analyses.

The distinction between a GIS system and the GIS software is necessary for clarity, the former refers to a comprehensive framework that integrates hardware, software, data, people and procedures to capture, store, analyze, and visualize geographic information., it includes the entire ecosystem for spatial data management, from collection to decision–making while the latter is a specific tool that enables users to perform GIS functions like mapping, spatial analysis, and data visualization, it is a component of a GIS system.

In engineering, GIS plays a vital role in improving planning, monitoring and management of natural and man– made systems. In regard to water quality management, especially borehole systems GIS supports data– driven planning, environmental protection and public health safety through its ability to analyze spatial patterns and trends.

2.8 Components of GIS

A fully functioning GIS system comprises five main components (Kufoniyi, 1998), these are:

a. Hardware: this refers to computer components and physical devices on which the GIS software operates. It is used to acquire, store, process and display data. This includes:

i. Data acquisition hardware such as Global Navigation Satellite System (GNSS), Unmanned Aerial Vehicles (UAV), Digital Image Processing System (DIP), etc. used for acquiring spatial data.
ii. Input devices such as keyboards and mouse used for logging spatial data collected.
iii. The host computer for data processing and analysis.
iv. Output devices such as graphic screen, printer, plotter etc. used for displaying input and processed data.
v. Storage devices such as hard drives, flash drives etc. for storing data.
vi. Servers are used for executing GIS applications via a network cloud.

b. Software: GIS software enables the manipulation and analysis of spatial data. Common GIS software includes ArcGIS, QGIS, and MapInfo. These platforms allow users to create, view and analyze maps and spatial relationships.

c. Spatial Database: This includes all geospatial and attribute data, relationship among these datasets, conventions and operations that help analyze the data sets used in GIS environment. Data may include satellite imagery, topographic maps, borehole coordinates, water test results, and demographic information.

i. Geospatial Data: These are data that are referenced to a specific location on the earth surface, describing both the locations and characteristics of spatial features on the earth's surface (e.g., the coordinates of a borehole, the length and direction of a road, or the boundaries of a watershed). GIS has the unique ability of processing geospatial data by integrating it with other datasets allowing advanced spatial analysis. These data are typically referenced using either a geographic coordinate system (longitude and latitude) or a projected coordinate system (x, y coordinates in a flat plane). A fundamental requirement in GIS is that all map layers must share the same spatial reference to ensure proper alignment. Geospatial data is represented in two primary formats: vector data (points, lines, polygons) for discrete features and raster data (grid cells) for continuous phenomena like elevation or temperature.
ii. Attribute data: these are the properties of spatial features (e.g., pH levels of borehole water, or land use classifications). These attributes are stored in a relational database management system (DBMS), organized as interconnected tables. The DBMS allows for efficient data manipulation, including adding, deleting, or updating records. A key feature is the ability to link tables through join operations (merging tables using a common identifier, such as a borehole ID) or relate operations (maintaining separate tables while establishing logical connections). GIS further enhances this capability with spatial joins, which associate features based on their geographic relationships (e.g., identifying all boreholes within 200 meters of a pollution source). Together, geospatial and attribute data form the backbone of GIS, enabling sophisticated mapping, analysis, and decision– making.

d. Procedures: These are the methods and workflows established to ensure GIS functions effectively. Procedures cover data collection protocols, analysis routines, data updating, and report generation.

e. Expertise (People): Trained personnel are essential for designing GIS systems, analyzing data, interpreting results, and applying findings to real– world problems. This includes GIS analysts, civil engineers, hydrologists, environmental scientists, and decision– makers.

2.9 Applications of GIS in Water Quality Management

Geographic Information Systems (GIS) have become indispensable tools for borehole water quality management, offering powerful capabilities for spatial analysis, visualization and decision support. GIS enables the integration of geospatial and attribute data to generate distributed water quality maps, track contamination sources, and predict pollution spread through advanced geostatistical models like kriging and DRASTIC indices (Abdelmonaim et al., 2024; Kanu et al., 2023). These applications are critical for ensuring safe drinking water, particularly in regions reliant on borehole systems. Below are key GIS operations in water quality management and their significance.

a. Database Querying and Spatial Analysis

GIS allows real– time querying databases to identify boreholes that are compliant or non–compliant as regards a specific criterion (e.g., those exceeding permissible nitrate levels or those located near industrial zones). Proximity analysis further assesses risks by buffering potential contaminant sources (e.g., septic tanks, landfills) and overlaying borehole locations (Eltarabily and Elshaarawy, 2023). This helps in identifying risky sites quickly and the likely cause of pollution.

b. Mapping and Visualization

GIS facilitates thematic mapping of water quality parameters (e.g., pH, turbidity, heavy metals) by visually representing compliance with WHO and NSDWQ standards (WHO, 2017; SON, 2007). Interpolation techniques like Inverse Distance Weighting (IDW) and Empirical Bayesian Kriging (EBK) create continuous surfaces from discrete borehole data, revealing spatial trends in contamination (Kanu et al., 2023; David, 2024). Such maps are vital for identifying high– risk zones, such as areas near industrial sites or waste dumps, where pollutants like nitrates or heavy metals exceed safe limits (Daffi et al., 2020).

c. Simulation and Predictive Modelling

GIS can be integrated with hydrological models to simulate groundwater flow and contaminant dispersion aiding long– term resource planning. DRASTIC models evaluate aquifer vulnerability by analyzing factors like soil permeability and recharge rates (Jaseela et al., 2016). Similarly, machine learning– GIS hybrids forecast water quality degradation, as seen in Saudi Arabia, where nitrate pollution was projected using historical data (El–Rawy et al., 2023). These tools empower policymakers to design targeted interventions, such as relocating boreholes or regulating land use.

d. Monitoring and Decision Support

GIS supports temporal monitoring by tracking water quality changes through repeated sampling. In Hungary, WebGIS platforms visualized decade– long contamination trends, revealing improvements post– sewerage installation (Balla et al., 2024). Such systems enhance transparency and stakeholder collaboration by providing accessible data to governments, NGOs and communities. Decision– makers leverage GIS to prioritize funding for high– risk areas, optimize infrastructure placement and enforce regulations thereby making key steps toward equitable water access (UNICEF, 2016).

In summary, GIS is a robust technology that can revolutionize how borehole water quality is monitored and managed. By integrating spatial and attribute data into a centralized decision– making platform, GIS supports better planning, risk mitigation, and sustainable water resource use. However, its successful application depends on addressing challenges related to funding, data access, technical capacity and institutional collaboration.

2.10 Previously Related Studies

Odeyemi et al., 2024 investigates the quality of borehole water, a critical resource for many communities in Nigeria. The study emphasizes the importance of clean drinking water for public health, particularly in developing countries where access to safe water is often limited. Borehole water is frequently perceived as safe; however, it may be contaminated due to various anthropogenic activities, including industrialization and poor sanitation practices. This context sets the stage for the study, which aims to assess the physicochemical, microbial and heavy metal contamination of borehole water in Ado Ekiti, addressing the urgent need for reliable water quality assessments in the region.

The scope of the research encompasses ten selected borehole locations within Ado Ekiti, utilizing standard procedures for water quality analysis. The results indicate that while most physicochemical parameters fell within the WHO permissible limits, microbial counts, including bacteria and fungi, exceeded these limits, suggesting potential health risks. Heavy metal analysis revealed that some samples contained metals like chromium and lead at levels above WHO guidelines, indicating further health hazards associated with water consumption. The discussion emphasizes the implications of these findings for public health and the necessity for improved water treatment practices and sanitation measures in the area. The study concludes borehole water in Ado Ekiti may not be safe for consumption without adequate treatment, urging for regular monitoring and better management of water resources to safeguard community health.

Oboh and Egun, 2017 provided a comprehensive examination of groundwater quality in proximity to a municipal dumpsite. The study highlights the critical role of groundwater as a primary source of drinking water for millions, particularly in rural areas of Nigeria, where it is often vulnerable to contamination from anthropogenic activities, including waste disposal practices. The authors emphasize that leachate from dumpsites poses significant risks to groundwater quality, necessitating thorough assessments to ensure public health safety.

The study aims to evaluate the suitability of groundwater for drinking and domestic use by analyzing various physical, chemical, and microbial parameters. The objectives include determining the concentrations of contaminants and assessing the Water Quality Index (WQI) to provide a clear indication of water quality across different borehole locations. The scope of the study encompasses four borehole sites in Agbor, with samples collected monthly over a six– month period. Results indicate that while some physicochemical parameters, such as pH and lead concentrations, were within acceptable limits, microbial contamination levels exceeded the standards set by the (NSDWQ) and the World Health Organization (WHO). The WQI values ranged from 4.15 to 5.54, indicating excellent water quality overall, but the presence of high microbial counts raised concerns about potential health risks associated with water consumption. In conclusion, although the groundwater in the study area generally meets the criteria for safe drinking water, the elevated microbial contamination necessitates improved public hygiene practices to mitigate health risks. They recommend regular monitoring of groundwater quality and the implementation of better waste management strategies to protect this vital resource from pollution. The study underscores the importance of safeguarding groundwater resources, particularly in areas adjacent to waste disposal sites, to ensure the health and well– being of local communities.

Kanu et al. 2023 assessed groundwater quality by analyzing groundwater contamination, lack of spatial analysis and health risks in Aba, Nigeria using the Water Quality Index (WQI) and comparing geostatistical GIS techniques such as Ordinary Kriging, Empirical Bayesian Kriging (EBK), Inverse Distance Weighting (IDW) and Spline interpolation methods in the spatial evaluation of variable concentrations using ArcGIS. The findings of this research showed that seasonal variations were evident with 100% of boreholes having WQI more than 100 during the dry season, this reduced to 87.5% during the rainy season due to dilution. GIS– generated maps highlighted pollution hotspots, showing higher WQI near dumpsites. Empirical Bayesian Kriging (EBK) outperformed other methods having a mean error of 0.372483, RMSE of 0.5515, and RMSSE of 1.030492 for the dry season and a mean error of 0.05625, RMSE of 10, and RMSSE of 0.986448 for the rainy season. proving GIS's precision in predicting water quality trends.

Correlation analysis used GIS to identify parameter relationships aiding pollution source tracking. The study demonstrated GIS's capacity to guide targeted interventions (e.g., monitoring near high– risk zones). It validated GIS as a tool for periodic quality assessments, crucial for your thesis on a "GIS– based decision system. The study concluded that groundwater in Aba is largely unfit for consumption, emphasizing the need for periodic monitoring.

Daffi et al. 2020 studied the groundwater quality in Vom community, Jos South, Plateau State, Nigeria. In this region, the primary source of water are hand– dug wells and shallow boreholes commonly located close to pit latrines and waste pits. The study focused on spatially visualizing and assessing eleven physical, microbiological and chemical parameters at six groundwater sampling points within a 22–100m radius of waste pits, providing insights into localized groundwater contamination dynamics. The chemical parameters in the samples tested met the WHO and NSDWQ limits except for pH which was slightly acidic for four samples. The findings indicated that E. coli was found in all the samples tested. This may be attributed to the proximity of the wells to pit latrines. A variation map of the results obtained from laboratory analyses was developed using ILWIS 3.8 software. The maps were classified based on their suitability for drinking and then overlaid in GIS to develop the groundwater quality information map where any point highlighted gives information on the parameters for that point.

Abdelmonaim et al. 2024, in arid and semi– arid regions such as the study area of Zagora region, South– East Morocco the primary source of water is groundwater, and the study implemented the use of Geographic Information Systems (GIS) and the Water Quality Index (WQI) to evaluate groundwater quality. GIS was used in visualizing and analyzing spatial data related to groundwater quality and through these trends and patterns not apparent to traditional methods were identified. Physiochemical analyses were conducted on nine wells with 12 monthly samples collected for a year (December 2020 – December 2021) measuring major cations/anions, TDS, turbidity and Water Quality Index (WQI) was conducted, as well as supplementary indices like SSP, SAR, PI, and KR. GIS– based spatial mapping (regression kriging) visualized seasonal water quality variation. The study found that dominant ions were Na^+, Mg^{2+}, Ca^{2+}; major anions were sulfate and chloride, the water quality declined significantly over time: from approximately 28.6% samples being “good” quality in 2020 to approximately 17.5% being “good” and up to 40% of drinking water samples became "unsuitable". Pollution was traced to nearby wastewater treatment facilities and mining activities, with stronger degradation in downstream areas. Elevated TDS, hardness, turbidity, and magnesium exceeded WHO limits in large proportions.

According to (David, 2024), the acquaintance on the manifestation of production boreholes, its replenishment and chemical distinctive have distinct significance where production boreholes are partially source of water used for domestics. The research sampled and analyzed production boreholes water quality parameters; pH, chloride, Iron, electrical conductivity and temperature from 26 production boreholes in Windhoek. Geostatistical analysis methods such as ordinary kriging interpolation and mapping of spatial distributions of water quality parameters were used. Ordinary kriging was applied to interpolate water quality parameters, leveraging spatial autocorrelation. Variogram models (e.g., spherical, exponential) were tested, with the best fit selected based on mean square error (MSE) and root mean square error (RMSE). hematic maps visualized parameter distributions (e.g., EC, chloride) against Namibian water quality guidelines. The findings indicated that most parameters (pH, EC, chloride, iron) met Group A (excellent quality) standards, except temperature in southwestern boreholes, which exceeded ambient levels (18–30°C), raising bacterial contamination risks and Kriging models achieved low prediction errors (e.g., RMSE ≈ average standard error), confirming reliability. Cross validation ensured unbiased estimates. The study recommended targeted monitoring of high– temperature zones and infrastructure near chloride sources to preempt contamination. The study exemplifies how GIS transforms sparse borehole data into spatially explicit insights, directly aligning with your thesis goal of a GIS– based DSS for water quality management.

Masood et al. 2022 focused on addressing the challenges of traditional groundwater monitoring using three methodologies: point– based measurements using geophysical techniques, satellite– based monitoring and numerical modelling. GIS was instrumental in integrating these diverse datasets, enabling spatial analysis and visualization of groundwater dynamics, techniques were used to process satellite data, validate groundwater potential zones, and create thematic maps for resource management. This aligns with your thesis, as GIS serves as a unifying platform for analyzing water quality data spatially and temporally.

The findings of this work justify the use of GIS and remote sensing as transformative tools for groundwater management as GIS facilitated the integration of GRACE satellite data with hydrological models (e.g., GLDAS, WGHM) to disaggregate terrestrial water storage components and assess groundwater anomalies. The study also highlights the utility of GIS in downscaling coarse– resolution satellite data using Artificial Neural Networks (ANN) and Analytical Hierarchy Process (AHP) to enhance local– scale accuracy. These findings underscore GIS's versatility in handling multi– source data, a capability equally vital for water quality management.

Balla et al. 2024 addressed the increasing groundwater contamination in the rural areas of Hungary where groundwater remains the primary source of drinking water for residents. In the research, forty municipal groundwater wells were routinely monitored from 2013 to 2022, to investigate changes in groundwater quality after the installation of a sewerage network. Most of the wells were categorized as contaminated and heavily contaminated, indicating an elevated level of contamination during the time prior to the sewerage network's installation (2014). This was determined by classifying the monitoring data into pollution categories based on the water quality index (WQI) and degree of contamination index (Cd). The chemical indicators examined (EC, NH_4^+, NO_2^-, NO_3^-, and PO_4^{3-}) showed a notable improvement over the monitoring period after the sewerage network was installed. With the aid of kriging techniques, the study generated precise contaminant distribution maps and the WebGIS platform provided easy public access to this information. The findings emphasized the utility of combining GIS, geostatistics, and web– based interfaces in monitoring and managing groundwater quality risks.

Eltarabily and Elshaarawy (2023) investigated the potential for groundwater contamination in the Central Valley Watershed of California, a region known for its extensive agricultural activities placing significant pressure on groundwater resources. The study was driven by the growing concerns about the infiltration of agricultural drainage water containing nitrates, pesticides, and other pollutants into aquifers that supply drinking and irrigation water. Integrating hydrogeological data, agricultural land use patterns and water quality parameters, GIS and geospatial modeling were used to evaluate spatial relationships and risk zones. Thereby examining distribution of potential contaminants, including nitrates, selenium, and pesticides, in relation to soil permeability, depth to water table and drainage infrastructure. According to the study, areas with shallow groundwater, extremely porous soils and extensive agricultural drainage techniques have the highest chance of contamination. The interaction between land use and hydrological elements to produce localized zones of high contamination potential was clearly depicted in the GIS–based risk maps. In these areas, nitrate levels were especially high and often exceeded drinking water guidelines set by the US EPA. The authors underlined that GIS was crucial for identifying priority locations for monitoring and repair as well as for displaying intricate environmental interactions.

Jaseela et al. 2016 conducted this study in response to increasing environmental and public health concerns about groundwater contamination from solid waste disposal sites. The research focused on the Muttom area in Kerala, India, where unscientific dumping of solid waste had raised alarm over leaching of contaminants into the aquifers. The research work applied the drastic model, a standardized method that evaluates groundwater vulnerability based on seven hydrogeological parameters such as depth to water table, net recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity and used ArcGIS 9.3 tools to spatially map and analyze vulnerability zones around the waste site. The GIS– DRASTIC model revealed that a significant portion of the area surrounding the waste disposal site fell within the moderate to high vulnerability zone. This result suggests that the groundwater near the waste site is at considerable risk of contamination due to the combination of shallow water tables, permeable soils, and high recharge rates. The study recommended immediate groundwater quality monitoring and better waste management practices to safeguard drinking water sources.

CHAPTER THREE: METHODOLOGY

3.1 Study Area

The water sample used for this research work was collected from 3 borehole water supply systems in University of Benin, Ovia North– East Local government Area, Benin City, Edo State, Nigeria.

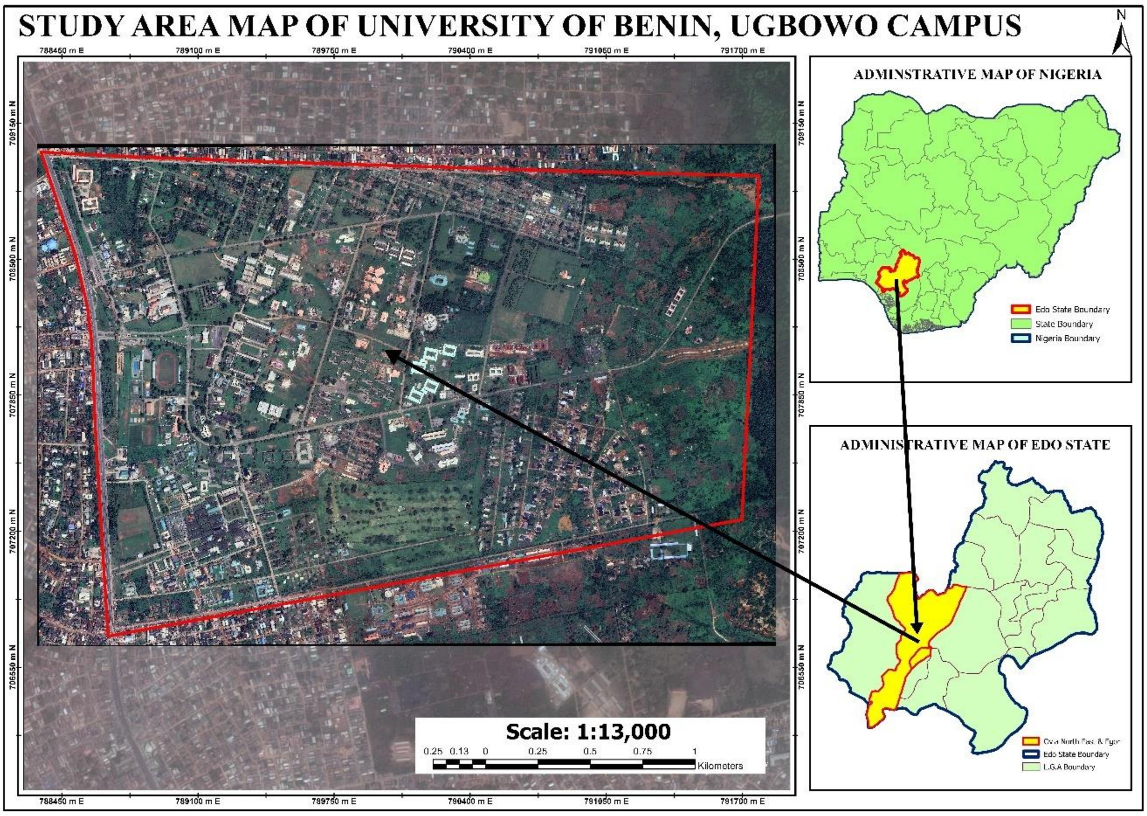

Figure 3.1: Study Area Map of University of Benin, Ugbowo Campus (Adapted from Google Earth)

3.2 Sample Collection and Geospatial Data Acquisition

Water samples were collected from three selected boreholes within Benin City, Edo State, representing different land-use categories. The sampling locations include:

Borehole A, located within an institutional zone (Faculty of Engineering);

Borehole B, situated within a hostel environment (Aminu Kano Hostel); and

Borehole C, located in a residential area characterized by moderate housing density and open surroundings (Blocks of Flats).

The geospatial locations of each borehole and their corresponding distribution points were determined using a Global Positioning System (GPS) navigation tool, the Coordinates App. The GPS readings were used to obtain the Universal Transverse Mercator (UTM) coordinates (Northing, Easting, and Zone) for each point. In addition, key environmental features within proximity to each borehole such as roads, septic tanks, storage tanks, vegetation cover and treatment facilities were recorded using the same GPS navigation tool and annotated for further GIS spatial analysis.

Each sampling location was coded for clarity and identification: Borehole A, Borehole B, and Borehole C represent the groundwater sources, while their respective distribution points were labelled Distribution A, Distribution B, and Distribution C. The straight-line distance between each borehole and its distribution point was measured using the GPS device to estimate the length of the water distribution pipeline and to evaluate the possibility of variances in water quality during conveyance.

For laboratory analysis, samples were collected using thoroughly washed and air-dried 750cm^3 plastic containers to prevent contamination. At each borehole location, two samples were collected: one directly from the source (borehole head) and another from the end of the distribution pipeline (consumer outlet). This dual-sampling approach was adopted to ascertain possible contamination along the distribution network and to compare the water quality between the groundwater source and the water supply system delivered to consumers.

3.3 Laboratory Analysis

After collection, the samples were securely sealed, preserved in plastic containers, and transported to the Marlet Environmental Research Laboratory Limited for physicochemical and microbiological analysis.

In order to determine the water quality of the boreholes in the study area, twenty (34) water quality parameters were performed in accordance with (APHA, 2017).

3.4 Physical Analysis

3.4.1 Determination of Colour

a. Apparatus

i. Spectrophotometer

ii. Cuvette

iii. Filter system

b. Procedure

Hazen or Platinum– Cobalt (Pt/Co) scale was applied using a spectrophotometer. The spectrophotometer was set to a standard of 455nm. The instrument was calibrated to zero using distilled water.

The filter was rinsed by pouring 50m^3 of the sample through it and discarding that water. Another 50m^3 was poured through the filter and 25m^3 of this filtered sampled water was used to fill a clean cuvette. The sample colour was read at 455nm. The colour of the samples was determined by using a spectrophotometer and recorded in as pt.co unit (PCU).

3.4.2 Determination of Electrical Conductivity

a. Apparatus

i. Conductivity meter (calibrated, temperature– compensated)

ii. Conductivity cell (platinum or graphite electrodes)

iii. Standard KCl solution (0.01 M, 1413 µS/cm at 25°C)

iv. Thermometer (if conductivity meter lacks automatic temperature compensation)

v. 100cm^3 Beakers

vi. Distilled Water

viii. lint– free wipe

b. Procedure

The conductivity cell was rinsed with distilled water, and the meter was calibrated to read in µS/cm using a standard potassium chloride (KCl) solution of 0.01M concentration having a conductivity of 1413µS/cm at 25°C.

The water sample was gently mixed to ensure uniformity; the cell was rinsed with distilled water and then filled with the sample water. The cell was immersed in the sample to ensure the electrodes were fully covered. The electrical conductivity (EC) and temperature reading was recorded after 10 seconds to ensure stability.

If the temperature is not at 25°C, a correction was applied using:

$$\mathrm{EC_{25}} = \mathrm{EC_t} \times [1 + 0.02 \times (\mathrm{t} - 25)] \qquad (3.1)$$

EC_{25} is the Electrical Conductivity at 25°C

EC_t is the Electrical Conductivity at t°C

t is the sample temperature in °C

3.4.3 Determination of Temperature

a. Apparatus

i. Mercury– in– glass thermometer

b. Procedure

The test was conducted at ambient temperature and the temperature of the water sample at the borehole, distribution point and laboratory was measured using a mercury– in– glass thermometer. The sample was in a thermally insulted container such as a thermoflask to prevent temperature drift. The thermometer was submerged in the sample by at least 10cm below the water surface for 2– 3 minutes for stabilization before reading was recorded in degree Celsius (°C) in one decimal place using an accuracy of ±0.1°C.

3.4.4 Determination of Turbidity

a. Apparatus

i. Nephelometer or turbidimeter

ii. Cuvettes

iii. Formazin

iv. Lint– free cloth

b. Procedure

The turbidity meter was calibrated using series of calibration standards by diluting formazin stock suspension to desired NTU levels of 0, 5, 10, 20, 40, 100 and 400 NTU. The cuvette was filled with each standard and placed in the turbidimeter to calibrate it.

The sample was stirred gently to distribute any settled particles and prevent creation of air bubbles, if large particles are present, they were decanted carefully to avoid affecting measurement readings.

The water sample was placed in a clean cuvette ensuring no air bubbles are formed. The exterior of the cuvette was wiped clean with a lint–free cloth to remove fingerprints and moisture before it was placed into the nephelometer. A stable reading of the turbidity was recorded after 10 to 20 seconds in Nephelometric Turbidity Unit (NTU).

3.4.5 Determination of Total Solids

a. Apparatus

i. Weighing balance (±0.1 mg sensitivity)

ii. Drying oven

iii. Desiccator

iv. Glass fiber filter

v. Filtration apparatus

vi. Evaporating dish

vii. Graduated cylinder

viii. Distilled water

ix. Wash bottle

x. Lint– free wipes

b. Procedure

The evaporating dish was cleaned, dried and placed in the drying oven at 103–105°C for at least 1 hour. It was allowed to cool in a desiccator at room temperature and weighed using a weighing balance with its weight recorded as W_1. The filter paper was placed on the filtration set up (flask and funnel) and washed using distilled water and then allowed to drain. It was oven dried at 103–105°C for 1 hour. It was allowed to cool in a desiccator at room temperature and weighed using a weighing balance with its weight recorded as W_2. The sample was shaken thoroughly and then filtered through the pre–weighed filter paper, to separate the dissolved solids and water (filtrate) from the suspended solids (residue).

A volume of $100cm^3$ of the filtrate was measured and placed in the pre–weighed evaporating dish. The dish was placed in a steam bath or hot plate at about 100°C until it is near–dry. After which, it was placed in the drying oven at 103–105°C for at least 1 hour. The dish was allowed to cool in a desiccator at room temperature and weighed using a weighing balance with its weight recorded as W_3. The TDS was computed in mg/l to the nearest whole number using:

$$TDS = \frac{W_3 - W_1}{\text{Volume of filtrate}} \qquad (3.2)$$

Where, TDS is the Total Dissolved Solids.

W_1 is the weight of the empty evaporating dish.

W_3 is the weight of the evaporating dish and oven dried filtrate.

The residue and filter paper was placed in the drying oven at 103–105°C for at least 1 hour and then allowed to cool in a desiccator at room temperature. The oven dried filter paper and residue was weighed using a weigh balance and the value read was recorded as W_4. The TSS was computed in mg/l to the nearest whole number using:

$$\mathrm{TSS} = \frac{W_4 - W_2}{\text{Volume of filtrate}} \tag{3.3}$$

Where, TSS is the Total Dissolved Solids.

W_2 is the weight of the filter paper.

W_4 is the weight of filter paper and oven dried residue.

The total solids (TS) was computed using:

$$\mathrm{TS} = \mathrm{TDS} + \mathrm{TSS} \tag{3.4}$$

Where, TS is the Total Solids

TDS is the Total Dissolved Solids

TSS is the Total Suspended Solids

3.5 Chemical Analysis

3.5.1 Determination of pH

a. Apparatus

i. pH meter (calibrated, with temperature compensation)

ii. Combination pH electrode (glass electrode + reference electrode)

iii. pH buffer solutions (pH 4.01, 7.01, and 10.01 at 25°C)

iv. Beakers

v. Stirring rod or magnetic stirrer

vi. Distilled water

vii. lint– free wipe

b. Procedure

The pH meter was turned on and allowed to stabilize for 30 minutes. It was calibrated using at least two standard buffer solutions. The electrode was rinsed with distilled water between buffer solutions to avoid contamination. The sample to be tested was placed in a beaker and temperature compensation was applied in the case of discrepancies between buffer and sample temperature. The electrode was immersed by 2cm ensuring the glass bulb and reference junction are fully submerged in the sample. The sample was stirred gently to ensure homogeneity without introducing air bubbles. At a stabilized reading the pH value was recorded.

3.5.2 Determination of Total Hardness

a. Apparatus

i. 50cm^3 Burette

ii. Pipette or measuring cylinder

iii. 250 cm^3 Conical (Erlenmeyer) flask

b. Reagents

i. 0.01 M Standard EDTA titrant

ii. Buffer solution (pH 10)

iii. Eriochrome Black T indicator

iv. Distilled water

c. Procedure

50cm^3 of the sample was measured into a clean conical flask and recorded as V_0. 2 cm^3 of the buffer solution of pH 10 was added to maintain pH condition of the reaction and about 2 drops of Eriochrome black T indicator was added. If hardness ions (Ca^{2+}or Mg^{2+}) are present, the solution will turn wine red and 0.01 M of ethylenediaminetetraacetic (EDTA) acid was used titrate the solution while stirring until the solution colour will change to blue. The volume of EDTA was recorded as V_1. This procedure was repeated using distilled water in place of the sample water and the volume of EDTA used was recorded as V_2.

The total hardness was calculated using:

$$\text{Total hardness (in mg/l of CaCO}_3\text{)} = \frac{(V_1 - V_2) \times M \times 50000}{V_0} \qquad (3.5)$$

Where, V_1 is the volume of the titrant used for titration of the water sample

V_2 is the volume of the titrant used for titration of distilled water

M is the molarity of EDTA solution to be used which is 0.01M

50,000 is the equivalent weight factor for $CaCO_3$

3.5.3 Determination of Sulfate

a. Apparatus

i. Nephelometer

ii. Beakers

iii. Volumetric Flasks

iv. Pipette

v. Magnetic Stirrer

b. Reagents

i. Barium chloride ($BaCl_2$) crystals

ii. Buffer solution composed of sodium chloride (NaCl), hydrocholoric acid (HCl) and glycerol

ii. Sulfate standard solution

iv. Distilled water

c. Procedure

The turbidimetric method was used. The calibration curve was prepared using a standard sulfate solution of 0– 100 mg/l prepared from the stock solution. 1cm^3 of the conditioning reagent composed of sodium chloride (NaCl), hydrocholoric acid (HCl) and glycerol were added to each standard. 0.5g of barium chloride ($BaCl_2$) crystals and stirred for 60 seconds at constant speed. The turbidity was measured at 420nm after 2 minutes when the reading stabilizes. The calibration curve of turbidity against sulfate concentration.

The sample was filtered using Whatman's filter paper and 50cm^3 of the filtrate sample was pipetted into a beaker. 1cm^3 of the conditioning reagent was added and stirred. 0.5g of $BaCl_2$ was added and stirred for 60 seconds. The turbidity was measured with a turbidity meter at 420nm. The sulfate concentration was determined from the calibration curve.

3.5.4 Determination of Nitrate

a. Apparatus

i. Spectrophotometer

ii. Cuvettes
iii. Volumetric flasks

iv. Pipettes
v. Distilled water

b. Reagents

i. Nitrate standard solution

ii. Sulfanilamide solution

iii. NED solution

iv. Distilled water

c. Procedure

Nitrate (No_3^-) was determined using the UV spectrophotometric method. Nitrate standard solutions were prepared. 1cm^3 of the buffer solution and 1cm^3 of sulfanilamide was added to each standard and then it was passed through cadmium column. 1cm^3 of NED was added and the solution was allowed to stand for 30 minutes for full colour development. The absorbance of each standard at 543nm was measured and the calibration curve was plotted. 50cm3 of the sample was measured and placed in a volumetric flask. The same procedure as the standards was applied, the absorbance was measured and the concentration of NO_3^- interpolated from the curve.

3.5.5 Determination of Nitrite

a. Apparatus

i. Spectrophotometer

ii. Volumetric flasks

iii. Cuvettes

iv. Pipettes

v. Whatman's filter paper (if necessary)

b. Reagents

i. Sulfanilamide solution (1% in 1.2 M HCl)

ii. NED solution (0.1%)

iii. Nitrite standard solution (100 mg/L NO_2^-)

c. Procedure

Nitrite concentration was measured using colorimetric diazotization. The calibration curve was prepared using nitrite standards (0, 0.1, 0.5, 1.0 mg/L NO_2^-). 1cm^3 sulfanilamide was added to each standard solution of nitrite, after 5 minutes, 1cm^3 of NED solution was added and a wait 10–30 min was observed for the color development. The absorbance was measured at 540nm and the calibration curve of the absorbance against sulfate concentration was plotted.

The sample was filtered through Whatman's Filter paper if turbid and then 50cm^3 of the filtrate was treated with reagents as above. The nitrite concentration was recorded from the calibration curve as mg/l NO_2^-.

If dilution was done a dilution factor was applied using:

$$\text{Nitrite (mg/l } NO_2^-) = \text{Result from curve} \times \text{Dilution factor} \quad (3.6)$$

3.5.6 Determination of COD

a. Apparatus

i. Reflux apparatus with condenser (or digestion vials with heating block for closed reflux)
ii. 50cm^3 Burette

iii. Volumetric flasks

iv. Pipettes
v. Hot plate

b. Reagents

i. Standard potassium dichromate solution (0.0417M of $K_2Cr_2O_7$)

ii. Concentrated sulfuric acid (H_2SO_4) with silver sulfate (Ag_2SO_4) catalyst

iii. Mercuric sulfate ($HgSO_4$)

iv. Standard ferrous ammonium sulfate (FAS) titrant (0.1 N)

v. Ferroin indicator

vi. Distilled or deionized water

vii. Standard COD solutions (potassium hydrogen phthalate for calibration)

c. Procedure

50cm^3 of the sample was measured into a conical flask, 1g of $HgSO_4$ and 5 mL H_2SO_4– Ag_2SO_4 reagent was added and mixed before 25cm^3 of 0.0417M of $K_2Cr_2O_7$ was added. A reflux greaseless condenser was attached, and the compound was heated gently for 2 hours and allowed to cool at room temperature. The excess dichromate was titrated using FAS and ferroin as indicators. The end point was a change of colour from bluish green to reddish brown.

A blank determination was performed with 50cm^3 of distilled water in place of the water sample and the procedure was repeated.

The Chemical Oxygen Deman was calculated using:

$$\text{COD (in mg/l)} = \frac{(V_A - V_B) \times M \times 8000}{\text{Volume of sample}} \tag{3.7}$$

Where, V_A is the volume of FAS used for the blank

V_B is the volume of FAS used for the sample

M is the molarity of FAS

8000 is the equivalent weight of oxygen × 1000

3.5.7 Determination of Chloride

a. Apparatus

i. Burette

ii. Pipette or measuring cylinder

iii. Conical flask (250 mL)

iv. White porcelain or plastic titration dish (to help visualize endpoint)

b. Reagents

i. Standard silver nitrate ($AgNO_3$) titrant

ii. Potassium chromate indicator solution (K_2CrO)

iii. Distilled water
iv. Standard sodium chloride solution

c. Procedure

The concentration of chloride was determined by argentometric titration, that is the reaction of chloride ions with silver nitrate ($AgNO_3$) of 0.0141M. 50cm^3 of the sample was pipetted into a conical flask and 1cm^3 of Potassium chromate indicator solution (K_2CrO) was added. The solution was titrated using AgNO3 until a reddish–brown precipitate of (Ag_2CrO_4) was formed.

$$\mathrm{Cl^-(in\ mg/l\,)} = \frac{\mathrm{V_{AgNO_3}\times M\times 35.45\times 1000}}{\text{Volume of sample}} \quad (3.8)$$

Where, $\mathrm{V_{AgNO_3}}$ is the volume of silver nitrate used

M is the molarity of $AgNO_3$

Atomic weight of chlorine is 35.35

3.5.8 Determination of Ammonium Nitrogen

a. Apparatus

i. Spectrophotometer or colorimeter — capable of reading at 640–660 nm

ii. Volumetric flasks, pipettes, conical flasks

iii. Glass– stoppered bottles or tubes

b. Reagents

i. Alkaline phenol solution
ii. Sodium hypochlorite solution (chlorinating solution)

iii. Sodium nitroprusside solution

iv. Ammonium standard solution

v. Distilled water

c. Procedure

The concentration of ammonium nitrogen was determined by phenate method. 50cm^3 of the sample was pipetted into a volumetric flask, 1cm^3 each of sodium nitroprusside solution, alkaline phenol and hypochlorite solutions was successively and then mixed thoroughly. The compound was allowed to stand at room temperature until the colour development is complete. The absorbance was measured at 640nm and compared to the calibration curve prepared with ammonium standards processed identically.

3.5.9 Determination of Heavy Metals

a. Apparatus

i. Atomic Absorption Spectrophotometer (AAS)
ii. Hot plate or digestion block
iii. Volumetric flasks

iv. Beakers

v. Pipette

vi. Graduated cylinders

b. Procedure

Heavy metals such as arsenic, mercury, chromium, copper, zinc and nickel were determined by atomic absorption spectrometry (AAS).

The water sample was acidified to a pH lower than 2 with nitric acid (HNO_3) using about 2cm^3 of HNO3 per m^3 of sample. 100cm^3 of the sample was placed in a digestion flask and heated gently until the volume reduces and the solution clears.

Using standard solutions, the flame AAS was calibrated, and the absorbance of each metal was measured and recorded. The metal concentration was determined from the calibration curve in mg/l.

Table 3.1: Wavelength for different metals using the AAS machine

Element	Wavelength (nm)	Lamp Current (mA)
Cadmium (Cd)	228.8	8
Chromium (Cr)	357.8	10
Copper (Cu)	324.8	5
Iron (Fe)	248.3	15
Lead (Pb)	217.0	10
Manganese (Mn)	279.5	12
Nickel (Ni)	232.0	15
Zinc (Zn)	213.9	10
Calcium (Ca)	422.7	10
Potassium (K)	766.5	8
Sodium (Na)	589.0	8
Magnesium)	285.2	4

Source: (Rakshit, 2016)

3.6 Microbiological Analysis

3.6.1 Determination of Total Heterotrophic Bacterial Count (THBC)

The total heterotrophic bacterial population in each water sample was determined using the pour plate technique on Nutrient Agar (NA). 1cm^3 of each sample serially diluted up to 10^{-4} using sterile distilled water to reduce bacterial density for accurate colony counting. 1cm^3 aliquot from appropriate dilutions was transferred aseptically into sterile petri dishes and about 20cm^3 of molten (45°C) Nutrient Agar was poured into each plate. The plates were gently rotated to ensure uniform distribution and allowed to solidify. Incubation was carried out at 37°C for 24–48 hours. After incubation, visible colonies were counted using a digital colony counter. Plates with 30–300 colonies were selected, and the Total Heterotrophic Bacterial Count (CFU/mL) was calculated as:

$$\mathrm{THBC}\left(\frac{\mathrm{CFU}}{\mathrm{ml}}\right)=\frac{\text{Number of colonies}\times\text{Dilution factor}}{\text{Volume of sample plated (ml)}} \tag{3.9}$$

3.6.2 Determination of Total *Escherichia coli* Count (TEC)

Water samples from positive EMB plates were streaked onto Eosin Methylene Blue Agar (EMB) and incubated at 44.5°C for 24 hours. Colonies showing green metallic sheen were recorded as *E. coli*. Typical *E. coli* colonies were sub-cultured onto Nutrient Agar for purification and further biochemical confirmation. Confirmatory tests were carried out using Indole and Methyl Red test. The *E. coli* isolates typically showed positive for Indole and Methyl Red.

3.6.3 Tentative Identification and Storage of Isolates

Distinct bacterial colonies from the different agar plates were sub-cultured on freshly prepared Nutrient Agar plates for purification and isolation of pure cultures. Pure isolates were transferred to Nutrient Agar slants and stored at 4°C for further biochemical and morphological identification. Identification was based on Gram staining, colony morphology, and standard biochemical tests.

3.6.4 Determination of Total Coliform Count (TCC)

The most probable number (MPN) technique was used for the isolation and enumeration of total coliforms. The media used was McConkey broth for the presumptive test and Eosin Methylene Blue (EMB) agar for the complete test, it was incubated at 37°C for 24 hours. Results were taken by referring to MPN statistical table and visual counts of bacterial colonies on the plates. Pink mucoid colonies were counted as total coliforms.

The number of positive tubes in each dilution set was compared to the MPN table to estimate total coliforms per 100 mL of water.

3.7 Water Quality Index Model

The WQI was calculated using the Weighted Arithmetic Index Method based on 10 water quality parameters.

Firstly, the relative parameter weightage (W_i) was calculated using the given formula:

$$W_i = \frac{K}{S_i} \tag{3.10}$$

Where, W_i is the relative parameter weightage

S_i is the standard permissible value of ith parameter.

K is the constant of proportionality; it was calculated using the formula:

$$K = \frac{1}{\Sigma(^1/_{S_i})} \tag{3.11}$$

The quality rating scale (Qi) which is a value that reflects the relative value of the given parameter in the water sample referring to its permissible standard value was computed using:

$$Q_i = \frac{V_i - V_o}{S_I - V_o} \times 100 \tag{3.12}$$

Where, Q_i is the quality rating scale of ith parameter,

V_i is the estimated permissible value of the ith parameter

V_o is the ideal value of the ith parameter.

All the values of V_o was taken as 0 for the drinking water, except for pH and DO which are 7.0 and 40 mg/l.

The water quality index was computed using:

$$WQI = \frac{\Sigma(Q_i \times w_i)}{\Sigma(w_i)} \tag{3.13}$$

3.8 Application GIS Techniques in Data Analysis

A spatial analysis framework was developed in ArcGIS Pro to visualize and analyze the spatial variation of borehole water quality parameters. The approach involved the use of georeferenced base maps and individual shapefiles. This method provided flexibility for layer editing, attribute linking, and spatial querying of both field and laboratory data.

a. Georeferencing of Base Map

A satellite imagery of the study area was imported into ArcGIS Pro and georeferenced to ensure accurate spatial alignment. The coordinate system was set to the Universal Transverse Mercator (UTM), WGS 1984, Zone 31N, which corresponds to the geographic location of Benin City, Edo State. Control points were established by matching identifiable ground features (such as road intersections and landmarks) on the image to their corresponding GPS coordinates collected during fieldwork. The root mean square (RMS) error was maintained below 3 meters to ensure high spatial accuracy. After successful alignment, the georeferenced image served as the base map upon which all other spatial layers were overlaid.

b. Creation of Shapefiles

Shapefiles were created for each spatial feature to allow simpler data management and direct attribute linkage. Point shapefiles were created for the boreholes and distribution points, using the GPS coordinates recorded during field sampling. Additional polygon and polyline shapefiles were generated for administrative boundaries, drainage networks, roads and land-use features to provide environmental context for spatial analysis. Each shapefile was projected to WGS 1984 UTM Zone 31N to maintain consistency with the base map.

c. Integration of Attribute Data

Laboratory results obtained for the physicochemical and microbiological parameters were compiled in Microsoft Excel and saved as CSV files. The data were then imported into ArcGIS and linked to the spatial shapefiles via a common attribute field (sample ID). Colour, Electrical Conductivity (EC), Temperature, Turbidity, Total Solids (TS), pH, Alkalinity, Total Hardness, Sulphate, Nitrate, Nitrite, Chloride, Fluoride, Biochemical Oxygen Demand (BOD_5), Ammonium Nitrogen, Heavy Metals (Fe, Zn, Cu, Pb), Total Bacterial Count, Total Coliform Count (TCC), Fungal Count, and the computed Water Quality Index (WQI).

d. Spatial Classification and Analysis

The attribute data were analyzed using GIS classification and query tools to assess compliance with the NSDWQ (2015) and WHO (2022) guidelines. Each parameter was classified into three quality categories: safe, marginal, and hazardous. Thematic maps were generated using graduated color symbology to illustrate the spatial distribution of WQI, iron concentration, turbidity, and nitrate levels. The classification enabled the identification of contamination hotspots and areas requiring intervention.

e. Visualization and Interpretation

Color gradients and proportional symbols were applied to represent varying concentration levels. Spatial overlays and buffering techniques (e.g., 150 m buffer zones) were used to evaluate the influence of nearby features such as septic tanks on groundwater quality.

The final thematic maps were exported at 300 dpi resolution the spatial relationships between borehole locations, water quality variation, and anthropogenic activities.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Spatial location of borehole source and distribution outlets

Table 4.1: Spatial location of boreholes and their respective distribution points

Location	Geographical Coordinates (in degrees)	Universal Transverse Mercator (UTM)		
		Rectangular Coordinates		Zone
		Northing (m)	Easting (m)	
Borehole Point A	6.403124, 5.616680	708504.6	789465.4	31N, North of equator
Borehole Point B	6.397143, 5.620774	707845.1	789922	31N, North of equator
Borehole Point C	6.404281, 5.631697	708641.2	791127.2	31N, North of equator
Distribution Point A	6.403271, 5.616252	708520.7	789418	31N, North of equator

Distribution Point B	6.397180, 5.620911	707849.3	789937.2	31N, North of equator
Distribution Point C	6.404460, 5.631767	7078661	791134.8	31N, North of equator

Table 4.1 presents the geographic coordinates of the three selected boreholes and their corresponding distribution points in Benin City, Edo State. This spatial referencing enabled accurate positioning of each borehole and the assessment of their proximity to potential contamination sources such as septic tanks, roads, and residential areas.

Borehole A is located in an institutional zone and lies adjacent to a minor road. The surrounding area is moderately vegetated, which may reduce surface runoff but also hinder easy access for maintenance. The distribution point, located about 50 meters and N70.77˚W of the borehole, lies along a slightly elevated terrain, reducing the likelihood of contamination from surface water flow. The proximity to a septic tank (located 6 meters from the borehole head) however, remains a potential source of microbial infiltration, especially during heavy rainfall.

Borehole B is located within the hostel premises, a densely populated area with high domestic water usage and frequent water discharge and has a treatment facility attached to the storage tank. This feature is notable, as it provides an additional stage for water quality improvement before distribution. The surrounding environment is partly built-up, with moderate vegetation cover that may provide some filtration benefits. The distribution point is approximately 16 meters N75.69˚E of the borehole and located near residential buildings. Given the treatment system in place, Borehole B is expected to exhibit better microbial and physicochemical water quality compared to other sites.

Borehole C is in a residential area characterized by moderate housing density and open surroundings. Its open environment suggests minimal anthropogenic influence, which may reflect in lower contaminant levels. The distribution point, located about 21 meters and N20.83˚E of the borehole, serves a smaller community cluster and is positioned on slightly sloping ground that enhances drainage. The surrounding area is densely vegetated, which may reduce surface runoff but also hinder easy access for maintenance. The proximity to a septic tank (located 19 meters from the borehole head) however, remains a potential source of microbial infiltration, especially during heavy rainfall.

The borehole sources and outlets are all connected with polyvinyl chloride (PVC) pipes.

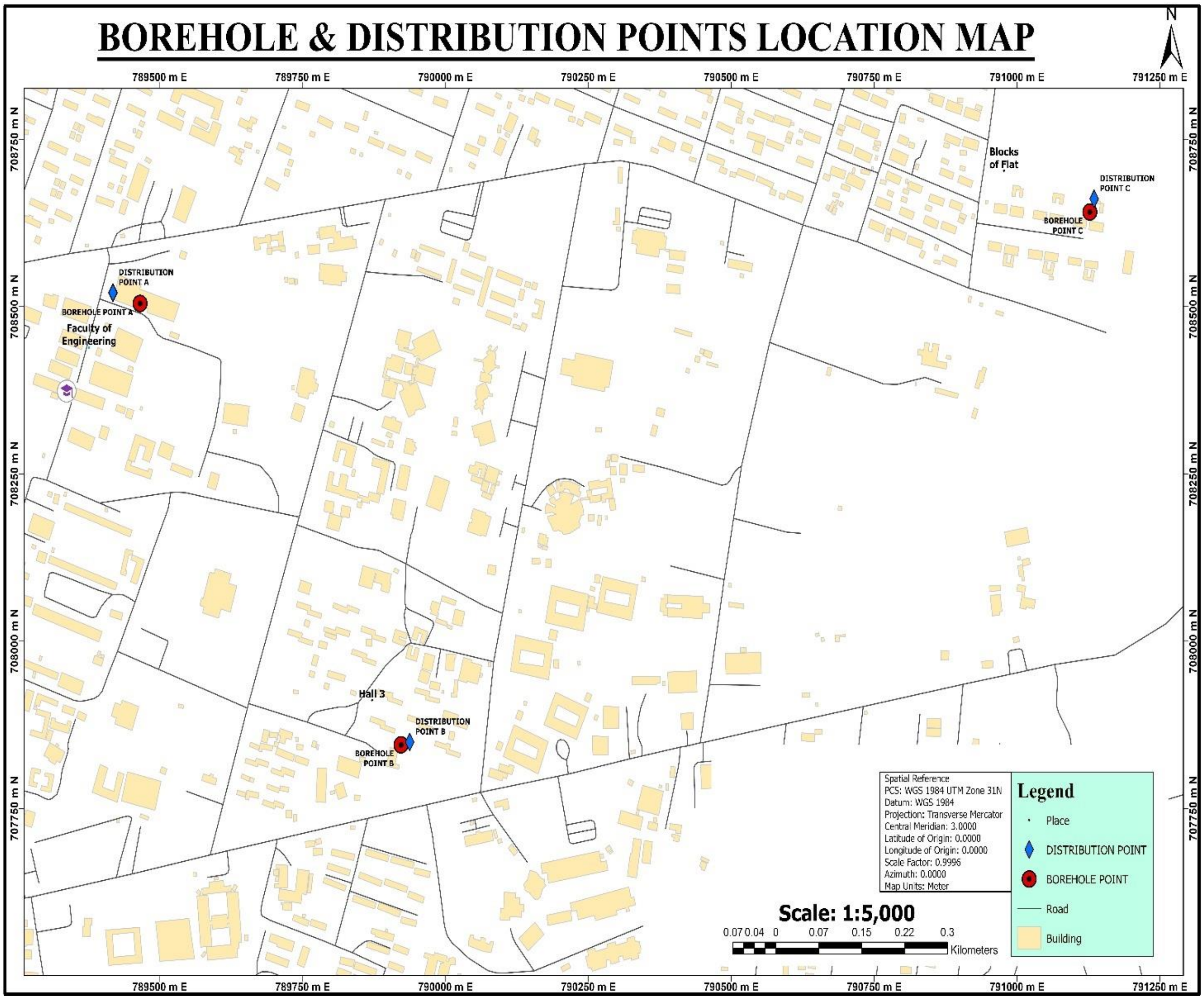

Figure 4.1: Borehole and Distribution Points Location Map (Adapted from Google Earth)

Figure 4.1 presents the spatial distribution of the boreholes A, B, and C as well as their corresponding distribution points within the study area in Benin City, Edo State. It provides a spatial framework that aids visualization of the relative distances between boreholes and distribution outlets, as well as their proximity to potential contamination sources such as roads, drainage channels, and septic tanks. The map also guided subsequent spatial analyses, including buffer creation and thematic mapping, allowing for a better understanding of how location and surrounding features influence borehole water quality.

4.2 Discussion of Physio-Chemical results

A total of 34 physicochemical and microbial parameters were analyzed for borehole and distribution point water samples from three selected locations in the University of Benin, Benin City (Table 4.1). The results were compared with the World Health Organization (WHO, 2017) and Nigerian Standard for Drinking Water Quality (SON, 2015) to assess compliance and potential risks to public health.

Table 4.2: Result of Physio-Chemical and Microbial Analysis

S/N	PARAMETER	STANDARD UNIT		BOREHOLE POINT A	BOREHOLE POINT B	BOREHOLE POINT C	DISTRIBUTION POINT A	DISTRIBUTION POINT B	DISTRIBUTION POINT C
		COORDINATES (in degrees)		6.403124, 5.616680	6.397143, 5.620774	6.404281, 5.631697	6.403271, 5.616252	6.397180, 5.620911	6.404460, 5.631767
			NORTHING (m)	708504.6	707845.1	708641.2	708520.7	707849.3	7078661

		UTM	EASTING (m)	789465.4	789922	791127.2	789418	789937.2	791134.8
			ZONE	31N, North of equator	31N, North of equator	31N, North of equator	31N, North of equator	31N, North of equator	31N, North of equator
1	pH			6	4.8	5.6	5.2	4.8	5.3
2	EC	µS/cm		301	305	112	110	192	118
3	Salinity	g/l		0.136	0.137	0.051	0.05	0.085	0.053
4	Colour	Pt.Co		ND	ND	ND	ND	ND	ND
5	Turbidity	NTU		3.95	3.5	3.81	4.04	3.48	3.41

6	TSS	mg/l	ND	ND	ND	ND	ND	ND
7	TDS		151	153	58	56	98	60
8	COD		12	16.6	6.3	6	10.3	7.4
9	HCO_3		53.3	61	36.2	17.3	28.1	20.1
10	Na		1.14	1.36	0.61	0.55	0.59	0.57
11	K		0.4	0.48	0.21	0.19	0.21	0.2
12	Ca		6.01	7.14	3.2	2.87	3.11	3.01
13	Mg		3.37	4	1.79	1.61	1.74	1.69

14	Cl	mg/l	51.2	61.3	44.2	18.4	22.7	17.3
15	P		0.074	0.087	0.035	0.021	0.033	0.018
16	NH_4N		0.086	0.111	0.06	0.033	0.041	0.021
17	NO_2		0.004	0.005	0.003	0.002	0.002	0.001
18	NO_3		0.038	0.049	0.026	0.015	0.018	0.009
19	SO_4		0.014	0.019	0.01	0.006	0.007	0.004
20	Fe		0.222	0.21	0.275	0.311	0.301	0.327
21	Mn		0.048	0.045	0.059	0.067	0.064	0.07

22	Zn	mg/l	0.113	0.107	0.14	0.159	0.154	0.167
23	Cu		0.018	0.017	0.022	0.025	0.024	0.026
24	Cr		ND	ND	ND	ND	ND	ND
25	Cd		ND	ND	ND	ND	ND	ND
26	Ni		ND	ND	ND	ND	ND	ND
27	Pb		ND	ND	ND	ND	ND	ND
28	V		ND	ND	ND	ND	ND	ND
29	THC		ND	ND	ND	ND	ND	ND

30	Hardness	mg/l of $CaCO_3$	28.9	37.6	15.4	13.8	14.9	14.5
31	Total Heterotrophic Bacterial Counts	CFU/mL	0×10^3	10×10^3	0×10^3	10×10^3	0×10^3	0.327
32	Total Coliform Counts		0×10^3	0×10^3	0×10^3	0×10^3	0×10^3	0.07
33	Total E.Coli Counts		0×10^3	0×10^3	0×10^3	0×10^3	0×10^3	0.167
34	Tentative Isolates	mg/l	*Nil*	*Nil*	*Nil*	*Nil*	*Nil*	0.026

4.2.1 Physical parameters

The pH values ranged from 4.8 to 6.0 in the boreholes and 4.8 to 5.3 at distribution points, indicating slightly acidic conditions below the WHO and NSDWQ acceptable range of 6.5 to 8.5. This acidity may be attributed to the natural geochemical composition of the aquifer and possible infiltration of organic matter from nearby septic systems, particularly around Boreholes A and C. The consistently low pH across sites suggests the water may cause mild corrosion in pipes and metallic fittings if untreated.

The turbidity values ranged from 3.48 to 4.04 NTU all falling within WHO and NSDWQ permissible limit of 0-5 NTU for drinking water.

Electrical conductivity (EC) values varied between 110 to 305 μS/cm, well below the WHO and NSDWQ limit of 400 μS/cm and 1000 μS/cm respectively, indicating low dissolved ionic content and minimal salinity impact. However, slight variations in EC among boreholes reflect differences in groundwater mineralization due to local geological composition.

TDS values ranged from 56 mg/L to 153 mg/L, falling within the WHO and NSDWQ guidelines of 1000 mg/L and 500mg/L respectively for potable water, signifying good palatability and low mineralization. All TSS values were reported as non-detectable (ND), implying clear water samples free of visible suspended matter. These results indicate effective natural filtration through soil layers before groundwater recharge.

4.2.2 Chemical parameters

a. Major Ions and Nutrients

Concentrations of major cations such as Calcium ranged from 2.87 to 7.14 mg/L and Magnesium from 1.61 to 4.00 mg/L were relatively low, consistent with soft water classification (hardness < 60 mg/L as $CaCO_3$). The low hardness values of 13.8 to 37.6 mg/L confirm that the water is soft and unlikely to cause scaling in pipes.

Chloride spanned from 17.3 to 61.3 mg/L, Sulphate from 0.014 to 0.019 mg/L, Nitrite from 0.001 to 0.005 mg/L, Nitrate from 0.038 to 0.049 mg/L, levels were all within WHO permissible limits (NO_2^- <3 mg/L ; NO_3^- <50 mg/L) and NSDWQ guideline (Cl^- <250 mg/L; SO_4^{2-} <200 mg/L; NO_2^- <0.2 mg/L; NO_3^- <50 mg/L). This indicates limited influence of domestic sewage or fertilizer leaching on the groundwater system.

Ammonium and nitrite levels were also minimal, suggesting low microbial nitrification activity in the subsurface

b. Heavy Metals

The concentrations of iron (Fe) ranged from 0.210 to 0.327 mg/L, with the boreholes approaching but not exceeding the WHO and NSDWQ limit of 0.3 mg/L an the distribution points exceeding the limit. The slight increase in iron at distribution points may result from mild pipe corrosion or oxidation processes during storage.

Manganese (Mn) values 0.045 to 0.070 mg/L and zinc (Zn) 0.107 to 0.167 mg/L were all within acceptable limits WHO: Mn <0.1 mg/L, NSDWQ: Mn <0.2 mg/L and Zn <3.0mg/L. Copper (Cu) levels of 0.017 to 0.026 mg/L were far below the WHO and NSDWQ limits of 2.0 mg/L and 1.0 mg/L, while toxic heavy metals such as cadmium (Cd), lead (Pb), nickel (Ni), and chromium (Cr) were not detected (ND), confirming the absence of industrial contamination.

4.2.3 Microbiological Parameters

Microbiological results revealed that total heterotrophic bacterial counts were present in Borehole B and some distribution points (A and C) at 10 × 10^3 CFU/mL, while all samples tested negative for coliforms and E. coli, indicating the absence of fecal contamination.

The presence of heterotrophic bacteria without coliforms suggests environmental or pipe-biofilm origins rather than direct sewage intrusion. The detection at distribution points A and C may be due to stagnation or insufficient disinfection.

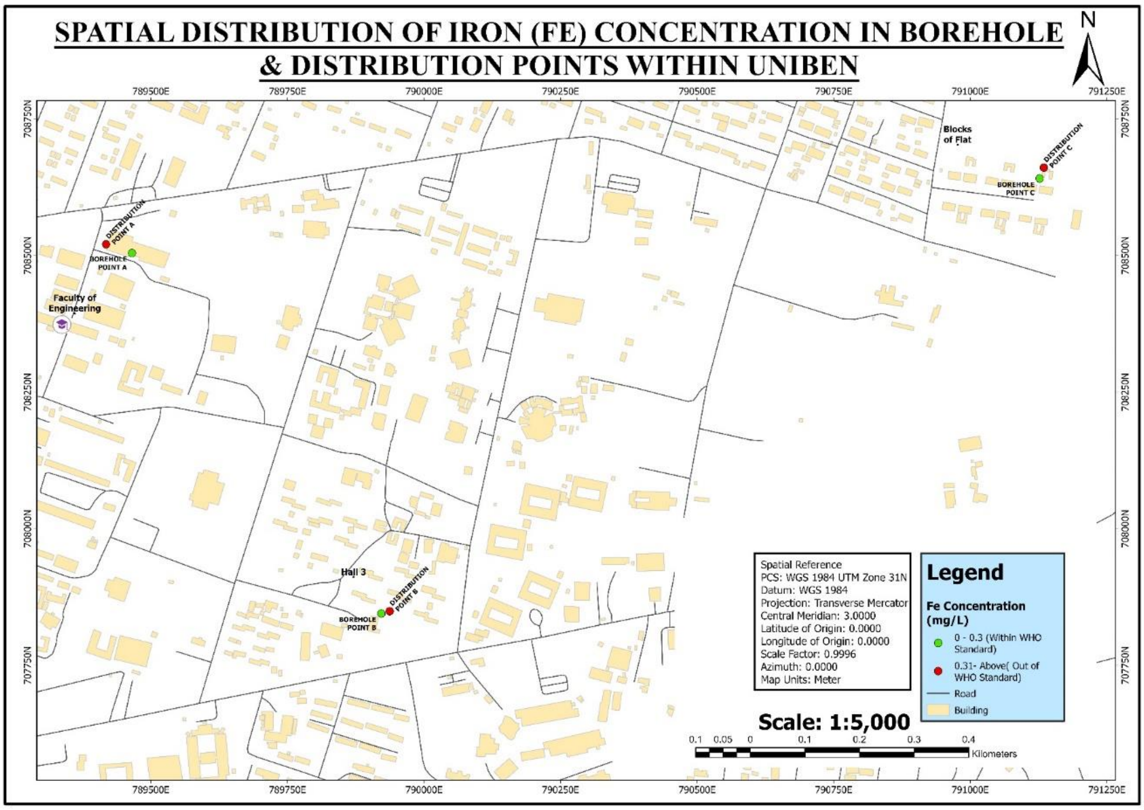

Figure 4.2: Spatial distribution of Iron concentration in borehole and distribution points (Adapted from Google Earth)

Figure 4.2 presents the spatial distribution of iron (Fe) concentration across the three boreholes and their corresponding distribution points within the study area. The map was produced through spatial interpolation in GIS using the Inverse Distance Weighted (IDW) method to visualize the concentration gradients and identify zones with potential iron contamination.

The results indicate that iron concentrations across all samples ranged from 0.210 mg/L to 0.327 mg/L, with values generally higher at the distribution points compared to the borehole sources. The WHO (2017) and NSDWQ (2015) recommend an aesthetic limit of 0.3 mg/L for iron to prevent taste, staining and color issues. Based on this guideline, most borehole samples were within or marginally below the permissible limit, while two distribution points (A and C) slightly exceeded this threshold, indicating potential water quality deterioration during storage and distribution.

Spatially, the GIS map reveals a progressive increase in iron concentration from the institutional zone (Borehole A) toward the residential zone (Borehole C). The lowest iron concentrations (0.21 mg/L) occurred near Borehole B within the hostel area, likely due to the presence of a treatment facility that reduces metal accumulation. Conversely, Borehole A and its distribution point, located near a septic tank and along a minor road, recorded slightly higher iron values 0.222 mg/L and 0.311 mg/L respectively, which may result from oxidation or metal leaching in the distribution system.

The residential zone (Borehole C) showed the highest iron levels 0.275 mg/L at the borehole and 0.327 mg/L at the distribution point, possibly due to a combination of naturally iron-rich soils, low pH (acidic) conditions and subsurface infiltration from nearby septic tanks. Acidic pH enhances the solubility of iron, explaining the slightly elevated concentrations observed in this area. These findings align with those of Daffi et al. (2020)

and Oboh and Egun (2017), who reported similar iron enrichment in boreholes located near waste disposal systems and lateritic soil formations.

The GIS visualization further highlights localized hotspots of high iron concentration, particularly around Borehole C and its immediate surroundings, suggesting that natural geochemistry and anthropogenic influence both contribute to spatial variability. The interpolated surface gradient demonstrates that iron mobility increases along drainage paths and low-lying zones, emphasizing the role of hydrogeological flow direction in trace metal transport.

Overall, the spatial distribution map serves as an important diagnostic tool for identifying areas where aesthetic water quality may be compromised. Regular flushing of storage tanks, periodic maintenance of pipelines, and pH adjustment at source points are recommended to prevent further accumulation of iron and ensure compliance with drinking water standards.

4.3 Water Quality Index (WQI) Analysis and Interpretation

The calculated WQI values for the borehole sources and their respective distribution outlets ranged from 57.30 to 98.80, falling into grades of C to E (i.e., moderate to very poor) reflecting variations in the combined influence of physicochemical parameters such as EC, turbidity, TDS, pH, iron, zinc, copper, chloride and nitrate concentrations, and E.*coli* due to spatial variations in groundwater quality influenced by environmental setting, distance between borehole and distribution points and the presence of infrastructure such as septic tanks and treatment facilities.

Borehole A, located within the Faculty of Engineering complex, recorded a WQI of 61.27, classifying it as moderate quality water. The relatively high WQI reflects slightly acidic pH value of 6.0 which increase the cumulative WQI score. The borehole lies adjacent to a minor road and within 6 m of a septic tank, conditions that make it susceptible to both surface runoff and possible subsurface infiltration of leachates, particularly during heavy rainfall events.

The distribution point A recorded an even higher WQI of 82.79, falling into the 'poor quality' category. This deterioration from source to outlet may be attributed to microbial regrowth or accumulation of metal ions during water conveyance, possibly due to corrosion within the pipe network. The short separation distance of 50 m (N70.77°W) between the borehole and outlet increases the likelihood of short-circuit contamination if the network is poorly sealed.

In terms of usage, Borehole A water is unsuitable for direct domestic consumption without treatment but may be used for non-potable purposes such as irrigation, car washing or industrial cooling, following WHO (2017).

Borehole B, situated within the hostel premises, yielded a WQI of 57.30, also within the moderate quality range but notably lower (better) than Borehole A and C.

The distribution point located 16 m away (N75.69°E), recorded a WQI of 79.64, indicating poor quality. This suggests that while the treatment unit effectively stabilizes source water, contamination may occur during storage or distribution. Given the dense population of the hostel and high frequency of water use, biofilm formation or microbial regrowth within pipes may have contributed to the deterioration. The presence of residual heterotrophic bacteria, even in the absence of *E.coli*, supports this inference. Consequently, Borehole B water is suitable for domestic use after mild disinfection or pH adjustment, and safe for irrigation and industrial applications.

Borehole C, located within a residential neighborhood characterized by moderate housing density and open surroundings, recorded the highest borehole WQI of 73.94, categorized as poor quality. Despite minimal anthropogenic activities, the presence of a septic tank 19 m from the borehole head and dense vegetation cover may have contributed to organic matter infiltration and acidity. The measured pH of 4.9, slightly elevated iron of 0.31 mg/L and nitrate of 0.049 mg/L levels reflect this influence.

The distribution point C exhibited the highest WQI value of 98.80 among all samples, signifying very poor-quality water. This indicates significant deterioration during conveyance, likely due to poor storage conditions, pipe corrosion or contamination from environmental exposure near the outlet. The distance of 21 m N20.83°E from the borehole and the presence of vegetation and slope-induced runoff may have increased the risk of contamination during rainfall.

Therefore, Borehole C water is unsuitable for drinking without treatment but may still be utilized for flushing, cleaning, or limited irrigation after appropriate pH correction.

Table 4.3: WQI Computation for Borehole A

S/N	Paramter	S_i	$\frac{1}{Si}$	$K = \frac{1}{\sum\left(\frac{1}{S_i}\right)}$	$W_i = \frac{K}{S_i}$	V_i	V_O	$V_i - V_O$	$S_i - V_O$	$Q_i = \frac{V_i - V_O}{S_i - V_O} \times 100$	$Q_i \times W_i$	$WQI = \frac{\sum(Q_i \times W_i)}{\sum(W_i)}$
1	Electrical Conductivity	400	0.0025	0.219876	0.00055	301	7	294	393	74.80916031	0.0411219	61.2704888
2	Turbidity	5	0.2	0.219876	0.04398	3.95	0	3.95	5	79	3.4740408	
3	Total Dissolved Solids	1000	0.001	0.219876	0.00022	151	0	151	1000	15.1	0.0033201	
4	pH	6.5	0.15385	0.219876	0.03383	6	0	6	6.5	92.30769231	3.1224994	
5	Iron (Fe)	0.3	3.33333	0.219876	0.73292	0.222	0	0.222	0.3	74	54.23608	
6	Zinc (Zn)	3	0.33333	0.219876	0.07329	0.113	0	0.113	3	3.766666667	0.2760665	
7	Copper (Cu)	2	0.5	0.219876	0.10994	0.018	0	0.018	2	0.9	0.0989442	
8	Chloride (Cl)	250	0.004	0.219876	0.00088	51.2	0	51.2	250	20.48	0.0180122	
9	Nitrate	50	0.02	0.219876	0.0044	0.038	0	0.038	50	0.076	0.0003342	
10	E.*Coli*	0	0	0.219876	0	0	0	0	0	0	0	
$\sum$			4.54801		1						61.270419	

Table 4.4: WQI Computation for Borehole B

S/N	Paramter	S_i	$\frac{1}{Si}$	$K = \frac{1}{\sum\left(\frac{1}{S_i}\right)}$	$W_i = \frac{K}{S_i}$	V_i	V_O	$V_i - V_O$	$S_i - V_O$	$Q_i = \frac{V_i - V_O}{S_i - V_O} \times 100$	$Q_i \times W_i$	$WQI = \frac{\sum(Q_i \times W_i)}{\sum(W_i)}$
1	Electrical Conductivity	400	0.0025	0.219876	0.00055	305	7	298	393	75.82697201	0.0416814	57.30262573
2	Turbidity	5	0.2	0.219876	0.04398	3.5	0	3.5	5	70	3.078264	
3	Total Dissolved Solids	1000	0.001	0.219876	0.00022	153	0	153	1000	15.3	0.0033641	
4	pH	6.5	0.15385	0.219876	0.03383	4.8	0	4.8	6.5	73.84615385	2.4979995	
5	Iron (Fe)	0.3	3.33333	0.219876	0.73292	0.21	0	0.21	0.3	70	51.3044	
6	Zinc (Zn)	3	0.33333	0.219876	0.07329	0.107	0	0.107	3	3.566666667	0.2614081	
7	Copper (Cu)	2	0.5	0.219876	0.10994	0.017	0	0.017	2	0.85	0.0934473	
8	Chloride (Cl)	250	0.004	0.219876	0.00088	61.3	0	61.3	250	24.52	0.0215654	
9	Nitrate	50	0.02	0.219876	0.0044	0.049	0	0.049	50	0.098	0.000431	
10	E.*Coli*	0	0	0.219876	0	0	0	0	0	0	0	
$\sum$			4.54801		1						57.302561	

Table 4.5: WQI Computation for Borehole C

S/N	Paramter	S_i	$\frac{1}{Si}$	$K = \frac{1}{\sum\left(\frac{1}{S_i}\right)}$	$W_i = \frac{K}{S_i}$	V_i	V_O	$V_i - V_O$	$S_i - V_O$	$Q_i = \frac{V_i - V_O}{S_i - V_O} \times 100$	$Q_i \times W_i$	$WQI = \frac{\sum(Q_i \times W_i)}{\sum(W_i)}$
1	Electrical Conductivity	400	0.0025	0.219876	0.00055	112	7	105	393	26.71755725	0.0146864	73.9443612
2	Turbidity	5	0.2	0.219876	0.04398	3.81	0	3.81	5	76.2	3.3509102	
3	Total Dissolved Solids	1000	0.001	0.219876	0.00022	58	0	58	1000	5.8	0.0012753	
4	pH	6.5	0.15385	0.219876	0.03383	5.6	0	5.6	6.5	86.15384615	2.9143328	
5	Iron (Fe)	0.3	3.33333	0.219876	0.73292	0.275	0	0.275	0.3	91.66666667	67.184333	
6	Zinc (Zn)	3	0.33333	0.219876	0.07329	0.14	0	0.14	3	4.666666667	0.3420293	
7	Copper (Cu)	2	0.5	0.219876	0.10994	0.022	0	0.022	2	1.1	0.1209318	
8	Chloride (Cl)	250	0.004	0.219876	0.00088	44.2	0	44.2	250	17.68	0.0155496	
9	Nitrate	50	0.02	0.219876	0.0044	0.026	0	0.026	50	0.052	0.0002287	
10	E.*Coli*	0	0	0.219876	0	0	0	0	0	0	0	
$\sum$			4.54801		1						73.944277	

Table 4.6: WQI Computation for Distribution A

S/N	Paramter	S_i	$\frac{1}{Si}$	$K = \frac{1}{\sum\left(\frac{1}{S_i}\right)}$	$W_i = \frac{K}{S_i}$	V_i	V_O	$V_i - V_O$	$S_i - V_O$	$Q_i = \frac{V_i - V_O}{S_i - V_O} \times 100$	$Q_i \times W_i$	$WQI = \frac{\sum(Q_i \times W_i)}{\sum(W_i)}$
1	Electrical Conductivity	400	0.0025	0.219876	0.00055	110	7	103	393	26.2086514	0.0144066	82.78694253
2	Turbidity	5	0.2	0.219876	0.04398	4.04	0	4.04	5	80.8	3.5531962	
3	Total Dissolved Solids	1000	0.001	0.219876	0.00022	56	0	56	1000	5.6	0.0012313	
4	pH	6.5	0.15385	0.219876	0.03383	5.2	0	5.2	6.5	80	2.7061662	
5	Iron (Fe)	0.3	3.33333	0.219876	0.73292	0.311	0	0.311	0.3	103.6666667	75.979373	
6	Zinc (Zn)	3	0.33333	0.219876	0.07329	0.159	0	0.159	3	5.3	0.3884476	
7	Copper (Cu)	2	0.5	0.219876	0.10994	0.025	0	0.025	2	1.25	0.1374225	
8	Chloride (Cl)	250	0.004	0.219876	0.00088	18.4	0	18.4	250	7.36	0.0064731	
9	Nitrate	50	0.02	0.219876	0.0044	0.015	0	0.015	50	0.03	0.0001319	
10	E.*Coli*	0	0	0.219876	0	0	0	0	0	0	0	
∑			4.54801		1						82.786849	

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Table 4.7: WQI Computation for Distribution B

S/N	Paramter	S_i	$\frac{1}{Si}$	$K = \frac{1}{\sum\left(\frac{1}{S_i}\right)}$	$W_i = \frac{K}{S_i}$	V_i	V_O	$V_i - V_O$	$S_i - V_O$	$Q_i = \frac{V_i - V_O}{S_i - V_O} \times 100$	$Q_i \times W_i$	$WQI = \frac{\sum(Q_i \times W_i)}{\sum(W_i)}$
1	Electrical Conductivity	400	0.0025	0.219876	0.00055	192	7	185	393	47.07379135	0.025876	79.63957908
2	Turbidity	5	0.2	0.219876	0.04398	3.48	0	3.48	5	69.6	3.0606739	
3	Total Dissolved Solids	1000	0.001	0.219876	0.00022	98	0	98	1000	9.8	0.0021548	
4	pH	6.5	0.15385	0.219876	0.03383	4.8	0	4.8	6.5	73.84615385	2.4979995	
5	Iron (Fe)	0.3	3.33333	0.219876	0.73292	0.301	0	0.301	0.3	100.3333333	73.536307	
6	Zinc (Zn)	3	0.33333	0.219876	0.07329	0.154	0	0.154	3	5.133333333	0.3762323	
7	Copper (Cu)	2	0.5	0.219876	0.10994	0.024	0	0.024	2	1.2	0.1319256	
8	Chloride (Cl-)	250	0.004	0.219876	0.00088	22.7	0	22.7	250	9.08	0.0079859	
9	Nitrate	50	0.02	0.219876	0.0044	0.038	0	0.038	50	0.076	0.0003342	
10	E.*Coli*	0	0	0.219876	0	0	0	0	0	0	0	
∑			4.54801		1						79.639489	

Table 4.8: WQI Computation for Distribution C

S/N	Paramter	S_i	$\frac{1}{Si}$	$K = \frac{1}{\sum\left(\frac{1}{S_i}\right)}$	$W_i = \frac{K}{S_i}$	V_i	V_O	$V_i - V_O$	$S_i - V_O$	$Q_i = \frac{V_i - V_O}{S_i - V_O} \times 100$	$Q_i \times W_i$	$WQI = \frac{\sum(Q_i \times W_i)}{\sum(W_i)}$
1	Electrical Conductivity	400	0.0025	0.219876	0.00055	118	7	111	393	28.24427481	0.0155256	98.80273475
2	Turbidity	5	0.2	0.219876	0.04398	3.41	0	3.41	5	68.2	2.9991086	
3	Total Dissolved Solids	1000	0.001	0.219876	0.00022	60	0	60	1000	6	0.0013193	
4	pH	6.5	0.15385	0.219876	0.03383	5.3	0	5.3	6.5	81.53846154	2.7582078	
5	Iron (Fe)	0.3	3.33333	0.219876	0.73292	0.327	0	0.327	0.3	109	79.88828	
6	Zinc (Zn)	3	0.33333	0.219876	0.026	0.167	0	0.167	3	5.566666667	0.1447333	
7	Copper (Cu)	2	0.5	0.219876	0.026	0.018	0	0.018	2	0.9	0.0234	
8	Chloride (Cl-)	250	0.004	0.219876	0.00088	17.3	0	17.3	250	6.92	0.0060862	
9	Nitrate	50	0.02	0.219876	0.0044	0.009	0	0.009	50	0.018	7.916E-05	
10	E.*Coli*	0	0	0.219876	0	0	0	0	0	0	0	
∑			4.54801		0.86877						85.83674	

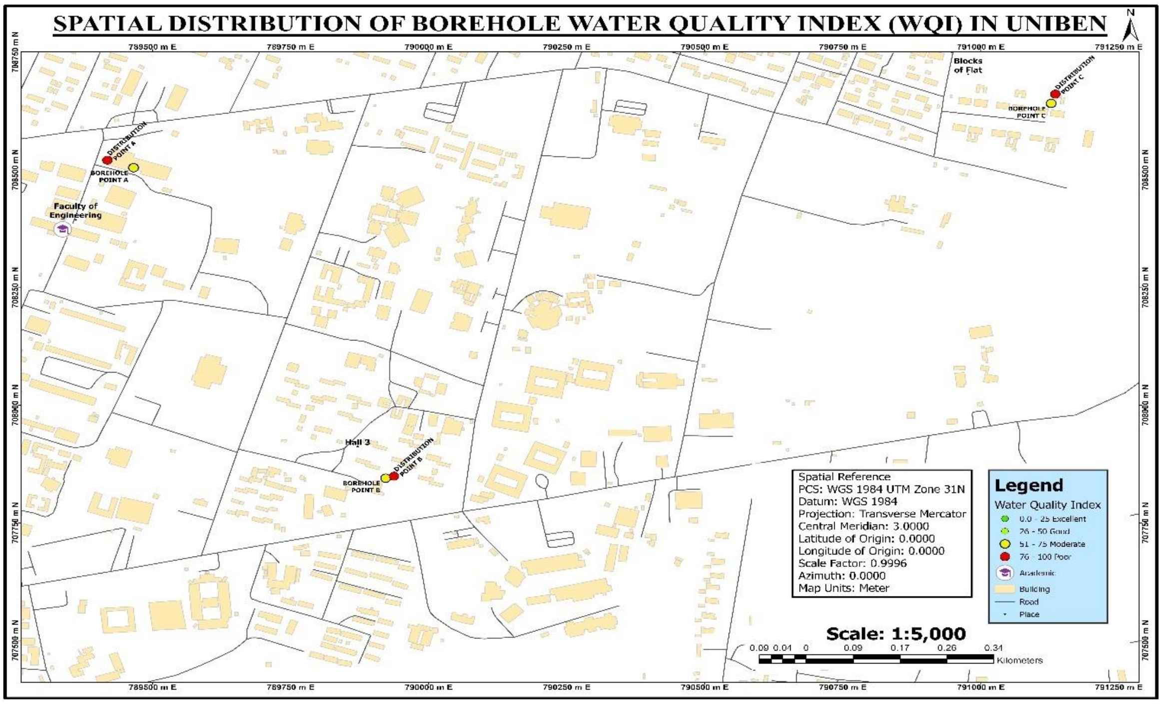

Figure 4.3: Spatial Distribution of Borehole Water Quality Index (Adapted from Google Earth)

Figure 4.3 illustrates the spatial distribution of WQI values across the study area, showing a gradual deterioration in water quality from institutional to residential settings. The shorter distances between boreholes and distribution points (ranging from 16–50 m) did not prevent degradation, suggesting that the quality loss is less a function of distance and more influenced by infrastructure condition and environmental exposure.

The presence of septic tanks near Boreholes A and C appears to be a key factor in their elevated WQI scores, consistent with previous studies which linked groundwater pollution to proximity to waste disposal systems. Conversely, the presence of a treatment facility at Borehole B corresponds with its lower WQI and better compliance with WHO standards, demonstrating the positive impact of localized treatment systems on groundwater quality.

The observed trend of increasing WQI values from source to outlet across all sites indicates deterioration during storage and distribution likely due to aging pipes, sediment deposition, or microbial regrowth.

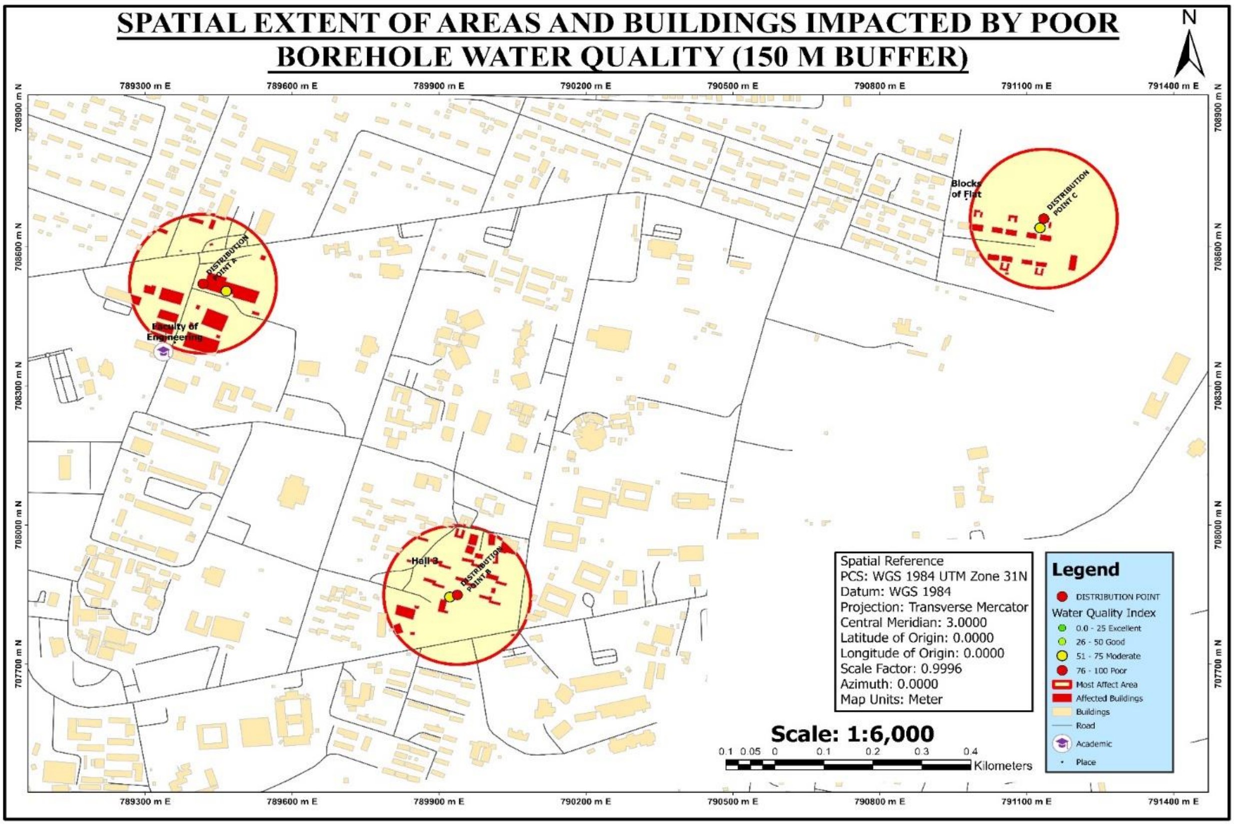

Figure 4.4: Spatial Extent of Areas and Building Impacted by Poor Borehole Water Quality using a 150m Buffer (Adapted from Google Earth)

Figure 4.4 illustrates the 150 m buffer zones generated around each of the three boreholes using GIS spatial analysis. The buffer represents the potential impact radius within which surrounding buildings, facilities, and land uses may influence or be affected by groundwater quality. The 150 m distance was selected based on WHO (2017) recommendations for minimum safe separation between boreholes and potential contamination sources such as septic tanks, refuse dumps and surface drainage systems.

Within the buffer of Borehole A (Faculty of Engineering), several structures including classrooms, workshops and a nearby septic tank fall inside the influence zone. This proximity indicates a moderate to high risk of localized contamination, particularly through leachate infiltration during heavy rainfall. The vegetative cover visible within the buffer may slightly reduce surface runoff but could also impede routine inspection and maintenance access.

Borehole B (Hostel area), the buffer encompasses several dormitory buildings, paved walkways and the treatment facility attached to the storage tank. Despite the dense infrastructure, the presence of the treatment system mitigates much of the potential microbial risk. However, high human activity and wastewater generation within this buffer underscore the importance of continuous monitoring and chlorination.

The Borehole C (Residential zone) buffer covers mainly low-density housing and open vegetated areas. Although fewer anthropogenic structures lie within the 150 m radius, a septic tank located about 19 m from the borehole remains a notable risk feature. The buffer highlights how contamination risks may still exist in less developed areas due to poor protection and shallow groundwater flow paths.

Spatially, the GIS overlay revealed that areas of poorer water quality (higher WQI values) generally coincide with zones of greater land-use intensity and closer proximity to waste disposal systems within each buffer. This relationship confirms the significance of maintaining adequate setback distances and implementing localized protection measures.

Overall, the 150 m buffer map provides a visual risk assessment tool, enabling decision-makers to prioritize borehole maintenance, enforce safe distances for septic system construction, and plan future groundwater abstraction points more sustainably.

CHAPTER FIVE: CONCLUSION

5.1 Conclusion

This study successfully demonstrated the application of Geographic Information System (GIS) techniques in assessing and analyzing borehole water quality in Benin City, Edo State, Nigeria. The integration of laboratory-based physicochemical and microbial analyses with spatial data provided a comprehensive understanding of the water quality distribution within the study area. Parameters such as pH, electrical conductivity, total dissolved solids, iron, zinc, copper, chloride, nitrate, and *E. coli* were analyzed and evaluated against the Nigerian Standard for Drinking Water Quality (SON, 2015) and World Health Organization (WHO, 2017) guidelines.

The computed Water Quality Index (WQI) revealed that most borehole water sources fell within the “good” to “poor” water quality grade, while the distribution points showed higher levels of contamination, likely due to environmental influences and storage conditions. GIS analysis effectively visualized the spatial variations in WQI and key parameters such as iron concentration, highlighting zones of potential risk, particularly near septic tanks and densely populated areas.

Overall, the study established that GIS serves as an efficient decision-support tool for identifying contamination hotspots, visualizing spatial trends and supporting effective management strategies for borehole water systems in urban settings.

5.2 Recommendations

i. Routine Monitoring: Regular GIS-integrated monitoring of borehole water quality should be implemented to promptly detect and manage emerging contamination issues. Periodic cleaning and inspection of borehole storage and distribution systems should be enforced to prevent post-storage contamination.

ii. Sanitary Setbacks: Boreholes should be sited at least 30 m away from potential pollution sources such as septic tanks, waste pits, and drainage channels.

iii. Policy Integration: The Standards Organization of Nigeria (SON), Federal Ministry of Water Resources, and State Environmental Agencies should integrate GIS-based water quality monitoring frameworks into their regulatory practices. A national geospatial database should be developed for continuous tracking of groundwater quality indicators across urban and rural areas.

iv. Collaboration: Encourage collaboration between research institutions, local councils, and water boards for data sharing and coordinated action on groundwater quality improvement.

v. Temporal Analysis: Future studies should include seasonal monitoring to assess how rainfall and dry periods affect borehole water quality. Studies should be extended beyond Benin City to compare spatial patterns across multiple regions and geological zones. Researchers can incorporate remote sensing and hydrological modeling to predict groundwater contamination trends over time. As well as applying AI or machine learning techniques to automate risk prediction and improve decision-making accuracy.

REFERENCES

Abdelmonaim, M., Radouane, E.M., Abdelkader, C., Mourad, D., Youssef, O., Abderrazzaq, B., Mhamed, K. and Taouraout, A. (2024). "Evaluating the quality of groundwater in the Zagora region, Southeast Morocco, using GIS and the Water Quality Index (WQI)", Geology, Ecology, and Landscapes, pp.1– 17.

APHA, AWWA and WEF (2012). "Standard method 2130: turbidity. Standard methods for the examination of water and wastewater, 22nd edition. Washington, DC: American Public Health Association, American Water Works Association and Water Environment Federation".

APHA, AWWA and WEF (2017). "Standard Methods for the Examination of Water and Wastewater". 23rd ed, American Public Health Association, Baltimore, Washington DC.

Aquafix (2024) How do boreholes work? Available at: https://www.aquafix.co.za/how–do– boreholes– work/ (Accessed: 3 June 2025)

Balla, D., Kiss, E., Zichar, M. and Mester, T. (2024). "Evaluation of groundwater quality in the rural environment using geostatistical analysis and WebGIS methods in a Hungarian settlement, Báránd", Environmental Science and Pollution Research, Vol.31(46), pp.57177– 57195.

Boyd, C.E., Tucker, C.S. and Somridhivej, B., (2016). "Alkalinity and hardness: critical but elusive concepts in aquaculture", Journal of the World Aquaculture Society, Vol. 47(1), pp.6– 41.

Brewer, G.J. (2010). “Risks of copper and iron toxicity during aging in humans”, Chemical research in toxicology, Vol. 23(2), pp. 319– 326.

Briffa, J., Sinagra, E. and Blundell, R. (2020). “Heavy metal pollution in the environment and their toxicological effects on humans”, Heliyon, Vol. 6(9), pp.e04691.

Brown, R.M., McClelland, N.I., Deininger, R.A. and Tozer, R.G. (1970). “A water quality index– do we dare”, Water and sewage works, Vol.117(10).

Chang, K.T. (2016). “Geographic information system”, International encyclopedia of geography: people, the earth, environment and technology, pp.1– 10.

Chatterjee, C. and Raziuddin, M. (2002). “Determination of Water Quality Index (WQI) of a degraded river in Asansol industrial area (West Bengal)”, Nature, Environment and pollution technology, Vol.1(2), pp.181– 189.

Daffi, R.E., Alfa, M.I. and Ibrahim, E.S. (2020). “GIS– Based Analysis of Water Quality Parameters of Groundwater with Proximity to On– Site Waste Pits in Vom Community of Jos South, Nigeria”, Journal of Engineering Research and Reports, Vol. 10(4), pp.6–18.

David, S. (2024). “Production boreholes water quality evaluation using GIS based geostatistical algorithms in Windhoek”, Int. J. Hydrol., Vol. 8(1), pp.1– 8.

Edokpayi, J.N., Odiyo, J.O. and Durowoju, O.S. (2017). “Impact of wastewater on surface water quality in developing countries: a case study of South Africa”, Water quality, Vol.10 (66561), pp.10– 5772.

El– Rawy, M., Batelaan, O., Alshehri, F., Almadani, S., Ahmed, M.S. and Elbeltagi, A., 2023. "An Integrated GIS and machine– learning technique for groundwater quality assessment and prediction in southern Saudi Arabia", Water, 15(13), pp.2448.

Eltarabily, M.G. and Elshaarawy, M.K. (2023). "Risk assessment of potential groundwater contamination by agricultural drainage water in the Central Valley Watershed, California, USA", Groundwater Quality and Geochemistry in Arid and Semi– Arid Regions, pp. 37– 76.

Google Earth (2023) Satellite image of University of Benin, Benin City, Edo state,, Nigeria. Available at: https://earth.google.com (Accessed: 15 June 2025).

Isa, M.A., Allamin, I.A., Ismail, H.Y. and Shettima, A. (2013). "Physicochemical and bacteriological analyses of drinking water from wash boreholes in Maiduguri Metropolis, Borno State", Nigeria. African Journal of Food Science, Vol.7(1), pp.9– 13.

Jaseela, C., Prabhakar, K. and Harikumar, P.S.P. (2016). "Application of GIS and DRASTIC modeling for evaluation of groundwater vulnerability near a solid waste disposal site", International journal of Geosciences, Vol.7(04), p.558.

Kanu, O.P., Ugwoha, E., Udeh, N.U. and Amah, V., (2023). "Groundwater Quality Assessment in Aba (Abia State) Using WQI and GIS Techniques". Asian Journal of Environment and Ecology, Vol. 22(4), pp.1– 15.

Kosgey, K., Zungu, P.V., Bux, F. and Kumari, S. (2022), "Biological nitrogen removal from low carbon wastewater", Frontiers in Microbiology, 13, p.968812.

Kufoniyi, O. (1998). “Database design and creation”, Principle and Applications of Geographic Information Systems, Department of Surveying, University of Lagos, pp.62– 63.

Liu, X., Beusen, A.H., Van Grinsven, H.J., Wang, J., Van Hoek, W.J., Ran, X., Mogollón, J.M. and Bouwman, A.F. (2024), “Impact of groundwater nitrogen legacy on water quality”, Nature Sustainability, Vol. 7(7), pp. 891– 900.

Manne, R., Kumaradoss, M.M.R.M., Reddy, R.S.R., Devarajan, A. and Mekala, N. (2022) . “Water quality and risk assessment of copper content in drinking water stored in copper containers”, Applied Water Science, Vol. 12(3), pp. 27.

Masood, A., Tariq, M.A.U.R., Hashmi, M.Z.U.R., Waseem, M., Sarwar, M.K., Ali, W., Farooq, R., Almazroui, M. and Ng, A.W. (2022). “An overview of groundwater monitoring through point– to satellite– based techniques”, Water, Vol. 14(4), pp.565.

Mohammed Ali Dan– Hassan (2017) Review of Borehole Failures: Causes and Remedies. Available at: https://www.researchgate.net/publication/334376977_Review_of_Borehole_Failure_Causes_and_Remedies (Accessed: 8 June 2025)

Muhammad, B.I., Shitu, T., Zambuk, U.U. and Amamat, A.Y. (2023). “Physicochemical characteristics of borehole water sources in a tertiary educational institution in Katsina, Katsina State, Nigeria”, Journal of Applied Sciences and Environmental Management, Vol. 27(5), pp. 974– 978.

NASA Space Place (2022) How much water is on Earth? Available at: https://spaceplace.nasa.gov/water/en/ (Accessed: 21 April 2025)

Oboh, I.P. and Egun, N.K., (2017). “Assessment of the water quality of selected boreholes close to a dumpsite in Agbor Metropolis, Delta State, Nigeria”. African Scientist, Vol. 18(1), pp.43– 53.

Odeyemi, D.F., Ogunniran, A.O., Omode, T.S., Ayeni, I.E. and Fagbure, A.F., (2024). “Assessment of water quality from selected borehole locations in Ado Ekiti, Ekiti State, Southwest Nigeria”. World Journal of Advanced Research and Reviews, Vol. 21(2), pp.1161– 1170.

Odonkor, S.T. and Mahami, T. (2020). “Escherichia coli as a tool for disease risk assessment of drinking water sources”, International Journal of Microbiology, Vol.2020(1), p.2534130.

Onu, B. (2024). “Analysis of the Quality of Water in Hand Dug Wells and Boreholes in Ogbia Local Government Area”, Greener Journal of Life Sciences, Vol.6(1), pp.1–9.

Organization of African Unity (1981) African Charter on Human and Peoples' Rights, 27 June 1981, CAB/LEG/67/3 rev. 5, art. 24 Available at: https://au.int/en/treaties/african– charter– human– and– peoples– rights (Accessed: 18 June 2025)

Oyaro, M., Momba, M.N.B. and Dhliwayo, P. (2018). “Physio-chemical and microbial analysis of selected borehole water in Mahikeng, South Africa”, Water SA, Vol. 44(1), pp. 101–110.

Penn State Extension (2023) Iron and Manganese in Private Water Systems. Available at: https://extension.psu.edu/iron– and– manganese– in– private– water– systems/ (Accessed: 24 June 2025).

Rakshit, A. (2016). “Basics of laboratory safety: Common laboratory rules and regulations”, International Association for Ecology.

Saalidong, B.M., Aram, S.A., Otu, S. and Lartey, P.O. (2022) “Examining the dynamics of the relationship between water pH and other water quality parameters in ground and surface water systems”, PLOS ONE, Vol. 17(1), pp. 1– 17.

Samie, A., Makonto, O., Mojapelo, P., Bessong, P., Odiyo, J. and Uaboi– Egbenni, P. (2013). “Physio– chemical assessment of borehole water used by schools in greater Giyani Municipality, Mopani district, South Africa”, African Journal of Biotechnology, Vol. 12(30), pp. 4858– 4865.

Sorlini, S., Palazzini, D., Collivignarelli, M.C. and Bertanza, G. (2018). “Assessment of drinking water quality in developing countries: A case study of Zanzibar, Tanzania”, Environmental Monitoring and Assessment, Vol. 190(4), pp. 223– 235.

Spellman, F.R. (2017). “The Drinking Water Handbook”, 3rd edn. Boca Raton, FL: CRC Press.

Standards Organization of Nigeria (SON) (2007) Nigerian Standard for Drinking Water Quality (NSDWQ) (NIS 554:2007)

Standards Organization of Nigeria (SON) (2015). Nigerian Standard for Drinking Water Quality (NIS 554:2015).

Stephen Agwaibor (2024) Nigeria's urban water provision crisis. Veriva Africa Insights Available at: https://www.verivafrica.com/insights/nigerias– urban– water– provision– crisis (Accessed: 6 June 2025)..

Tiwari, R. and Mahalpure, G.S. (2024). “A detailed review of pH and its applications”, Journal of Pharmaceutical and Biopharmaceutical Research, Vol. 6(2), pp.492–505.

Udongwo, A.M. and Sambo, D.D. (2022). “Assessment of heavy metal contamination in boreholes around mechanic workshops in Uyo Metropolis, Akwa Ibom State, Nigeria”, Journal of Chemical Society of Nigeria, Vol. 47(4), pp. 931 – 942.

UNESCO (1998) World Water Resources: A New Appraisal and Assessment for the 21st century. Available at: World water resources: a new appraisal and assessment for the 21st century – UNESCO Digital Library (Accessed: 21 April 2025)

UNICEF (2016) Strategy for Water, Sanitation and Hygiene 2016–2030. New York: UNICEF. Available at: https://www.unicef.org/wash/3942_91538.html (Accessed: 18 June 2025)

United States Environmental Protection Agency US EPA (2024) What is pH? United States Environmental Protection Agency. Available at: https://www.epa.gov/goldkingmine/what– ph (Accessed: 23 June 2025)

United States Geological Survey (USGS) (no date) Hardness of water. Available at: https://www.usgs.gov/special– topics/water– science– school/science/hardness– water (Accessed: 26 June 2025).

Wiesmann, U. (2005). “Biological nitrogen removal from wastewater”. Biotechnics/wastewater, pp.113– 154.

Wilson, P.C. (2019) Water Quality Notes: Alkalinity and Hardness, SS540. University of Florida Institute of Food and Agricultural Sciences (UF/IFAS) Extension. Available at: https://edis.ifas.ufl.edu/publication/SS540 (Accessed: 18 June 2025).

World Health Organization (2020), “Physiochemical analysis of borehole water samples”, Journal of chemistry, 54, pp. 924– 929.

World Health Organization (WHO) (2017) Guidelines for Drinking– water Quality, 4th ed. Geneva: WHO Press.

Yan, C., Wan, W.D., Wang, R.N., Lai, T.N., Ali, W., He, S.S., Liu, S., Li, X., Nasir, Z.A. and Coulon, F. (2024). “Quantitative health risk assessment of microbial hazards from water sources for community and self– supply drinking water systems”, Journal of Hazardous Materials, (465), p.133324.

APPENDIX A

Photographic Image of the Student Collecting Water Samples from the Study Area

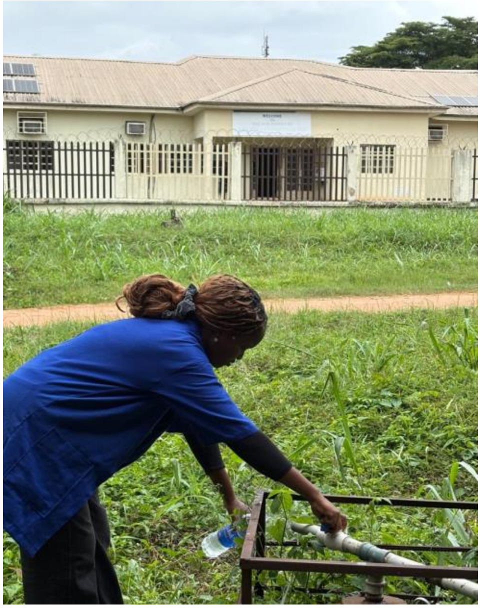

Plate A-1: Collection of Water Sample from Borehole A

Plate A-2: Collection of Water Sample from Distribution Point A

Plate A-3: Borehole B

Plate A-4: Distribution Point B

Plate A-5: Collection of Water Sample from Borehole C

Plate A-6: Collection of Water Sample from Borehole C

Plate A-7: Septic Tank at Location C

APPENDIX B

Photographic Images of the Student Performing Laboratory Analysis on Collected Water Samples

Plate B-1: Performance of laboratory analysis

Plate B-2: Performance of laboratory analysis