GEOSPATIAL DISTRIBUTION AND QUALITY OF DRINKING WATER IN SHALLOW WELLS IN KIPSONOI SUB-CATCHMENT IN BOMET COUNTY, KENYA.

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DECLARATION

This thesis is my original work and has not been presented for a degree or any other award in any other university.

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DEDICATION

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LIST OF UNITS

Mg/L	Milligrams per litre
MPN/100L	Most probable number per 100 milliliters
NTU	Nepthalometric Turbidity Unit
µS/cm	Micro Siemens per centimeter

ABBREVIATIONS AND ACRONYMS

APHA	American Public Health Association
BOMWASCO	Bomet Water Services Company
EC	Electrical Conductivity
EDTA	Ethylene Diamine Tetra Acetic Acid
FAO	Food and Agriculture Organization
GPS	Global Positioning System
KEBS	Kenya Bureau of Standards
KNBS	Kenya National Bureau of Statistics
KRCS	Kenya Red Cross Societies
NEMA	National Environment Management Authority
TDS	Total Dissolved Solids
UNEP	United Nations Environment Program
USEPA	United States Environmental Protection Agency
WHO	World Health Organization
WQI	Water Quality Index
WRA	Water Resource Authority

OPERATIONAL TERMS AND DEFINITIONS

Drinking water	Water utilized for consumption or meal preparation.
Geo spatial distribution of shallow wells	Is the distribution of shallow wells on the surface of the earth.
Groundwater pollution	Is the remolding in the state and quality of water owing to human activities or as a result of the introduction of pollutants.
Groundwater quality	Is the physico-chemical and microbial attributes of water with reference to its appropriateness for a specific use.
Groundwater	Is the water located below the ground's surface and held or stored in the aquifers.
Potable water	Water that is utilized for drinking or cooking purpose.
Shallow wells	Wells that are less than 15 m deep. They are normally dug by hand and are mostly susceptible to contamination from percolation.
Sub catchment	A distinct part of a catchment (an area from which water drains into a particular area of a large river, including its tributaries).
Water quality index	Is a sole numeral that can be easily computed and then employed in generally characterizing water quality.

ABSTRACT

Surface runoff from agricultural land has crucial consequential challenge to the quality of water in shallow wells, introducing pollutants such as fecal contaminants, herbicidal and pesticidal residues, and chemical fertilizers. This research focal point is to examine the condition and potability of drinking water sourced from shallow wells in the Kipsonoi Sub-Catchment. The specific objectives included: mapping the spatial arrangement of shallow wells the region, assessing key physical, chemical, and biological water quality indicators, and determining the fitness of these water sources for human utilization. The spatial mapping of wells with depths below 15 meters was conducted using handheld GPS devices, and their coordinates were plotted using ArcGIS software version 10.8. A total of 31 shallow wells were sampled during both the wet season (April) and the dry season (January) to analyze selected parameters. Laboratory analyses were conducted following standard procedures, and the outcomes were benchmarked against water quality guidelines provided by NEMA, USEPA, and WHO. The WQI was computed to evaluate the potability of the sampled water. Findings from the study indicate the existence of roughly 321 shallow wells within the Kipsonoi Sub-Catchment, with 150 (47%) serving as sources of drinking water—96 wells (64%) located in the upper catchment and 54 (36%) in the lower zone. Widespread contamination was noted, with more than 60% of samples exceeding acceptable thresholds for nitrates (61.29%), turbidity (70.97%), and faecal coliforms (80.66%), as outlined by the referenced environmental and health authorities. A student's t-test performed at a 95% confidence level showed a statistically meaningful difference ($p \leq 0.05$) in E. coli concentrations between the dry and rainy seasons. Elevated extends of faecal coliforms during the rainy season pointed to human and livestock waste as principal sources of contamination during periods of heavy rainfall. According to the WQI assessment, over 60% of the sampled wells produced water that met the criteria for potable use, whereas 32.2% were classified as having substandard quality. The analysis highlights extensive contamination, particularly from nitrates, turbidity, and faecal indicators. The assessment recommends that water quality in the Kipsonoi Sub-Catchment is substantially compromised by agricultural runoff, which contributes to the increased concentration of pollutants in shallow groundwater. To mitigate these risks, government entities for instance the Ministry of Water, Water Resources Authority, and Geological Survey should initiate geophysical assessments to identify potential aquifers for deeper well development, even in areas constrained by clay layers. It is imperative that wells are properly sealed to prevent infiltration from surface contaminants. Moreover, water from shallow sources should undergo appropriate treatment before consumption to reduce excessive levels of turbidity, nitrates, and microbial pathogens, thereby aligning with national and international water safety standards.

CHAPTER ONE: INTRODUCTION

1.1 Background Information

Groundwater performs an extremely fundamental function in the lives of man, both economically and socially regarding domestic, industrial and agricultural utilization (Priyan, 2021). Shallow well water is susceptible to pollution caused by human activities as well as other sources for instance, the application of chemical pesticides, agricultural waste, domestic discharge and the effluents from the industries to groundwater and also other water bodies (Zhang *et al.,* 2019).

In response to the growing optimization of chemicals, pesticides, fertilizers, industrialization and other human factors, the water from various sources is heavily polluted daily including the shallow well water (Chowdhary *et al.,* 2020). On a global scale, approximately 1.2 billion individuals consume dirty and polluted water which is the root cause of waterborne illnesses (W Jayawardena, 2021). Contaminated water is a global health hazard putting people in danger for being affected by diarrhea as well as other illnesses along with chemical poisoning (Mohiuddin, 2019).

Sidhu *et al.* (2019) reported shallow wells in the Mansa district of Punjab in India exhibited dangerous levels of nitrate, fluoride, and microbial contaminants due to fertilizer overuse and poor sanitation. The research conducted by Craswell (2021) indicated that water from shallow wells is unsuitable for human use attributable to the indiscriminate application of chemical fertilizers.

The safety and quality of potable water have inhibited growth and development in African countries for many years (Raghav *et al.,* 2019). In less developed countries, approximately 1.8 million individuals, predominantly children, die yearly in consequence of ingesting polluted water (Lin *et al.,* 2022). 80% of the diseases in less developed countries arise from water and sanitation status (Fuente *et al.,* 2020). There is inadequate supply of drinking water in less developed nations and this has left most people with no choice but to use groundwater, for instance, hand dug wells, boreholes and shallow wells, to meet their day-to-day demand for water. These water sources are immensely vulnerable to pollution, making the water unfit for drinking needs (Reaver *et al.,* 2021). Research done by Ogendi *et al.,* (2025) Kitwe district in Ipusukilo informal settlement in Zambia found significant microbial and chemical contamination in shallow wells, especially in the rainy season, because of surface runoff and insufficient well safeguarding.

In Kenya, most of the health hazards are caused by insecure water quality that emanates from pollutants, the use of chemicals for farming practices and industrial effluents that contaminate the drainage basins and the sources (Gevera *et al.,* 2020). Within the Keiyo Highlands, shallow wells showed high levels of microbiological contamination (Mbaka *et al.,* 2017).

In Kisumu County, Onyango (2023) observed elevated nitrate and coliform levels in shallow wells located near farms and pit latrines. Similarly, Odiwuor (2018) reported contamination of shallow wells in Migori County due to pit latrines located close to water sources and fertilizer use in tea farms.

It is paramount to state that Bomet County is a tea farming region with approximately 24,868 homesteads relying completely on tea as a major income birthsource (Bett, 2015). Farmers in Bomet County have invested heavily in intensive agriculture and fertilizer use to boost food production (Bomet County Development Plan, 2018; Ateka *et al.,* 2018).

Kipsonoi Sub-catchment have both surface and ground water. Accessible drinking water sources in Bomet County are, surface water, which is 29.3%, unprotected dug wells, 12.1%, piped water, 6.6%, rainwater collection, 16.4%, unprotected spring, 14.8%, protected spring, 9.9%; protected dug well, 4.3%, tube well/borehole connected to a pump, 2.9%, other, 1.0%, small water vendor, 0.4%, and tanker truck, 0.1% (KRCS, 2016). Bomet Water Services Company (BOWASCO) maintains and operates water supply, sewerage and sanitation utilities for residents in the Kipsonoi Sub-catchment. Research done by Chebet (2017) indicated that piped water supply by Bomet Water Services Company (BOMWASCO) was only available to 8.6% of the residents. Similar research by Tole (2018) and Bomet County Development Plan (2018) found that only 11,940 households access piped water, which is equivalent to 8.45%. Mutai *et al.* (2021) observed that 67% of households inadequate access to secure water for consumption. The inadequate piped water infrastructure has compelled residents to seek alternative sources, such as shallow wells which are easily hand-dug because of the high water table that is in the catchment and are inexpensive to construct. Unfortunately, shallow wells are at risk of pollution resulting from heavy agricultural activities, especially tea farming, where chemicals from herbicides, pesticides, fertilizers and disease-causing organisms could easily be carried by runoff during the rainy days. In addition, the available water resources in Kipsonoi Sub-catchment are heavily utilized for social economic activities such as farming, drinking and domestic chores. Therefore, this research looks at the shallow wells that are predominantly used, analyzing the quality of water and its potability water purposes. As an outcome, shallow wells are vulnerable to human activities, so it is essential to determine their water characteristics.

1.2 Statement of the Problem

The state of water quality and groundwater resources in Bomet and Kipsonoi sub-catchment is a critical concern for general health, public health, welfare and living standards of the area's residents. While various water sources exist, including surface water and piped connections managed by Bomet Water Services Company (BOMWASCO), ensuring a steady supply of safe and adequate water remains problematic. Studies indicate that piped water supply reaches a limited portion of the population leaving a significant majority of households reliant on alternative sources. In response to insufficient piped water, a notable proportion of the population in the Kipsonoi sub-catchment relies on shallow wells for drinking water needs due to the shallow water table and ease of construction. However, these shallow wells are particularly vulnerable to contamination from the prevalent heavy agricultural activities in the region, especially tea farming. Runoff during rainy seasons can easily carry pollutants such as chemical residues from herbicides, pesticides, and fertilizers, as well as disease-causing microorganisms, directly into these shallow groundwater sources. BOMWASCO has implemented measures aimed at improving the safety and purity of water through treatment and distribution within their limited network, and potentially by community initiatives to protect springs and wells.

Existing research elucidates a broad overview of water access predicaments and limited reach of piped water but lacks a focused assessment on the condition of water drawn from these critical shallows well sources remain a concern. Consequently. This study aspired to bridge the knowledge gap regarding the potability of water sourced specifically from shallow wells within the Kipsonoi sub-catchment, Bomet County. By analyzing the physicochemical, microbiological, and bacteriological properties of water from these commonly used sources, the assessment seeks to evaluate their suitability for human consumption and enhance understanding of water quality challenges impacting the local population.

1.3 Justification of the Study

Access and availability of safe, potable and clean water is a vital human right. Ensuring availability to clean and reliable drinking water is a core objective of Sustainable Development Goal 6 (SDG 6), which denotes the importance of achieving universal access to water and sanitation, alongside the sustainable stewardship of these resources. In the Kenyan context, this goal is echoed in Kenya Vision 2030 and the Water Act of 2016, both of which emphasize the imperative of fair and inclusive access to high-quality water resources and advocate for the responsible usage of water systems, especially in rural regions such as the Kipsonoi Sub-catchment.

This study filled a critical knowledge gap by: mapping the geospatial distribution of shallow wells, which aided local government and development agencies in identifying water-scarce areas and informing infrastructure development; assessing key water quality parameters—physical, chemical, and biological—to generate up-to-date, location-specific data that informed health and environmental policy decisions at both county and national levels; and evaluating the suitability of shallow well water for man consumption based on international World Health Organization (WHO) and national Kenya Bureau of Standards (KEBS) standards, thereby providing a scientific basis for water treatment recommendations and public health interventions.

By integrating geospatial analysis with water quality assessment, the study directly supported national water policies and offered practical insights for stakeholders such as the Ministry of Health, Ministry of Water and Sanitation, non-governmental entities, and local water management committees. Furthermore, by demonstrating the practical application of geospatial technologies in evaluating rural water security, the study contributed to the academic advancement of hydrology

1.4 Objectives of the Study

1.4.1 General Objective

The overall objective is to determine the drinking water quality in shallow wells in the Kipsonoi Sub catchment.

1.4.2 Specific Objectives

i) To determine the geospatial distribution of shallow wells in the Kipsonoi Sub catchment.

ii) To determine the physical, chemical and biological indicator parameters in shallow wells in the Kipsonoi Sub catchment during the wet and dry seasons.

iii) To determine the aptness of water from the shallow wells in the Kipsonoi Sub catchment for drinking purposes.

1.5 Research Question

i) What is the geospatial distribution of shallow wells in the Kipsonoi Sub catchment?

ii) What are the levels of physical, chemical and biological parameters from shallow wells in the Kipsonoi Sub catchment during the wet and dry seasons?

iii) What is the suitability of water from the shallow wells in the Kipsonoi Sub catchment for drinking purposes?

1.6 Hypotheses

i. Shallow wells in Kipsonoi Sub-catchment are homogenously distributed.
ii. There is no notable difference in the mean concentrations of each of the physical, chemical and biological contaminants in shallow wells in Kipsonoi Sub-Catchment at the wet and dry seasons.
iii. Water from shallow wells in Kipsonoi Sub-Catchment are suitable for drinking.

1.7 Significance of the Study

The findings provided an accurate depiction of the water quality conditions in the shallow wells within the Kipsonoi Sub-catchment and served as a valuable reference for future studies. By examining physicochemical and microbiological properties of the water obtained from these wells, the study effectively alerted the local population to potential health risks associated with its consumption. This insight enabled them to make informed decisions regarding purification techniques and potential alternative water sources, thereby contributing to the safeguarding of their health and general well-being. Furthermore, the data produced provided crucial evidence for public health authorities to evaluate the prevalence of waterborne illnesses associated with shallow well usage in the sub-catchment. This enabled them to design targeted interventions, implement suitable health policies, and allocate resources efficiently to reduce water-related health risks. As a consequence, apprehending spatial distribution and condition of shallow groundwater allowed the agencies responsible for water regulation to spearhead an extensive yet intensive assessment of the entire water supply within the Kipsonoi Sub-catchment. This underpinned the design of sustainable strategies for water resource management, including the protection of groundwater reserves and the establishment of programs aimed at improving water quality.

1.8 Scope and Limitation

The assessment was executed at Kipsonoi Sub catchment in Bomet County, Kenya. The investigation assessed the geospatial distribution of shallow wells within this defined area and determined the physico-chemical and biological characteristics from 32 shallow wells focusing on areas where ground water has been used for drinking purposes. Analysis of physical, chemical, and biological attributes will be limited to a definite set of parameters comprising of Temperature, Electrical conductivity, pH, Total hardness (TH), Alkalinity, Na^+, Phosphates (PO_4^{3-}), K^+, Nitrates (NO_3^-), Total dissolved solids (TDS), Potassium, Flouride, and Turbidity basing on available laboratory facilities and budgetary constraints. Furthermore, suitability of this shallow well water for consumption was determined using the Water Quality Index, and ten parameters the chosen were limited to TDS, pH, TH, alkalinity, EC, turbidity (Turb), sodium (Na^+), phosphates (PO_4^{3-}), potassium (K^+) and nitrates (NO_3-).

CHAPTER TWO: LITRERATURE REVIEW

2.1 Geo-spatial distribution of Shallow Wells

Geographic positioning is crucial in hydrogeological studies, particularly for mapping the distribution of shallow wells (Ranasinghe & Patabandi, 2024). Precise spatial information is vital for comprehending groundwater availability, aquifer properties, and possible contamination sources (Díaz-Alcaide & Martínez-Santos, 2019).

Ibitoye (2017) used a Global Positioning System (GPS) receiver to geographically locate various water facilities for instance reservoirs, pumping stations and the distribution of water pipelines and their elevations in Abeokuta. Many other researchers have used the GPS to locate wells geographically where the samples for analysis were to be taken (Sarwar *et al.,* 2021; Ewaid *et al.,* 2021; El Mountassir *et al.,* 2020; Liu *et al.,* 2021; Ahamad *et al.,* 2020). The incorporation of GPS information into GIS has markedly improved the visualization and interpretation of groundwater data (Thakur *et al.,* 2017).

Spatial analysis using Geographic Information System (GIS) enables the spotting of locations at high risk where shallow wells could be susceptible to pollution, particularly from agricultural runoff, pit latrines, or industrial waste (Wechuli, 2022). Moreover, analyzing geo-spatial data over time enables the observation of changes in well locations and conditions, which is vital for evaluating the sustainability of groundwater resources (Mumtaz *et al.,* 2019). By conducting repeated GPS surveys, seasonal fluctuations in water table levels can be detected, guiding alterations in well depth and adjustments in pumping schedules (Liu *et al.,* 2019).

Additionally, participatory GIS (PGIS) methods have been employed in community water initiatives to empower local communities in the mapping and monitoring of their water sources (Malakar & Roy, 2024). The widespread accessibility of mobile devices equipped with GPS technology has facilitated the gathering of geo-referenced data, leading to more inclusive and data-informed in making decisions in of water resources management (Lemmens *et al.,* 2017).

2.2 Characteristics of Water Quality

Characteristics of water quality have been classified into chemical, physical and biological. Guidelines have been recommended by WHO for water for drinking purposes in less developed nations and have also been adopted as the basis for formulating local values (WHO, 2022).

2.2.1 Water quality in shallow wells

Jat Baloch *et al.,* (2021) explored the shallow groundwater quality while concentrating in Sakrand, Sindh, Pakistan, analyzing 95 samples to evaluate fitness for consumption. Hydrogeochemical analysis revealed that sodium (Na^+) was the supreme, succeeded by magnesium (Mg^{2+}), and potassium (K^+). The research inferred that although a majority of groundwater samples met the criteria for potable use, a notable fraction presented potential health hazards, especially to children, and several were deemed unfit for irrigation owing to elevated salinity levels. In their investigation, Wang and Li, (2022) evaluated the condition of shallow groundwater and the corresponding public health implications during both wet and dry times in the rural regions of the Guanzhong Plain, China. They found that nitrate (NO_3^-) were identified as the primary contaminants adversely affecting water quality. Nitrate was the major contributor to health risks, followed by fluoride. The southern and southwestern areas exhibited higher health risks, underscoring the necessity for targeted water quality management in these regions.

Odey *et al.,* (2018) found that shallow wells in Northern Cross-River, Nigeria, were often contaminated with microbial pathogens such as fecal coliforms and exhibited elevated levels of physico-chemical attributes such as turbidity, TDS, and nitrate concentrations, exceeding safe drinking water standards. These contaminations and elevated parameters pose significant health risks, emphasizing the vulnerability of shallow wells to pollution from poor sanitation and environmental influences. Abaasa *et al.* (2024) found that shallow wells in Mbarara City, Uganda, were frequently contaminated with microbial pathogens, particularly *E. coli* and other fecal coliforms, indicating poor sanitary conditions. Certain physico-chemical factors, like turbidity and TDS, also exceeded safe limits in these wells, posing potential health risks to users. Namatovu et al. (2023) unveiled that nutrient and anion degree in water samples from sixteen districts in Uganda varied, with some sites showing elevated concentrations of specific nutrients such as nitrates (NO_3^-) and phosphates (PO_4^{3-}) exceeding recommended safety limits. These elevated nutrient levels indicate potential contamination from agricultural runoff and pose risks to water quality and public health.

Kanda *et al.* (2023) investigated the quality of groundwater in Vihiga County, Kenya, with a focus on hand-dug wells near pit latrines in Sabatia Sub-county. Through the examination of 48 water samples, the study identified that certain physico-chemical indicators surpassed acceptable thresholds, while microbiological assessments detected the presence of Escherichia coli. The elevated E. coli concentrations were attributed to the close proximity of sanitation facilities and poor hygienic conditions surrounding the wells. The research showed that the microbial condition of the water was compromised. Contamination renders water unfit, hazardous and detrimental to human health if ingested without treatment. Mbura (2018) investigated groundwater quality in Tharaka Nithi County, Kenya, focusing on physico-chemical parameters. The study found that fluoride and electrical conductivity levels exceeded national standards, making the water unsuitable for consumption. High fluoride concentrations, in particular, posed risks to human health for instance dental fluorosis, especially during the dry season. In their study, Odwori and Wakhungu, (2023) found that dug wells in Kakamega County were among the most contaminated water sources. The wells exhibited high levels of faecal coliforms often exceeding WHO and KEBS guidelines for safe drinking water. This contamination was attributed to poor protection of the wells, proximity to latrines, and inadequate waste disposal practices, rendering the water unsaf and unfit to human health if ingested without treatment for human consumption without treatment. Wachira *et al.* (2023) found that shallow groundwater status in Mathira East Sub-County, Kenya, varied significantly with land use. Urban and agricultural areas showed higher levels of contamination, particularly in turbidity, nitrates, phosphates, and faecal coliforms, rendering many sources unsuitable for drinking.

2.2.2 Physical Characteristics

The organic and inorganic components found in water in either suspended or dissolved manner influences the physicochemical characteristics important in determining water quality (Ustaoğlu *et al.,* 2021). These are some physical aspects of water quality that help assess if the water is contaminated or not (Kamboj *et al.,* 2021).

Temperature of the air, surface runoff, water that percolates into the ground water, turbidity, and exposure to sunlight all influence temperature. Wang *et al.* (2023) found that temperature is among the essential elements that affect bacterial growth in underground waters. Micro-organisms grow faster with an rise in temperature (Wen *et al.,* 2020). Branco *et al.* (2014) found out that temperature plays a very essential function in regulating the solubility of gases in water. The acceptable limit for drinking water is 28–32 °C (WHO, 2004; NEMA, 2006). The temperature of the air, surface runoff, water that percolates into the ground water, turbidity, and exposure to sunlight all influence temperature.

It assesses the hydrogen ion level to establish water's acidity or alkalinity. It ranges between 0 and 14 pH units (Yehia and Said, 2021). The set standards for pH for water meant for drinking purposes range between 6.5 and 9.2 (WHO, 2004) and 6.5 and 8.5 (NEMA, 2006; USEPA, 2012).

EC represents the capacity of substances within water to transmit electrical current. It works as crucial indicator of concentration of dissolved ions in water (Corwin & Yemoto, 2020). A notable rise in conductivity may signal the introduction of pollutants or foreign discharges into the water system (Turunen *et al.,* 2020). Essentially, EC is a reflection of the sum dissolved solids present in the water body (Corwin & Yemoto, 2020). The set standards for electrical conductivity for water meant for drinking purposes is 1500 µS/cm (WHO, 2004) and1200 (NEMA, 2006).

Turbidity is the degree of holds materials in water (Bright *et al.,* 2020) and is evaluate the of water clarity (Bright and Mager, 2020). It shows the quantity with which the water is contaminated (Howladar *et al.,* 2021). Suspended particles consist of the particles of soil, for instance, sand, silt and clay, microbes, material substances and plankton which cause turbidity (Boyd and Boyd, 2020c; Adjovu *et al.,* 2023). The water turbidity is of great impact due to the fact that colloidal debris offers hide-place for pathogens (Adongo *et al.,* 2022). The dimension of turbidity offers the most effective illustration of the quantity of contamination (Gu *et al.,* 2020). Turbidity in water is of extraordinary significance as a result of the fact that disease-causing organisms can conceal themselves in tiny colloidal debris (Kusuma *et al.,* 2021). The permitted levels for potable water for turbidity is 5 NTU (WHO, 2004; NEMA, 2006).

2.2.3 Chemical Characteristics

2.2.3.1 Total Dissolved Solids

TDS mainly consist of inorganic salts, including potassium, sodium, calcium, bicarbonate, chloride, magnesium, and sulfate ions, along with a small fraction of dissolved organic compounds present in water (Nayar, 2020; Boyd & Boyd, 2020b). TDS in drinking water can be linked to a variety of origins, such as sewage, natural causes, industrial effluent, urban waste, and agricultural fertilizers (WHO, 2017; Chowdhary *et al.,* 2020). TDS is determined by the total organic and inorganic components in the water (Corwin and Yemoto, 2020; Peng *et al.,* 2020). It can also cause gastrointestinal irritation and corrosion (Balanquit *et al.,* 2024). Elevated concentrations of TDS in water used for drinking may pose a threat to expectant mothers with high blood pressure since it may enhance the risk of cardiovascular illness and pre-eclampsia, among other complications linked to pregnancy (Amrose *et al.,* 2020). The set standards for pH for water meant for drinking purposes is 500mg/L (USEPA, 2012), 1000mg/L (WHO, 2004) and 1200mg/L (NEMA, 2006).

2.2.3.2 Total Hardness

The water hardness is a mostly natural phenomenon showing the existence of high levels of sodium, magnesium and calcium ions and anions for instance, bicarbonates Cl and SO_4 in water (Sudia *et al.,* 2021). Strong degree of total hardness in water for human utilization may cause a variety of health concerns, including diarrhea, gas difficulties, and kidney stones (Dey *et al.,* 2024). When the water is hard, it can result in soap wastage, the formation of scum, and an increased boiling point (Boyd and Boyd, 2020d). Sewerages and soil run-off, specifically soils that contain substances like magnesium, limestone and calcium oxide materials are the sources of hardness in water (Nayar, 2020). The acceptable limits for drinking water for hardness is 500 mg/L (WHO, 2004; NEMA 2006).

2.2.3.3 Alkalinity

The allowed limit for alkalinity in drinking water is set at 500 mg/L by the WHO (WHO, 2004). When alkalinity levels surpass this limit, it may pose significant health hazards, including the formation of kidney stones, gastrointestinal disturbances such as bloating or gas accumulation, and ocular irritation (Peerapen & Thongboonkerd, 2023). Elevated alkalinity levels in groundwater are often indicative of anthropogenic influences, particularly industrial effluents or the infiltration of chemically contaminated runoff (Jehan *et al.,* 2019). Such occurrences not only compromise water safety but also highlight underlying environmental degradation linked to inadequate waste disposal or unregulated agricultural practices. Consequently, monitoring alkalinity serves as a vital element in the assessment of water safety and pollution sources.

2.2.3.4 Nitrates

Ingestion of nitrates in high quantities leads to blue baby syndrome in infants (Brender, 2020), diabetes (Kotopoulou *et al.,* 2022) as well as gastric carcinoma (Buller *et al.,* 2021; Seyyedsalehi *et al.,* 2023). It also causes thyroid cancer (Garcia Torres *et al.,* 2022), colorectal cancer (Hosseini *et al.,* 2021), and cerebromedullary tube defects, for instance, birth defects in the spinal cord, brain, or spine (Dwyer, 2022). Prolonged ingestion of drinking water containing even trace amounts of nitrates and nitrites has been associated with serious health outcomes, including various forms of cancer as a result of creation of carcinogenic N-nitroso elements within the human system (Said Abasse *et al.,* 2022). Elevated nitrate levels are particularly hazardous for expose populations like pregnant women and infants. For expectant mothers, high nitrate intake may impair thyroid function, potentially leading to hypothyroidism, which can adversely affect fetal development (Srivastav *et al.,* 2021). In neonates, excessive nitrate consumption is associated with methemoglobinemia, commonly known as “blue baby syndrome,” which inhibits the blood’s oxygen-carrying capacity. Moreover, García-Torres *et al.* (2021) emphasize that chronic exposure to nitrates may disrupt endocrine function and pose additional long-term health risks.

NO^{3}- which is derived from wastewater, urea fertilizers, and animal manures (Craswell, 2021). Additional sources of nitrates in drinking water can arise from the over application of fertilizers and manures that contain nitrogen (Alam *et al.,* 2024; Kou *et al.,* 2021), as well as from the inappropriate disposal of waste (Alex *et al.,* 2021). Infiltration of surface water contaminated with nitrate contaminates ground water (Rotiroti *et al.,* 2023).

A high intake of nitrate, teamed with a deficiency in iodine, can hinder the absorption of iodine and potentially possess negative impact on the thyroid (Winder *et al.,* 2022). Animal waste and decomposing vegetation are two examples of natural sources of nitrates in groundwater. One of the most widespread and detrimental consequences of the more utilization of nitrogen-infused agro-inputs in agricultural practices is the degradation of groundwater resources, which significantly compromises the quality of drinking water. This contamination poses both short-term and prolonged threats to human well-being, especially in countryside areas where shallow boreholes serve as the primary sources of potable water. Elevated levels of nitrates in drinking supplies can impair the blood's capacity to transport oxygen, predominantly affecting infants and expectant mothers, thus increasing the risk of severe medical conditions like blue baby syndrome (methemoglobinemia) and thyroid dysfunctions. In light of these hazards, regulatory thresholds for water safety established by WHO (2004), the National Environment Management Authority (2006), and USEPA (2012) stipulate a maximum allowable nitrate concentration in drinking water of 10 milligrams per liter. Surpassing this benchmark indicates a contamination level that requires urgent action to protect public health.

Table 2.1: Nitrate Levels in Groundwater and Their Impact on Intended Uses

Levels of Nitrate (mg/L)	**Interpretation**
0-4	Standard and non-toxic for human and livestock consumption
5-10	Indicates pollutants/pollution
11-20	Unsafe/unfit for infants younger than 5 years
21-40	Water at these levels is not good for human optimization.
41-100	Risky for human ingestion but can used for cattle if suggested.
>100	Should not be consumed by human beings or livestock.

Source: Audrey (2002)

2.2.3.5 Sodium

Excessive concentrations of sodium in drinking water are a critical health concern, particularly for sensitive groups such as the elderly, individuals with hypertension, and those suffering from kidney or cardiovascular conditions. Sodium, while essential in small amounts for normal cellular function and fluid balance, can become detrimental when ingested in excess through water supplies. WHO (2004) stipulates an acceptable threshold of 200 mg/L in drinking water, beyond which health risks significantly increase. Chronic consumption of water with high sodium levels may aggravate hypertension regulation, leading to hypertension—a key risk factor for stroke, heart disease, and renal impairment. Additionally, excessive sodium intake places undue burden on the kidneys, potentially resulting in decreased filtration efficiency and eventual renal failure. This is particularly dangerous for individuals with compromised renal function or those on medically advised low-sodium diets. Furthermore, high sodium content in water can intensify salt retention in the body, contributing to fluid imbalance and congestive heart conditions. For infants and people with underdeveloped or weakened kidneys, the consequences may be even more severe. Therefore, the continuous monitoring and regulation of sodium levels in community water supplies is essential to protect public health and support long-term wellness.

2.2.3.6 Potassium

Potassium detected in shallow well water can primarily be ascribed to the natural leaching of minerals from weathered geological formations. Nonetheless, elevated degree of potassium in groundwater are often indicative of anthropogenic influences. These include the infiltration of wastewater from poorly managed sewage systems located near the wells and the unregulated optimization of chemical fertilizers especially potassium-based compounds like potassium nitrate on nearby agricultural land (Hamdan *et al.,* 2020; Buvaneshwari *et al.,* 2020; Zakaria *et al.,* 2021). Such activities significantly contribute to the accumulation of potassium in aquifers, potentially compromising water quality. As per WHO (2004), the acceptable concentration of potassium in potable water is 200 mg/L. Surpassing this threshold may raise health concerns, particularly for individuals with compromised kidney function or those on potassium-restricted diets. Consequently, routine monitoring and proper land-use management around water birth source are essential to protect the deterioration of drinking water quality.

2.2.3.7 Phosphate

Razzaque (2011) established that while phosphates are generally not acutely harmful to humans or animals, their ingestion in excessive quantities can lead to gastrointestinal disturbances, including conditions such as stomach cancer. Environmentally, elevated phosphate levels in water bodies are highly detrimental as they accelerate eutrophication, raise the Biological Oxygen Demand (BOD), and significantly lower diffused oxygen (DO) levels—thereby threatening aquatic ecosystems (Heneash *et al.,* 2021). The infiltration of phosphates into groundwater commonly originates from agricultural runoff containing phosphate-rich fertilizers (Kou *et al.,* 2021).

Furthermore, various human activities contribute to phosphate contamination in drinking water sources. These include discharges from agricultural fields, domestic sewage (both human and animal waste), and effluents from industries such as pulp and paper processing, fertilizer and chemical manufacturing, and the use of phosphate-based detergents (Segun and Raimi, 2021). Both point sources (like direct discharge from industrial outlets) and non-point sources (such as surface runoff and erosion) facilitate the introduction of phosphates into groundwater systems. Additionally, natural processes like the decomposition of rocks holding phosphate minerals (El Bamiki *et al.,* 2021) also contribute to background phosphate levels. WHO (2004) and NEMA (2006) have uncovered optimum allowable threshold of 200 mg/L for potassium in water for human consumption. However, strict regulation and control measures are essential to limit phosphate intrusion, thereby protecting both environmental and public health.

2.2.3.8 Flouride

According to KEBS (2010), fluoride levels in potable water need not surpass 200 mg/L to ensure public health safety. The presence of fluoride at optimal levels partake a vital position in the development and maintenance of dental enamel, moreso in children, as supported by Johnston and Strobel (2020) and Grohe and Mittler (2021). Empirical findings suggest that minimal fluoride exposure aids in lowering the cases of dental caries (WHO, 2004; Sasanka *et al.,* 2020). Nevertheless, when the fluoride concentration exceeds 1.2 mg/L, the risk of developing dental fluorosis increases markedly, with more severe outcomes such as skeletal fluorosis also being documented in prolonged exposure scenarios (Sarwar *et al.,* 2018; Hung *et al.,* 2023; Srivastava and Flora, 2020). Furthermore, to these skeletal effects, various assessments have unveiled a possible connection amid excessive fluoride consumption and carcinogenic risks (Ghosh and Mukhopadhyay, 2019; Rao *et al.,* 2021).

Choubisa (2022) further emphasized that ingestion of fluoride-laden water at high levels leads to visible dental mottling, a common early sign of fluorosis. Prolonged intake may impair not only dental and skeletal integrity but also adversely affect renal function and overall bone structure (Lasagna *et al.,* 2020). Drinking water remains the predominant route through which individuals ingest fluoride on a daily basis (Sun *et al.,* 2013). The chronic health implications associated with long-term fluoride exposure have been extensively studied, consistently showing detrimental impacts on calcified tissues, especially bones and teeth.

Geologically, elevated fluoride in groundwater is often attributed to the drip of fluoride-rich minerals from rocks and soils. Solanki *et al.* (2022) highlighted that intensive weathering and heightened hydrological movement, often exacerbated by extensive irrigation practices, accelerate the mobilization of fluoride from geological formations into aquifers. Ali *et al.* (2016) also confirmed that naturally occurring fluoride originates primarily from fluoride-bearing rocks. As per established standards, the recommended guideline limit for fluoride in drinking water is 1.5 mg/L (WHO, 2004; NEMA, 2006) and 2 mg/L (USEPA, 2012), reinforcing the necessity for vigilant regulating and sustainable water resource management to safeguard health hazards.

2.2.4 Biological Characteristics (E. coli)

The main cause of bacteria in water is pollution emanating from human and animal feces, among other sources (Malla *et al.,* 2018), which is a threat to human beings if consumed in potable water (Sharma *et al.,* 2023). In regions whereby the communities predominantly rely on shallow wells as their major provider/sources of drinking water, bacteriological contamination of groundwater emerges as a critical public health concern (Vasudevan *et al.,* 2021). The infiltration of microbial pathogens into groundwater is often attributed to anthropogenic sources such as pit latrines, leaking septic tanks, and poor waste disposal infrastructure (Kapembo *et al.,* 2019). Additionally, runoff from livestock and animal waste contributes significantly to the introduction of fecal matter into aquifers, compounding the risk of microbial pollution (Díaz-Gavidia *et al.,* 2022).

Kapembo *et al.* (2019) emphasized that the detection of fecal signaling bacteria, particularly *E. coli* and fecal coliforms, in water designated for human ingestion is a definitive marker of faecal pollutants and a strong indicator of the potential occurrence of pathogenic microorganisms. Such contamination poses significant health threats, especially through the transmission of waterborne diseases. Ingesting water tainted with fecal matter exposes individuals to life-threatening infections such as cholera, typhoid fever, bacillary dysentery, diarrheal diseases, and other enteric infections. Kristanti *et al.* (2022) also noted that fecal contamination in groundwater may not only lead to gastrointestinal disorders but can also result in dermatological conditions and broader community health risks.

Given the severity of these health implications, stringent bacteriological standards have been established by regulatory agencies. According to WHO (2004), NEMA (2006), and USEPA (2012) guidelines, the acceptable limit for *E. coli* in drinking water is 0 MNP/100 mL, signifying that no detectable presence of this bacterium should exist in any sample of potable water. This standard underscores the necessity for continuous monitoring and robust sanitation infrastructure to safeguard groundwater sources, particularly in rural and peri-urban regions dependent on shallow wells

Table 2.2: Fecal Pollution in Water Used for Drinking and its Risks

Faecal Coliform level (MNP/100 mL Sample)	Risk	Recommended Action
0-10	Reasonable quality	Consume the water just the way it is.
10-100	Polluted	Treatment is necessary even though may be consumed that way. Water should be treated if at all feasible, even though may be consumed that way.
100-1000	Dangerous	Must be treated
>1000	Incredibly Dangerous	Should either rejected or must be treated very well before consumption.

Source: (Harvey, 2007)

2.3 Water Quality Index

By consolidating various chemical, physical, and microbiological parameters into one unified aggregate indicator, the WQI offers a simplified and uniform framework for examining the condition of water resources. Parameters frequently employed in the determination of WQI include hydrogen ion Levels (pH), levels of DO, BOD, total dissolved constituents (TDS), concentrations of nitrates and phosphates, as well as the presence of toxic trace elements like lead and arsenic. The proportional significance of these factors to environmental and public health requirements determines their weights (Chidiac *et al.,* 2023). Geographical location, water usage purpose, and local regulatory restrictions can all influence the factors used and the weighting scheme (Zhao *et al.,* 2021).

WQI represents a consolidated numerical value that encapsulates the general status of water quality at a specific location, derived from a range of critical water quality parameters (Jha *et al.,* 2020). It effectively condenses extensive and multifaceted data into a single value and categorizes water into defined quality classes very poor, poor, fair, marginal, good, and excellent (Manna and Biswas, 2023). WQI has experienced widespread international adoption as a standardized indicator for assessing the state of both surface and subsurface water bodies (Chabuk *et al.,* 2020; Ram *et al.,* 2021; Khan *et al.,* 2023; Patel *et al.,* 2023). It operates as a crucial evaluative structure that streamlines intricate water quality parameters into a unified, intelligible metric, thus facilitating efficient appraisal of drinking water suitability and ecosystem integrity. Moreover, WQI acts as a vital informational conduit, equipping policy formulators, environmental regulators, and interested parties with a coherent interpretation of overall water condition to promote evidence-based planning and sustainable aquatic resource governance (Banda and Kumarasamy, 2020).

In Kenya, the utilization of WQI has become increasingly vital for evaluating the status of surface and groundwater resources (Ochungo *et al.,* 2019). Research has indicated that groundwater from shallow wells and boreholes within agricultural regions often receives low WQI ratings due to pollution from fertilizer application and agrochemicals (Bretcan *et al.,* 2022). As a result, WQI functions not only as a pivotal metric for continuous surveillance of water quality but also as an indispensable instrument in guiding strategic decisions related to public health, environmental conservation, and the long-term stewardship of water resources (Gitau *et al.,* 2016). Furthermore, WQI has demonstrated significant utility in capturing and representing spatial and temporal fluctuations in water quality conditions. When coupled with GIS technologies, spatial visualization of WQI distributions allows policymakers and environmental planners to identify zones of critical contamination and allocate resources efficiently for remedial actions (Basharat *et al.,* 2025). This geospatial approach strengthens public engagement and fosters community-driven initiatives, especially in remote and rural localities where formal water quality assessments may be infrequent or lacking (Das, 2025). The advancement of mobile-based WQI evaluation applications further enhances this capability by enabling rapid, on-site testing and instant communication of results, thus promoting timely interventions and reinforcing transparency in water management practices (Ramesh, 2025).

A considerable number of researchers have consistently applied WQI to examins the safety and suitability of drinking water across diverse environmental and geographical contexts. For instance, Baloch *et al.* (2021) optimized the WQI framework to evaluate shallow groundwater in a semi-arid region of India. Their findings revealed that approximately 32.6% of the analyzed water samples were deemed unsuitable for human consumption due to elevated concentrations of specific harmful contaminants, such as nitrates, heavy metals, and microbial agents. The remaining samples exhibited a wide range of quality classifications, spanning from “good” to “poor,” thereby reflecting significant variability in overall water condition. Notably, several samples fell below acceptable safety thresholds and were identified as requiring pre-treatment measures such as filtration or disinfection prior to being considered safe for household or drinking purposes.

Similarly, Nsabimana *et al.* (2021) executed extensive evaluation of shallow groundwater quality in Tongchuan, China, using the WQI approach. The study revealed that 77.1% of the samples exhibited “excellent” quality, affirming the general portability of the water sources. However, the detection of specific contaminants underscored the necessity for regulating and sustainable water resource management to safeguard public health.

In a related study, Atta *et al.* (2022) evaluated groundwater near the Ismailia Canal in Egypt using WQI metrics. The outcomes unveiled that around 61% of the wells had water classified as “excellent” to “good,” whereas approximately 40% fell within the “poor” to “unsuitable” categories. This disparity reflects significant spatial variability in groundwater quality, necessitating targeted interventions and water quality improvement measures in the more affected areas

Onyango (2023) assessed the water quality in shallow wells in Nyalenda Estates, Kisumu County, Kenya, using WQI. The assessment established that 50% of the wells had "good" water quality, 30% were "fair," and 20% were "poor." These variations were attributed to factors such as nearness to pit latrines, waste disposal sites, and the depth of the wells. These results emphasize the necessity for enhanced sanitation and water management practices in informal settlements to ensure safe drinking water.

Table 2.3: Water Quality Index Categories and its Suitability

Water Quality Indwx level	**Status of Water Quality**	**Relation to Suitability Suitability of water for various purposes**
0-50	Excellent quality	Safe for drinking
50-100.1	Good water quality	Needs treatment. Water with few pollutants and are generally considered suitable for consumption with minimal or no treatment.
100-200.1	Poor water quality	Unsafe for drinking presence of some pollutants that may exceed recommended levels for drinking water. Water requires treatment to attain drinking water standards and may pose health risks if consumed untreated.
200-300.1	Extremely poor water quality	Unsafe for drinking must be treated thoroughly
300 and above	Not suitable water for consumption	Rejected or must be treated thoroughly, since it possesses serious health risks if consumed due to high concentrations of harmful contaminants, including pathogens and toxic chemicals.

Source: (Hamlat and Guidoum, 2018)

2.4 Conceptual Framework

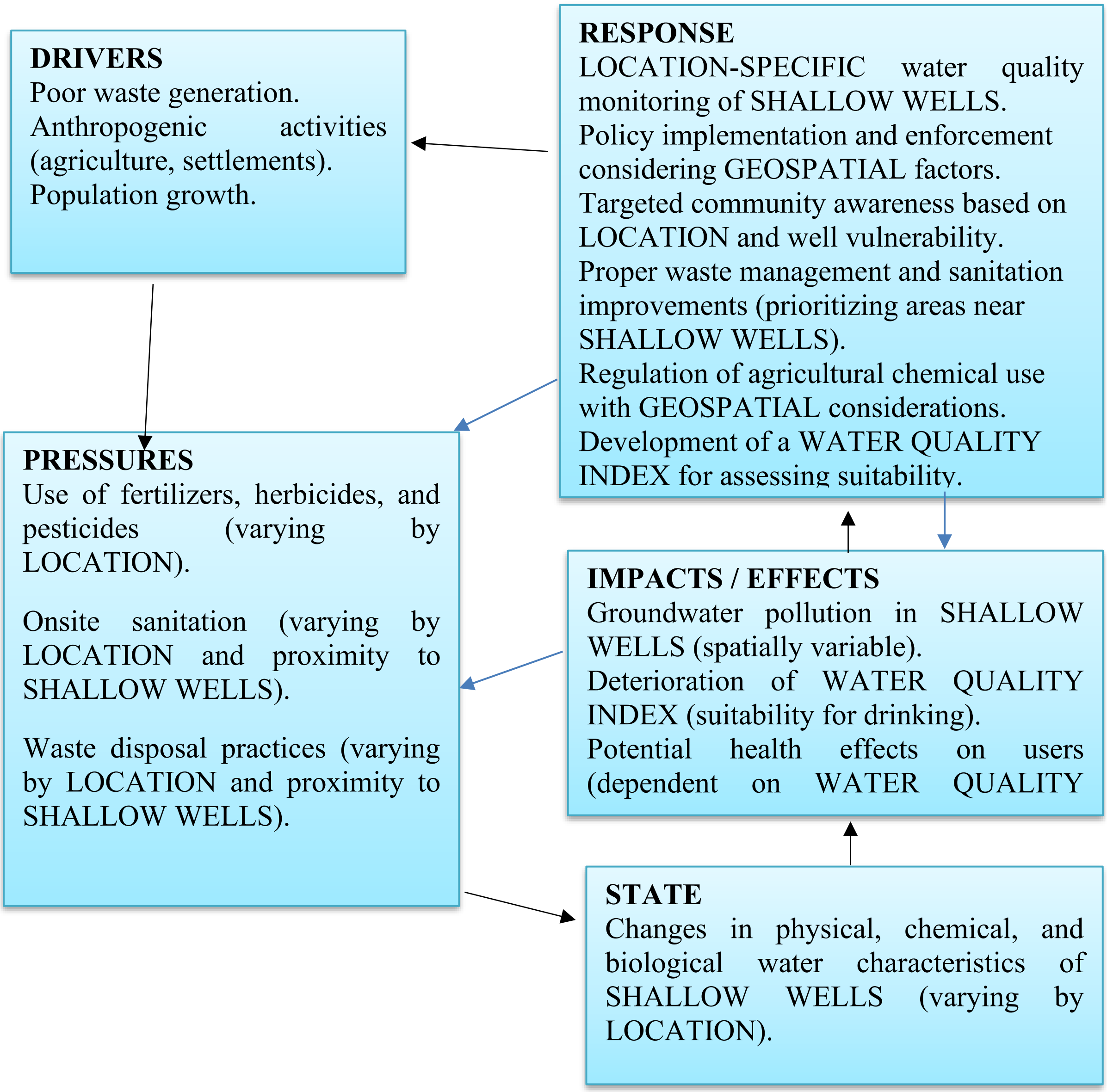

Figure 2.1: Conceptual framework for water quality in shallow wells in Kipsonoi sub catchment.

Source: Adopted and modified from the DPSIR framework from Europe Environmental Agency (1999).

This framework describes the reasons for the deterioration of water quality in the shallow wells in the Kipsonoi Sub-catchment caused by the drivers and pressures (Figure 2.1).

The conceptual framework demonstrates how various factors interact with one another to influence the water quality in shallow wells within the Kipsonoi sub-catchment, organized according to the DPSIR model (Drivers–Pressures–State–Impacts–Responses). Central to this model are socio-economic drivers such as inadequate waste management, human activities (like agriculture and urban development), and population increase, which place stress on the environment. These stresses are evident through the application of fertilizers, herbicides, pesticides, insufficient onsite sanitation, and improper waste management practices, all of which vary according to location and closeness to shallow wells. Such pressures result in alterations to the state of the environment, particularly affecting the physical, chemical, and biological properties of groundwater found in shallow wells. The resulting decline in water quality leads to consequences including groundwater contamination, a decrease in the Water Quality Index (WQI), and potential health hazards for users. In response, the framework proposes context-specific interventions including targeted monitoring, strict policy enforcement, community education initiatives, improved sanitation facilities, geospatial regulation of agrochemical applications, and the creation of a WQI to evaluate water safety. The model emphasizes the spatial differences in both contamination and vulnerability, pointing to the necessity for customized management approaches to guarantee safe drinking water within the sub-catchment.

2.5 Findings from Other Scholars

Numerous researchers have examined the geospatial arrangement of shallow wells and how their placements affect groundwater availability and quality (Chidiac *et al.,* 2023). These investigations utilize GIS, remote sensing, and field mapping methods to uncover spatial characteristics and the environmental or human factors that affect well locations.

Bonetto *et al.* (2021) analyzed the spatial arrangement of shallow wells in Central Rift Valley of Ethiopia. Their findings indicated a dense concentration of shallow wells in populated areas and agricultural regions which is along the eastern escarpment and highland margins. This distribution pattern was shaped by both the demand for water and the ease of drilling wells in particular soil types, raising concerns about groundwater over-extraction and potential contamination issues. Noori & Singh (2024) employed GPS data and GIS mapping to investigate the distribution of shallow wells. They noted that these wells were primarily situated along seasonal riverbeds and in depressions where groundwater levels were most accessible. Khan *et al.* (2021) conducted a mapping of shallow wells in the semi-arid areas of Rajasthan, India. Their spatial analysis revealed a clustering of wells in regions possessing greater infiltration capacity and alluvial deposits. The research underscored the impact of geomorphological features on the positioning of wells.

Kumar et al. (2023) undertook an extensive study across parts of Asia and identified that the fecal coliform content in groundwater frequently exceeded the maximum allowable concentrations stipulated by WHO for potable use, thereby deeming the water unsafe for human consumption. Correspondingly, Kipchumba (2015) analyzed physico-chemical attributes of water drawn from shallow wells. The context of this research was Koitoror Location and observed that nitrite levels surpassed the KEBS regulatory standards quality parameters for potable water during both the arid and rainy seasons, indicating persistent contamination. In support of these findings, Mbaka *et al.* (2017) assessed the water quality in selected shallow wells within the Keiyo Highlands and concluded that fecal coliform levels consistently violated WHO benchmarks, pointing to microbial infiltration and potential public health risks associated with untreated water usage.

Lutterodt *et al.* (2018) assessed the biological characteristics of shallow wells as well as boreholes in the Dodowa Area of Ghana and discovered that there was widespread fecal and bacterial pollution of groundwater. Chebet (2017) carried out research on patients with amoebiasis and found out that only 22 out of 255 patients (8.6%) interviewed had access to piped water. Mutai *et al.* (2021) examined the determinants contributing to infant mortality. The study was conducted in Chepalungu Sub-County, Bomet County, Kenya. The research found out that in households with unsafe drinking water, 27.5% of women lost more than one newborn, but only 9.7% of mothers lost more than one infant while using safe drinking water. Bomet County, Development Plan, 2018) carried out research in Bomet County and found out that only 11,940 households (8.45%) access piped water. Kaur and Sinha (2019) carried out research in Punjab (India) on the effects of pesticides in agricultural run-offs on water resources and found that the groundwater is at risk of pollution resulting from agricultural activities carrying herbicides, pesticides, fertilizers, and disease-causing organisms through infiltration or run-offs into the groundwater.

Numerous researchers have employed WQI as a standardized metric to evaluate the suitability and safety of drinking water across various geographic settings. Nsabimana *et al.* (2021) undertook a detailed investigation of shallow groundwater in Tongchuan, China, applying the WQI framework, and found that approximately 77.1% of the samples were classified as exhibiting superior, exceptional and high-grade quality. In contrast, Khan *et al.* (2023) conducted a study in Lahore, Pakistan, and reported WQI values ranging from 87 to 220, with the majority of sites surpassing the acceptable limit of 100, thereby deeming the water unsuitable for domestic consumption.

Table 2.4: Summary of Some Literature Reviewed and Gaps Identified.

S/n	Author	Research title	Summary finding	Gaps identified
1.	Kanda *et al.* (2023)	Assessment of groundwater quality in Vihiga County, Kenya	The water was contaminated with total coliforms and fecal coliforms due to the presence of the pit latrines and the sanitation around the dug-wells.	The geospatial distribution of the shallow wells were not determined.
2.	Mbura, (2018)	Assessment of selected physico-chemical factors of ground water in Tharaka Nithi county.	The water from the wells in the assessment area is not potable.	Biological analysis was not determined.
3.	Nyakundi *et al.* (2020).	Assessment of drinking water quality in Umoja Innercore Estate, Nairobi.	100% of boreholes recorded unsatisfactory water with up to 1100 *E. coli* indicating high contamination with faecal coliforms and 83% recording pH of up to 9.53.	Its effects on shallow wells were not determined.
4.	Tonui, (2018)	Impacts of effluent discharge from the Kapkoros tea factory into the Kipsonoi River on the local community of Bomet County, Kenya.	Water pollution (Kipsonoi River) emanates from factory discharges and farming as a consequence of the application farm chemicals like pesticides and fertilizers.	No laboratory tests were done. Its effects on the shallow wells were not determined.
5	Kipchumba (2015)	Assessment of drinking water quality in shallow wells in Koitoror location of Uasin Gishu County, Kenya.	Nitrite levels exceeded the KEBS acceptable limits for the water meant for drinking purposes both in dry and wet seasons.	Water Quality Index not determined.

2.6 Summary of Gaps in Literature

The empirical evidences reviewed reveals several deficiencies in evaluating groundwater and drinking water quality in Kenya. Kanda *et al*. (2023) noted contamination in shallow wells linked to inadequate sanitation practices, yet they did not ascertain the geospatial distribution of these wells. Mbura (2018) discovered that the groundwater in Tharaka Nithi County was unsuitable for drinking; however, the research lacked biological analysis, fundamental for well examination of water quality. Likewise, Nyakundi *et al.* (2020) documented significant faecal contamination and high pH levels in borehole water in Umoja Innercore Estate, Nairobi, but did not explore the impacts of such contamination on shallow wells.

Tonui (2018) associated water pollution in the Kipsonoi River with industrial discharges and agricultural runoff but failed to carry out laboratory tests or evaluate the effects of this pollution on adjacent shallow wells. These shortcomings emphasize the necessity for more integrated and spatially detailed studies that incorporate both physico-chemical and biological analyses, geospatial mapping, and more extensive environmental impact evaluations. Kipchumba (2015) carried out a detailed investigation into the physicochemical quality of drinking water extracted from shallow wells within the Koitoror locality of Uasin Gishu County, Kenya. The study established that nitrite concentrations in the groundwater samples consistently exceeded the maximum allowable threshold prescribed by KEBS for potable water, regardless of seasonal variations occurring during both the dry and rainy periods. Despite yielding critical insights into chemical contamination, the study's analytical depth was constrained by the omission of WQI evaluation, which could have facilitated a more integrated and multidimensional interpretation of the water's aggregate conformity to human consumption requirements.

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 Location of the Study area

3.1.1 Geographical Setting

The research region is the Kipsonoi Sub-Catchment in Bomet County, as seen in Figure 3.1. It spans an area of approximately 564 square kilometers. Bomet County shares a large length of Mau. The forest ecosystem functions as a vital sanctuary for a diverse array of flora and fauna, and is officially designated as a native or indigenous woodland. Spatially, it is situated between latitudinal coordinates 0º 29' and 1º 03' South, and longitudinal boundaries 35º 05' and 35º 35' East. This natural reserve shares its boundaries with Kericho County to the north and east, Narok County to the south, west, and southeast, Nyamira County to the northwest, and Nakuru County to the east. The forest occupies a total expanse of approximately 2,037.4 square kilometers, of which nearly 1,716.6 square kilometers are classified as agriculturally productive land, making it viable for farming and cultivation activities. This fertile terrain contributes significantly to regional food security and livelihoods (Bomet County Integrated Development Plan, 2018). Moreover, the forest plays a crucial ecological role in climate regulation, water catchment protection, and biodiversity conservation in the surrounding regions.

3.1.2 Topographical Features

Most of the Kipsonoi Sub-catchment has rolling hills, with flatter land in the western part. The sub-catchment is situated at an altitude/elevation ranging from approximately 1,540 to 3,000 meters above mean sea level (Bomet County Integrated Development Plan, 2018). The predominant topographical gradient descends southward across most of the area. However, the north-eastern section exhibits an upward incline, ascending eastward towards the Mau Ridges, which reach altitudes of about 3,000 meters.

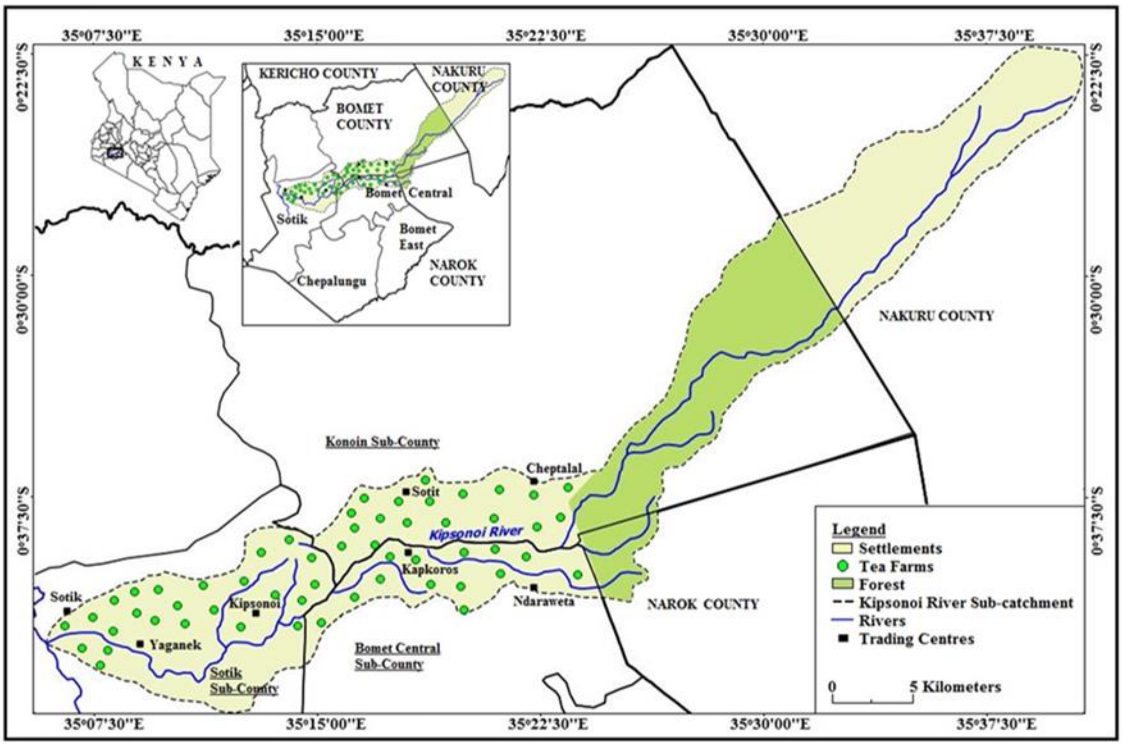

Figure 3.1: Location of Kipsonoi Sub Catchment in Bomet County

Source: Google Earth Satellite Image 2021, Topographic Sheet for Kisumu (SA-36-4)

3.1.3 Climatic Conditions

3.1.3.1 Rainfall

Kipsonoi Sub-catchment experiences moderate to substantial rainfall, typically ranging between 1,000 millimeters and 1,400 millimeters per annum. The distribution of rainfall is relatively consistent throughout the year, with the exception of a brief arid interval occurring in the months of January and February. The maximum rainfall levels are generally recorded during the months of April and May, marking the apex of the rainy season. The shift between the short dry period and the prolonged rainy phase is notably gradual and exhibits minimal variation across the entirety of Bomet County. This steady hydrological pattern contributes significantly to the reliability of water resources in the area, supporting both agricultural activities and ecological balance. Furthermore, the predictable climatic behavior enhances land-use planning and assists local communities in aligning farming cycles with seasonal changes (BCIDP, 2018).

3.1.3.2 Temperature

Kipsonoi Sub-Catchment experiences relatively moderate mean annual temperatures averaging approximately 21 °C. Temperature fluctuations typically range amid 16 °C and 24 °C throughout the year. The coldest period generally occurs between June and July, whereas the warmest season is observed amid January and February (BCIDP, 2018).

3.1.4 Socio-Economic activities

Agriculture is the main economic activity in the Kipsonoi Sub-catchment, where the majority of farmers practice mixed farming, with tea cultivation being the most dominant. Other crops cultivated in the region include Irish potatoes, beans, finger millet, sorghum, sweet potatoes, onions, tomatoes, kales, cabbages, avocados, and pyrethrum. Livestock farming is also common, involving cattle, sheep, goats, and poultry. Within the study area of Bomet County, tea farming stands out as the leading economic activity, as highlighted in the Bomet County Development Plan (2018).

3.1.5 Geology and Soils

The majority of Kipsonoi Sub-Catchment is underlain by Tertiary volcanic formations, whereas smaller portions comprise granitic, Bukoban, and Precambrian basement rock structures, as illustrated in Fig. 3.2. The predominant soils within the sub-catchment have developed on volcanic foothill ridges and are derived from dissected, ancient volcanic materials located on lower mountain slopes with undulating to hilly terrains. These soils typically exhibit a reddish-brown to dark brown coloration, possess a friable texture, feature acidic humus-rich topsoil, and demonstrate efficient drainage characteristics. In the western section of Kipsonoi Sub-Catchment, soils are primarily classified as clayey in nature. The hilly, rugged and elevated topography of the region contributes to reduced soil fertility, thus necessitating the regular application of chemical or organic fertilizers to support sustainable agricultural productivity

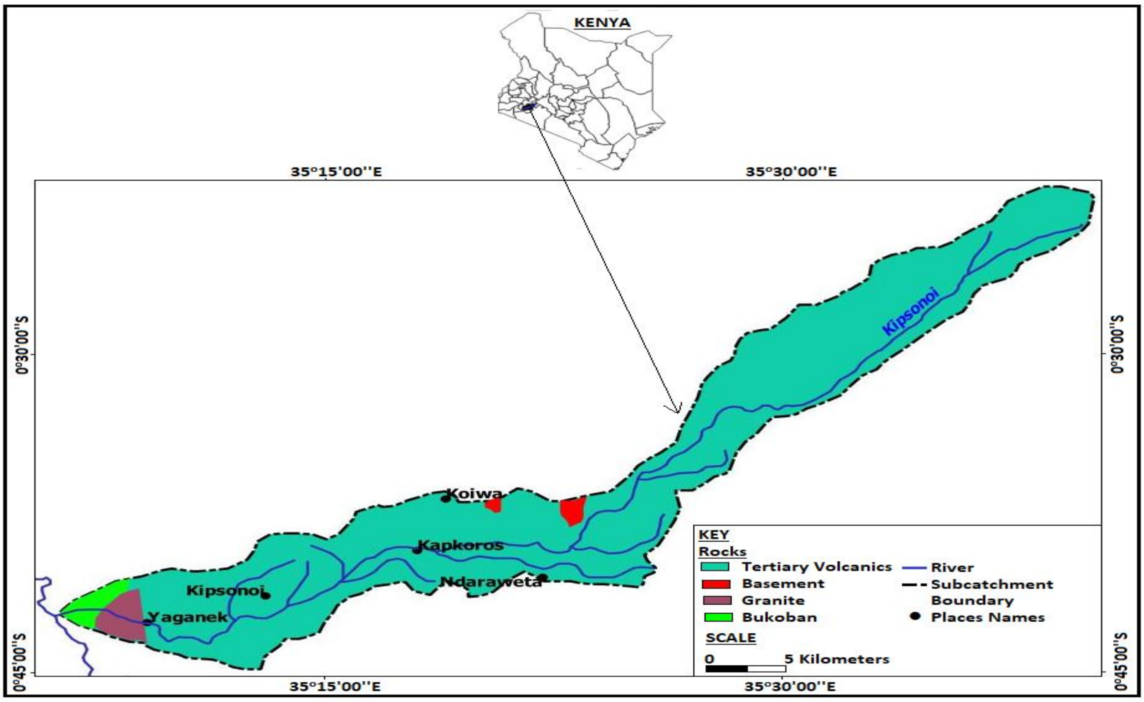

Figure 3.2: Geological Map of Kipsonoi Sub-catchment

Source: National Atlas of Kenya and Topographic Sheet for Kisumu (SA-36-4), Survey of Kenya.

3.1.6 Water and Sanitation

There is lack of sewage network in Kipsonoi Sub catchment and most of the residents use latrine for human waste disposal. Inadequate sewerage system in

Kipsonoi sub catchment has forced people to use soak pits and septic tanks for sewage disposal (Korir, 2018).

Oinab Ng'etunyet, Kipsonoi, Nyongores, Itare, Chemosit, Kiptiget, Maramara and Amalo rivers are permanent arising from the Mau Forest and flowing through Bomet County. River Sisei is rapidly shrinking as a result of intensive farming in the catchment areas and along the banks and it arises from numerous swamps that are found in Bomet Central Sub-county (Rotich, 2024).

3.2 Research Design

The assessment combines experimental and descriptive methods to comprehensively address the research objectives. The experimental method was selected for its capacity to produce accurate, empirical data on water quality indicators. This approach directly addressed the establishment of the basic physical, chemical, and biological indicator factors in shallow wells. Descriptive method was utilized in generating line graphs to interpret and communicate the experimental findings and generate maps showing the arrangement of shallow wells in connection to land use and potential contamination sources.

Table 3.1: Names of the sampled shallow wells in Kipsonoi sub catchment

LOWER CATCHMENT	MIDDLE CATCHMENT	UPPER CATCHMENT
SW5	SW4	SW2
SW6	SW8	SW3
SW7	SW11	SW18
SW9	SW12	SW15
SW10	SW13	SW16
SW23	SW14	SW17
SW24	SW21	SW18
SW25	SW26	SW19
SW27	SW28	SW20
SW29	SW30	SW22
	SW31	

3.3 Sampling Technique

The study utilized purposive sampling method. The survey discovered 150 shallow wells utilized for drinking water in the sub-catchment. The sub-catchment was divided into administrative units, in this case, 3 sub-counties and then sampling points were picked from the three sub-counties Sotik (lower catchment), Bomet Central (middle catchment) and Konoin (Upper and part of the middle catchment). The 31 wells were picked depending on the no of wells used for drinking in each sub county for instance 58 wells for drinking in Sotik Sub-county 12 wells were picked, 68 in Konoin Sub-county and 14 were picked and 24 in Bomet Central Sub-county and 5 wells were picked which makes a total of 31 sampled shallow wells. All existing shallow wells within the Kipsonoi Sub-catchment were first systematically identified. Subsequently, the minimum required sample size was determined using Lohr's (2021) sampling formula, taking into account the total population of shallow wells in the region. Sampling points were then strategically selected from various sub-counties, guided by both the density of wells and the intensity of anthropogenic activities observed within each respective area.

3.4 Data collection

Water samples were systematically gathered during both the dry and rainy seasons to capture and reflect possible seasonal variations in water quality elements. Shallow wells for sampling were picked considering their proximity to human activities like tea farms and dairy farms. Sampling and collecting were done early in the morning, before the sun warms up the air and ground, which may warm the water since high water temperatures encourage bacterial development, including potentially dangerous pathogens such as *E. coli*, since it allows for same-day delivery to the lab for faster analysis, which can be crucial for time-sensitive tests. Water specimens were obtained for physico-chemical evaluation and transferred into one-liter high-density linear polyethylene containers that had been pre-cleaned using 10% nitric acid. For microbiological examination, the samples were drawn into sterilized glass flasks, which had been decontaminated through dry heat sterilization at approximately 170 °C for a duration of three hours. Standardized protocols for sampling, preservation, transportation, and laboratory analysis, as recommended by Ameerican Public Health Association (APHA) guidelines, were strictly followed. Each specimen was appropriately labeled with relevant source information, including the collection date and time. The samples were then set in insulated cooler boxes for safe transport and were examined upon arrival at the analytical facility. All collected water specimens were tested within a 24-hour timeframe to maintain integrity and reliability of results.

3.5 Determination of Geospatial distribution of Shallow Wells

A handheld GPS receiver was utilized to pick the location and the geospatial distribution of the shallow wells, as well as to record their geographically referenced coordinates, which were then mapped using Arc GIs. This was done by importing the shape files to the Arc map as a layer, and then geographically referenced coordinates in Excel format were overlaid on it. A spatial map illustrating the geographical arrangements of shallow wells within the sub-catchment was subsequently developed.

3.5.1 Determining the Sample size

During the pre-visit a month prior to sampling 150 shallow wells were identified. Lorh's (2021) formula, $n = \frac{k}{1} + \frac{N}{k}$ which gives the method for getting the sample size was be used in this research which gives the phases for gaining the least sample size.

Where: n = the Sample size,
N = represent Total population size
S = Denotes the greatest in the population factor (total error $=0.1$at a confidence degree of 95%)
While V = Denotes standard error of sampling distribution which is equals to 0.05,
P = Denotes population factors, and

$$k=\frac{s^2}{v^2}$$

$$n=\frac{k}{1}+\frac{N}{k}$$ ………………………………………………………………….. *Equation 3.1*

$k=\frac{s^2}{v^2}$ Where,

$$S=P(1-P)=0.5(1-0.5)=0.25^2$$

Therefore, $s^2=0.25^2$

In establishing the least sample size of the shallow wells where:

$$N=150$$

$$k=\frac{s^2}{v^2}=\frac{0.25}{0.05225}$$

$$n=\frac{k}{1}+\frac{N}{k}$$

$$=\frac{25}{1}+\frac{150}{25}$$

$$=30+1=31$$

This makes the sample size to 31.

3.5.2 Sampled shallow wells in Kipsonoi Sub-Catchment.

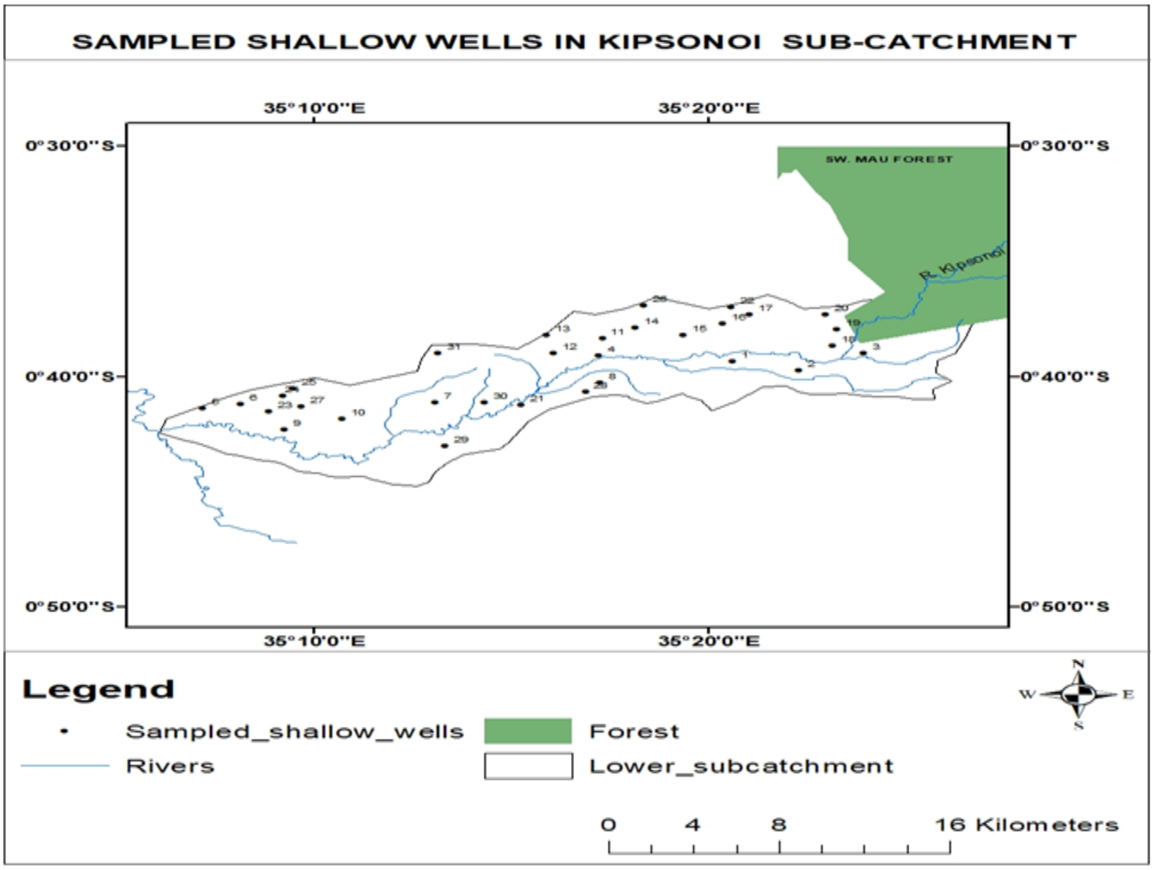

Figure 3.3: A Map of Kipsonoi Sub Catchment showing the sampled shallow wells

3.5.3 Field Analysis (Determination of basic Physical Parameters)

Indicator parameters, for instance, TDS, pH, temperature, EC and turbidity, were determined insitu due to their susceptibility to rapid alteration influenced by temporal and thermal variations. The on-site assessment of these parameters was conducted using a portable multiparameter probe (Hanna HI 9829, manufactured in 2017). For pH, EC and TDS analysis, the conducting cells were calibrated prior to analysis using predetermined readings from known standards. This was done by immersing the probe in calibration solutions with known conductivity values for EC and TDS and pH in buffer solutions with known pH values. At every stage of assessment, the probe cells were meticulously washed with distilled water, and then the experiment's control was run. The probe cells were then lowered into the sample, and then the sample was logged in and waited for it to stabilize. Finally, the readings for electrical conductivity in micro Siemens units, TDS in mg/L, pH temperature in degrees Celsius, and turbidity in NTU were taken and recorded.

3.5.4 Chemical Laboratory Analysis

Other parameters were analyzed in Water Resources Authority and Tea research laboratories using standard methods of analysis. The parameters to be analyzed were selected based on the predominant agricultural activities in the area.

3.5.4.1 Determination of Total Hardness

To accurately gauge aggregate hardness present in the collected water samples, the Ethylene Diamine Tetra Acetic acid (EDTA) complexometric titration method was employed due to its high precision and reliability in quantifying calcium and magnesium ions. A measured volume of 100 milliliters of the water sample was transferred into a clean and dry Erlenmeyer flask, ensuring there was no prior contamination. Subsequently, 1 milliliter of buffer solution was added to adjust and maintain the pH around 10, which is optimal for complex formation. A few drops of Eriochrome Black T indicator, known for its sensitivity to metal ions, were introduced to the solution. The contents were gently but thoroughly shaken to achieve a uniform mixture. Titration was then carried out using a standardized EDTA solution until the solution's color shifted from purplish to a stable sky-blue, signaling the endpoint, which indicates the complete complexation of hardness-causing ions. The total hardness was finally determined using Equation 3.2

$$Total\ Hardness = \frac{ml\ EDAT * B\ 1000}{ml\ of the\ Sample} \quad (3.2)$$

Where: B = CaCO3 in mg, which is equal to 1milliliter of EDTA standard solution

3.5.4.2 Determination of Alkalinity

Alkalinity was determined through the standard titration method to assess the buffering capacity of the water sample. A volume of 40 milliliters of the sample was carefully measured and transferred into a clean conical flask. Subsequently, 2 milliliters of reagent were added, followed by a single drop of buffer solution. The mixture was then thoroughly stirred to ensure complete interaction. It was then titrated against methyl *blue* orange using a digital titrator until colour color changed to blue, then measurements were read and values recorded.

3.5.4.3 Determination Analysis of Nitrate Concentration

The colorimetric technique was optimized to determine the nitrate levels present in the water specimens. Precisely 20 milliliters of the sample were introduced into a test tube designated for calibration. Subsequently, 2 milliliters of SPADNS reagent were incorporated into another 10 milliliters of the sample within a separate test tube, followed by vigorous shaking until a yellow coloration appeared, corresponding to the nitrate concentration. The resulting solution was then analyzed using a DR/890 portable colorimeter, and the readings were systematically recorded.

3.5.4.4 Determination Analysis of Sodium Concentration

Flame Photometric Method was optimized to establish degree of sodium (Na^+). To standardize the flame photometer, a 20 mg/L solution of NaCl was prepared. The photometer's filter dial was adjusted to choose the sodium wavelength, after which the device was powered on and configured to the 20 mg/L reference point. The instrument was then standardized to confirm the attainment of the targeted concentration. Following each of the ten sample measurements, the apparatus was re-standardized to maintain accuracy within the 20 mg/L threshold. Calibration graphs for sodium were generated and utilized to compute the concentrations in milligrams per liter (SM 3500 APHA, 2023).

3.5.4.5 Determination of Potassium Concentration

The Flame Photometric technique was optimized to quantify concentration of sodium (Na^{+}). To standardize the flame photometer, a 20 mg/L solution of NaCl was prepared. The photometer's wavelength selector was adjusted to detect sodium, and the device was powered on and configured to the 20 mg/L benchmark. The instrument was subsequently fine-tuned to confirm that the target concentration of 20 mg/L was attained. Following every ten sample assessments, the equipment was re-adjusted to verify that the measurements remained within the specified 20 mg/L limit. Calibration plots for sodium were developed and employed to determine the concentration values in milligrams per liter (SM 3500 APHA, 2023).

3.5.4.6 Determination of phosphate Concentration

The level of phosphate in the obtained water specimens was assessed through the colorimetric technique, a dependable procedure for identifying and quantifying phosphate content. Initially, 20 milliliters of the specimen were precisely transferred into a sanitized test vessel for calibration purposes. In a separate tube, a 10-milliliter fraction of the water sample was blended with 2 milliliters of SPANDS reagent, a compound that selectively interacts with phosphate ions. The mixture was then vigorously agitated to ensure thorough reaction. The emergence of a blue corolation/tint signified the existence and magnitude of phosphate elements. The chromatic intensity was subsequently evaluated using a DR/890 photometer, and the corresponding values were meticulously documented for additional interpretation

3.5.4.7 Determination of fluoride Concentration

The colorimetric method was utilized to evaluate the fluoride concentration in the collected water specimens. Initially, 20 milliliters of the water sample were accurately transferred into a test tube designated for calibration purposes. In a separate test tube, 10 milliliters of the sample were mixed with 2 milliliters of SPANDS reagent, a chemical compound that reacts selectively with fluoride ions. The solution was then vigorously agitated to promote complete interaction until a reddish coloration developed, with the intensity of the hue corresponding to the fluoride levels present in the sample. The resulting color intensity was subsequently assessed using a DR/890 colorimeter, and the respective values were systematically recorded for analysis.

3.5.5 M microbial Analysis (Determination of E. coli)

The water samples was then be removed from the ice chest as soon as they get to the laboratory, where they were given some time to warm to a normal temperature. Prior to any analysis, the incubation chamber was sterilized and cleaned thoroughly to prevent contamination. Fecal coliform (*E. coli*) and total coliform counts was done using defined substrates. These were chosen since their presence in water indicates fecal pollution. *E. coli* levels were quantified using the multiple-tube fermentation (MTF) method, a standard approach for detecting coliform bacteria in water. Initially, all glassware, including pipettes and test tubes, was disinfect by an autoclave set at 121 °C for a duration of 15 minutes to ensure aseptic conditions. A nutrient medium, MacConkey broth, was then prepared by dissolving 40 grams of the powder in 1 liter of distilled water within a volumetric flask to form a homogeneous solution. Subsequently, aliquots of 10 ml, 1 ml, and 0.1 ml of the water sample were aseptically dispensed into three sets of sterilized test tubes using sterile pipettes. Correspondingly, 10 ml, 5 ml, and 5 ml of the prepared MacConkey broth solution were added to each respective set of tubes and mixed gently to ensure uniform distribution. The inoculated tubes were incubated in an upright orientation at 37 °C for 24 hours. A color change across the serial dilutions indicated microbial activity, and the existence of E. coli was interpreted using the (Most Probable Number) MPN technique. The MPN per 100 ml of the original sample was estimated by cross-referencing the observed outcomes against standard MPN tables, providing a statistically derived estimation of E. coli concentration in the sample.

3.6 Determination of the Water Quality Index

Sampling

In the assessment of WQI, ten critical water quality indicators were systematically selected based on their occurrence frequency and potential health hazards linked with potable water, in alignment with WHO guidelines (2006). The selected parameters comprised TDS, pH level, total hardness, alkalinity, EC, turbidity, sodium ions (Na^+), phosphate ions (PO_4^{3-}), potassium ions (K^+), and nitrate ions (NO_3^-). The inclusion of these variables was primarily guided by their recurrent detection in various groundwater sources and their considerable impact on the general quality and safety of drinking water, as substantiated by Ibrahim (2019). These parameters collectively offer extensive general view of the physicochemical profile of water, thus ensuring a more vigorous and holistic examination of its suitability for human consumption.

Data Collection

For each of the selected parameters, groundwater samples were analyzed to obtain measured concentrations. The obtained measurements were subsequently evaluated against WHO (2006) guidelines for drinking water to determine conformity with international standards and to identify potential health hazards. Every water quality factor was allocated a specific unit weight (wi), reflecting its relative significance to human health. Parameters considered to exert minimal health effects, such as EC, potassium (K^+), and phosphates (PO_4^{3-}), were assigned the lowest weight of 1. A moderate weight of 2 was attributed to total hardness, denoting its intermediate relevance. Conversely, parameters with elevated health implications, including pH level, sodium (Na^+), and turbidity, were given a higher weight of 4. The most critical parameters TDS, nitrates (NO_3^-), and fluoride received the optimum weight of 5, due to their pronounced consequential significance on overall water safety and public health.

Data Analysis

The data analysis involved several computational steps to derive the WQI. First, the relative weight *(Wi)* of every parameter was computed by dividing its unit weight by the total sum of all assigned weights which is 32, utilizing equation 3.3. This ensured that every element's contribution to the overall index was proportional to its health relevance.

$$Wi = \frac{wi}{\sum_{i=1}^{n} wi} \qquad (3.3)$$

Whereby, Wi = *Relative weight*

n = *no of parameters*

wi = *weight of each parameter*

Next, a rating scale (Qi) was computed using equation 3.4 for each parameter by dividing the measured concentration by the WHO's acceptable limit and multiplying by 100. The ideal value for each parameter was also considered, with pH having an optimal value of 7, while all others were assumed to be 0 in pure water.

$$Qi = \left(\frac{ci - 1i}{si - 1i}\right) x100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.$$

.(3.4)

Where,

Ci = the concentration equivalent to the ith parameter in mg/L at a particular sampling point,

Ii = the optimal value of the ith parameter in pure water (i.e., the optimal value for pH is equals to 7 and 0 for all the other parameters),

Si = the WHO acceptable limits for drinking water for the ith parameter in mg/L

Following this, sub-indices (SIi) were determined by multiplying the rating scale of each parameter by its respective relative weight using equation 3.5.

$$SIi = WixQi \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.5)$$

Whereby, *SIi is the sub-index value for the ith parameter.*

The final Water Quality Index (WQI) was then obtained by summing all sub-indices using equation 3.6.

$$WQI = \sum_{t=1}^{n} SIi \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.6)$$

The calculated WQI values were employed to classify water quality into five descriptive categories: excellent (0–50), good (50.1–100), poor (100.1–200), very poor (200.1–300), and unfit for drinking (above 300), following the classification system outlined by Hamlat and Guidoum (2018). This method offered a thorough and quantitative means of evaluating the suitability of groundwater for human consumption, based on standards and calculation procedures endorsed by the WHO.

Table 3.2: Standards and unit weights for groundwater quality parameters

	Standard limitations (s_i)	**Weight assigned(w_i)**	**Relative weight (W_I)**	**Rating scale(Q_i)**
Conductivity	1200	1	0.03125	16.8
Potassium	200	1	0.03125	3.65
Phosphate	30	1	0.03125	16.33
Total Hardness	500	2	0.0625	3.8
pH	6.6-9.2	4	0.125	321.25
Sodium	200	4	0.125	4.975
Turbidity	5	4	0.125	1420
TDS	1000	5	0.15625	10
Nitrates	10	5	0.15625	379
Fluoride	1.5	5	0.15625	27.33
		$\sum wi = 32$	**$\sum WI = 1.00$**	

Source: Ram *et al.* (2021); El Baba *et al.* (2020).

3.7 Statistical Data analysis

The exact geographic coordinates of all identified shallow wells within the Kipsonoi Sub-Catchment were captured using a handheld GPS device. These spatial data points were digitized and mapped in ArcGIS to produce a detailed geospatial distribution map of the wells. Laboratory analysis results from the collected water samples were carefully recorded in Microsoft Excel spreadsheets for organization and initial processing. Subsequent statistical analysis was performed using SPSS to extract meaningful insights from the data. Descriptive statistical measures—including arithmetic mean, standard deviation, and variance—were calculated to summarize the central tendencies and variability of the observed parameters. To aid interpretation and effectively illustrate trends, line graphs were created in Microsoft

Excel, comparing the physical, chemical, and microbiological characteristics of groundwater against regulatory standards set by agencies such as NEMA, USEPA, and WHO.

To examine seasonal fluctuations, inferential statistical techniques were employed, specifically utilizing the Student's t-test, to compare the average concentrations of water quality indicators between samples collected during the dry and humid (wet) periods. A confidence level of 95% was applied, whereby a p-value less than 0.05 denoted a statistically significance difference, while a value exceeding 0.05 implied the absence of significant seasonal variation. Furthermore, to appraise the drinkability and appropriateness of groundwater for human intake, the Water Quality Index (WQI) was meticulously computed. This aggregated metric provided a comprehensive representation of the cumulative effects of various physicochemical parameters on public well-being and ecological security, serving as an essential tool for water resource management and policy development.

Table 3.3: Matrix of Statistical Analysis Methods and Presentation Tools by Objective

Objective	Variables/Indicators	Analysis Method	Statistical Tool/Software	Presentation Method
i) To establish the geospatial distribution of shallow wells	GPS coordinates of shallow wells	Geospatial mapping	ArcGIS 10.8	Maps showing spatial distribution of shallow wells
ii) To establish the physical, chemical and biological indicator parameters in shallow wells in the Kipsonoi Sub catchment during the dry and wet season	Physical Parameters: Temperature, pH, EC, Turbidity Chemical Parameters: Nitrate, Fluoride, Iron, etc.Biological Parameters:, *E. coli*	Descriptive statistics, seasonal comparison	SPSS v20 (t-test, mean, Standard Deviation), MS Excel	Line graphs, comparative tables
iii) To establish e the suitability of water from the shallow wells in the Kipsonoi Sub catchment for drinking purposes	Combined water quality indicators	Water Quality Index (WQI) computation	SPSS/Excel (WQI formula)	WQI rating tables, interpretation against WHO/NEMA /USEPA guidelines

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Introduction

This section comprehensively delineates the findings associated with the spatial distribution and density of shallow wells located within the Kipsonoi Sub-Catchment. In addition, it presents detailed results derived from the physico-chemical and microbiological evaluations conducted on groundwater samples obtained during extensive field investigations. The analyzed data are systematically presented using statistical tools, including line graphs and tabular formats, to illustrate trends, variations, and relationships among the measured water quality parameters. These analyses aim to offer a clear apprehension of groundwater quality variations, highlighting potential public health concerns and environmental implications linked to human consumption and agricultural use in the region.

4.2 Geospatial Distribution of Drinking Water Shallow Wells in Kipsonoi Sub-Catchment

The study documented a total of 321 shallow wells distributed across Kipsonoi Sub-Catchment (Figure 4.1), serving multiple domestic and agricultural purposes. Of these, 150 wells representing approximately 46.7% are primarily utilized for drinking water. A spatial breakdown reveals that 96 of these drinking wells (64%) are pinpointed in the upper section of the sub-catchment, while the rest 54 wells (36%) are situated in the lower region. The notable concentration of wells in the upper Kipsonoi Sub-Catchment can likely be attributed to factors such as higher population density, favorable hydrogeological conditions, or greater water demand in that area. of a higher population density necessitating more wells to gather for the water demand in the region. Additionally, favorable topographic conditions for groundwater accumulation, potentially more permeable soils, and proximity to surface water sources.

What influences the optimization of the shallow wells, either for drinking needs or for livestock, is that the residents relied on traditional knowledge to determine fitness of a shallow well for different uses for instance, presence of small aquatic organisms like frogs and fish may be used to detect clean water since their presence is seen as a sign of safe water for drinking.

The study found that there are many shallow wells in Konoin Sub-county and Sotik Sub-county due to the larger population, which led to a greater demand for water for various purposes, including drinking. There were no shallow wells at all in other sections of the lower Kipsonoi Sub-catchment due to the soil composition of the region, which was mainly clayey, allowing small or no water transmission to aquifers. Alternative water sources like rainwater harvesting, bore holes (which are very few), springs and water from the nearby rivers were used in some parts of the sub catchment, and therefore fewer shallower wells were found there.

Some wells were found to be unfunctional due to poor construction and workmanship; for instance, a lack of standard sealing allowing surface water and contaminants to seep in, compromising the water quality and potentially clogging the well over time, rendering it unusable over time (Taleghani & Santos,2023). In addition, there was also the lowering of the water table or completely drying up of some shallow wells during the dry season. Plate 4.1 is a sample of a shallow well in the Kipsonoi sub-catchment, and Figure 4.2 depicts the sampled shallow wells in the sub-catchment.

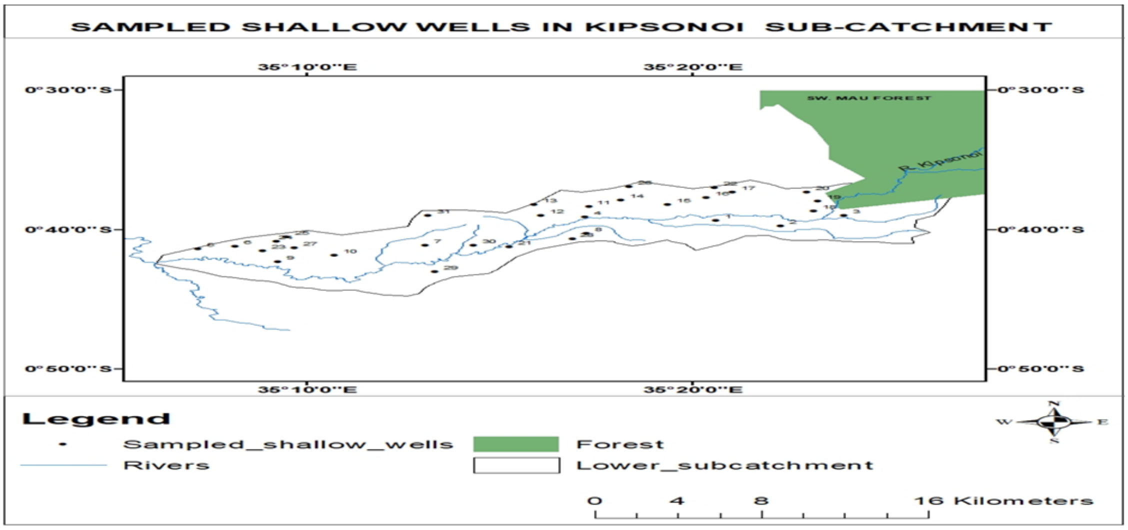

Figure 4.1: Geospatial distributions of drinking water shallow wells in Kipsonoi Sub-Catchment

Plate 4.1: Sample of a shallow wells in Kipsonoi Sub Catchment.

4.3 Levels of Physical, Chemical and Biological Parameters from Shallow Wells in Kipsonoi Sub Catchment

4.3.1 Physical Parameters

4.3.1.1 Temperature

The average temperature values recorded from shallow wells within the Kipsonoi Sub-Catchment ranged between 21.42 °C and 22.85 °C, as shown in Figure 4.2. The lowest temperature, 21.42 °C, was recorded at sampling point SW31, while the highest, 22.85 °C, was observed at SW19. All recorded temperatures were within the acceptable range for drinking water, which spans from 20 °C to 35 °C, as outlined by the The average temperature values recorded from shallow wells within the Kipsonoi Sub-Catchment ranged between 21.42 °C and 22.85 °C, as shown in Figure 4.3. The lowest temperature, 21.42 °C, was recorded at sampling point SW31, while the highest, 22.85 °C, was observed at SW19. All recorded temperatures were within the acceptable range for drinking water, which spans from 20 °C to 35 °C, as outlined by NEMA (2006) and WHO (2004).

Temperature is a key physicochemical parameter in water quality assessment due to its influence on gas solubility, chemical reaction rates, and microbial growth in aquatic systems (Prest *et al.,* 2016). Fluctuations in temperature can also impact the taste and palatability of drinking water, highlighting the need for regular monitoring. As temperature increases, water tends to lose dissolved carbon dioxide and other volatile compounds that contribute to its taste, thereby reducing its palatability (Shahjahan *et al.,* 2018).

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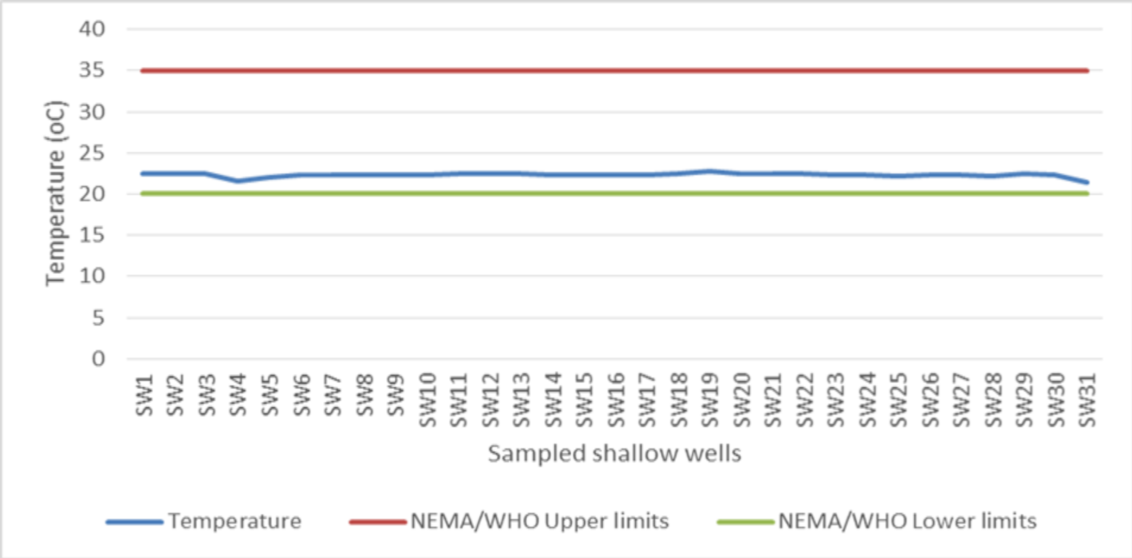

Figure 4.2: Levels of Temperature of the sampled shallow wells.

The thematic map (Figure 4.3) displays the distribution of temperature. Differences in the shallow well water temperatures could be due to different water table depths, as seen in research done by Cavelan *et al.* (2022).

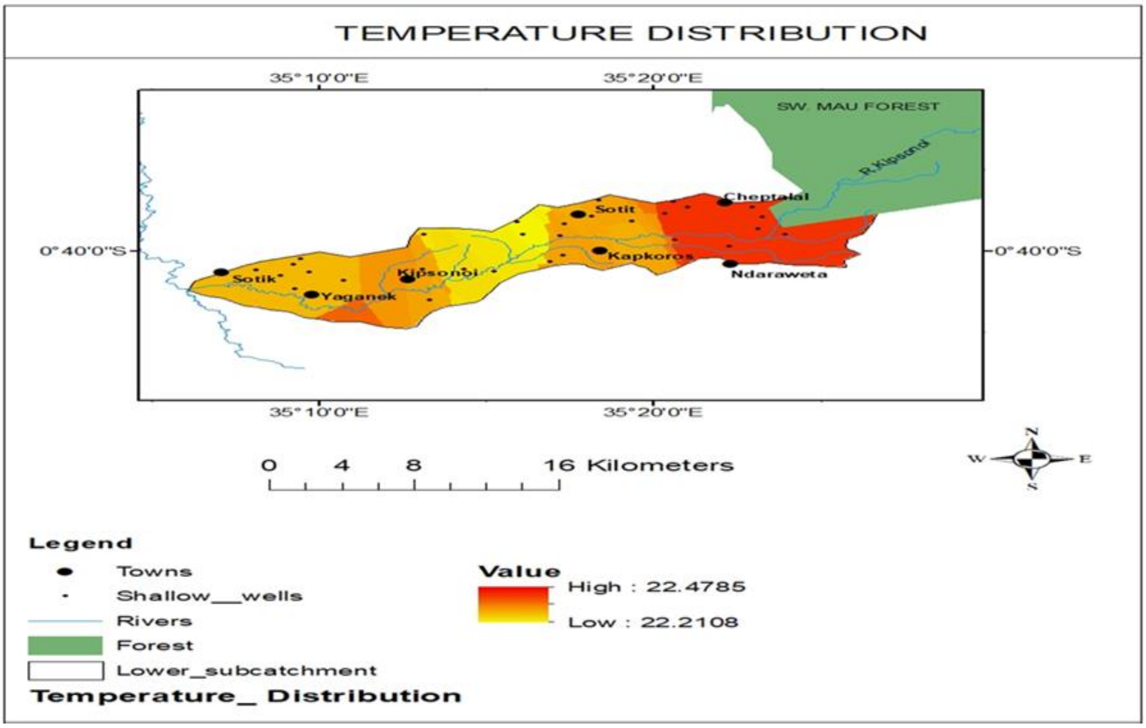

Figure 4.3 Spatial distribution of Temperature in Kipsonoi Sub Catchment.

4.3.1.2 Turbidity

Average turbidity concentrations recorded in the examined shallow wells changed amid 1.12 NTU and 75.5 NTU, as depicted in Figure 4.4. A considerable fraction approximately 70.97%—of the assessed wells displayed turbidity levels that exceeded the allowable threshold of 5 NTU, as outlined by NEMA (2006) and WHO (2004) for potable water. The least turbidity measurement, 1.12 NTU, was observed at SW22. This particular well was partially protected by natural grass vegetation, which served to reduce the influence of erosion caused by wind and rainfall commonly responsible for transporting loose soil particles into exposed water bodies, especially during the rainy season.

On the other hand, the peak turbidity value of 75.5 NTU was detected at SW7, a site characterized by insufficient structural safeguards. The well was inadequately enclosed with loosely positioned timber planks and a makeshift drum cover, which failed to block the entry of suspended solids. Its proximity to inclined farmlands subjected to continuous tilling may have further amplified sediment infiltration through surface runoff. Field observations indicated that about 90% of the sampled shallow wells were shielded using temporary wooden coverings, making them highly susceptible to contamination from overland flow, as portrayed in Plates 4.3 and 4.4. The use of degraded tyres (Plate 4.2) and corroded metal drums (Plate 4.4) as substitute covers also aggravated the likelihood of foreign material and pollutant ingress.

These outcomes are aligned with earlier investigations executed by Adongo et al. (2022) and Ashun (2014), who discovered that pollution of shallow well water was largely attributed to poor engineering of the wellheads and the absence of reinforced protective aprons. These structural inadequacies play a pivotal role in undermining groundwater integrity, particularly during intense rainfall episodes.

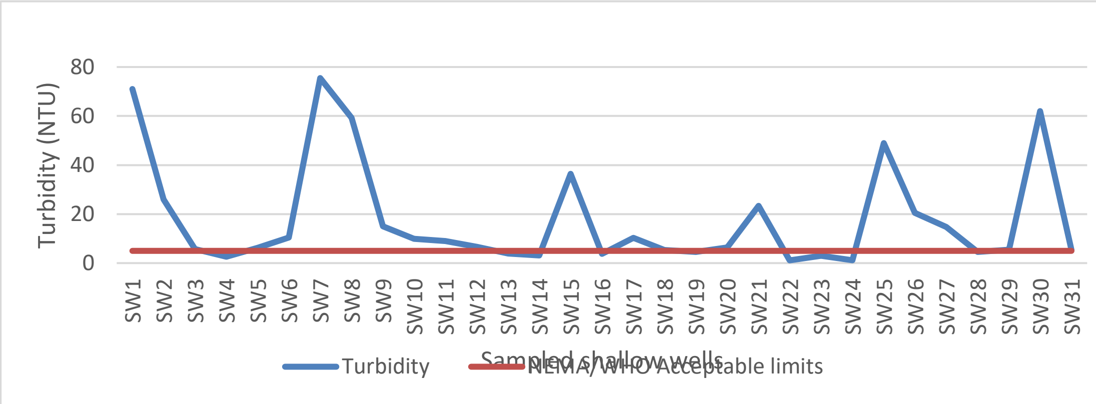

Figure 4.4: Levels of Turbidity of the sampled shallow wells

Plate 4.2: An unprotected shallow well (SW1) located near maize farm

Plate 4.3: An unprotected shallow well (SW30) located near maize farm.

Plate 4.4: An unprotected shallow well (SW8) located near tea farm and cattle Kraal.

Plate 4.5: An unprotected shallow well (SW7) located near a banana farm and cattle Kraal.

The thematic map in Figure 4.5 indicates the distribution of turbidity in the assessment area. Parts that exhibited high levels of turbidity could be attributed to increased runoff incidents, especially during tilling or harvest seasons, leading to contamination. Sections that exhibited low levels of turbidity had vegetation cover, for instance, grass around the shallow wells.

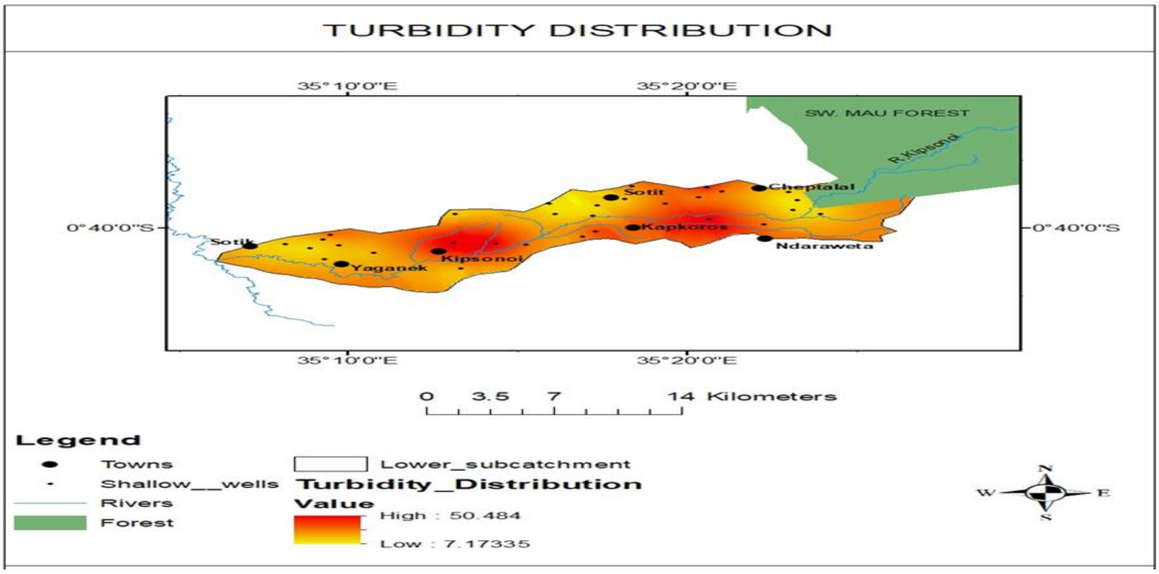

Figure 4.5: Spatial distribution of turbidity in Kipsonoi Sub Catchment

4.3.1.3 pH

The average pH levels in the shallow wells that were sampled in Kipsonoi Sub Catchment were ranging from 5.21 to 7.85(Figure 4.6). The lowest levels of pH of 5.21 was recorded in SW30. This could be as result of excessive utilizationof acidic fertilizers like DAP and NPK fertilizers applied to the maize and tea farms in areas near the shallow well. The highest levels of 7.85 was recorded in SW8 and this might be attributed to the weathering of rocks. The listed geological formations (tertiary volcanics, granites, and Bukoban rocks) can all contribute to the high pH following weathering (Gevera and Onyari, 2024).

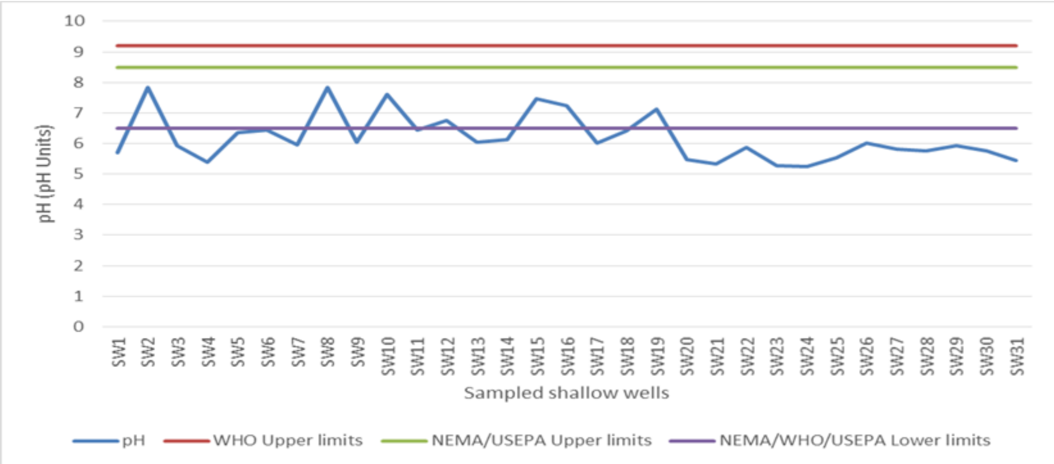

Figure 4.6: Levels of pH of sampled shallow wells.

The thematic map for pH is shown in Figure 4.7. Parts that exhibited low pH levels (acidification) of water could be due to the release of acidic water from the tea farms with excessive use of acidic fertilizers and also compost manures from the livestock kraals and farms. Conversely, parts that exhibited high pH concentrations could be due to the weathering of tertiary volcanic, granitic, basement and bukoban rocks present in the Kipsonoi Sub catchment. The geological formations (tertiary volcanics, granites, basement and Bukoban rocks) can all contribute to the high pH following weathering since, during weathering, they release alkaline elements into the surrounding soil and water, raising the pH (Gevera and Onyari, 2024; Adabanija *et al.,* 2020; Embaby and Ali, 2021).

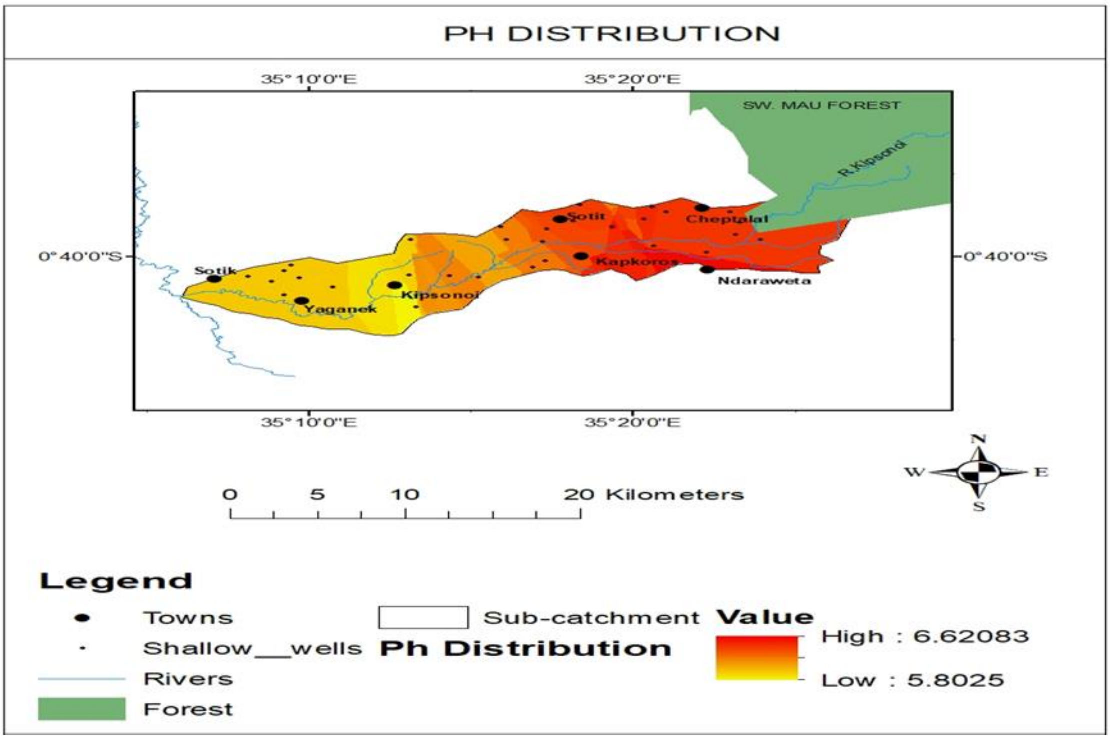

Figure 4.7: Spatial distribution of pH in Kipsonoi Sub Catchment.

4.3.1.4 Total Dissolved Solids

TDS's mean value for water from the shallow wells in Kipsonoi Sub-Catchment spanned from 10 mg/l to 100 mg/l (Figure 4.8). All values recorded for TDS were within the USEPA (2012), WHO (2004) and NEMA (2006) acceptable limits for drinking purposes. TDS of 10 mg/l was recorded in SW22, which had a drum surrounding it and some grass cover around the well, whereas TDS of 100 mg/l was recorded in SW1, which had a timber cover and no vegetation to reduce runoff. This is corroborated by the assessment executed by the Mbaka *et al.* (2017), who discovered that wooden boards employed to seal the shallow wells did not fully enclose them, thereby permitting debris and surface flow to infiltrate the wells

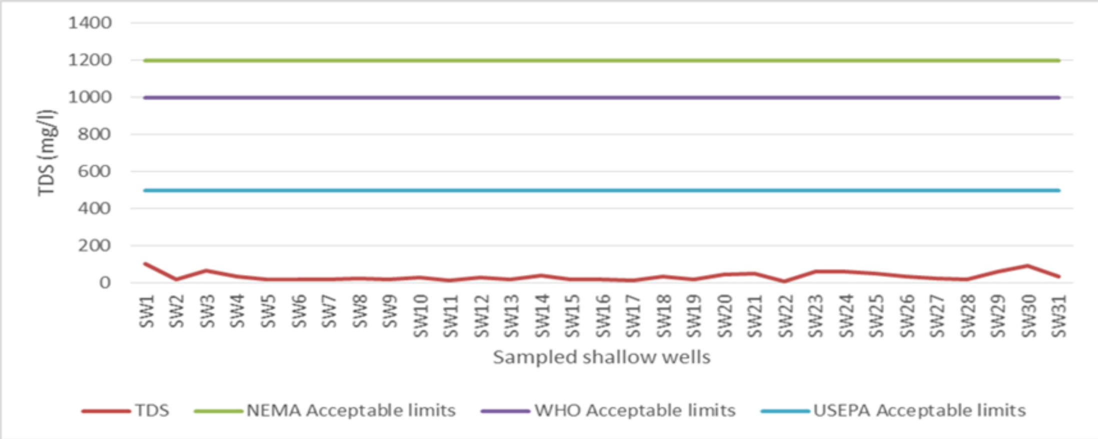

Figure 4.8: Levels of Total Dissolved Solids of the sampled shallow wells

The thematic map generated for TDS is shown in Figure 4.9. Parts that exhibited high levels of TDS could be attributed to intensive agriculture coupled with the fact that over 80% of the sampled shallow wells were not well protected, hence contributing to surface runoff, especially during heavy rainfall events, carrying dissolved salts through agricultural runoff and other contaminants from fields into the shallow wells.

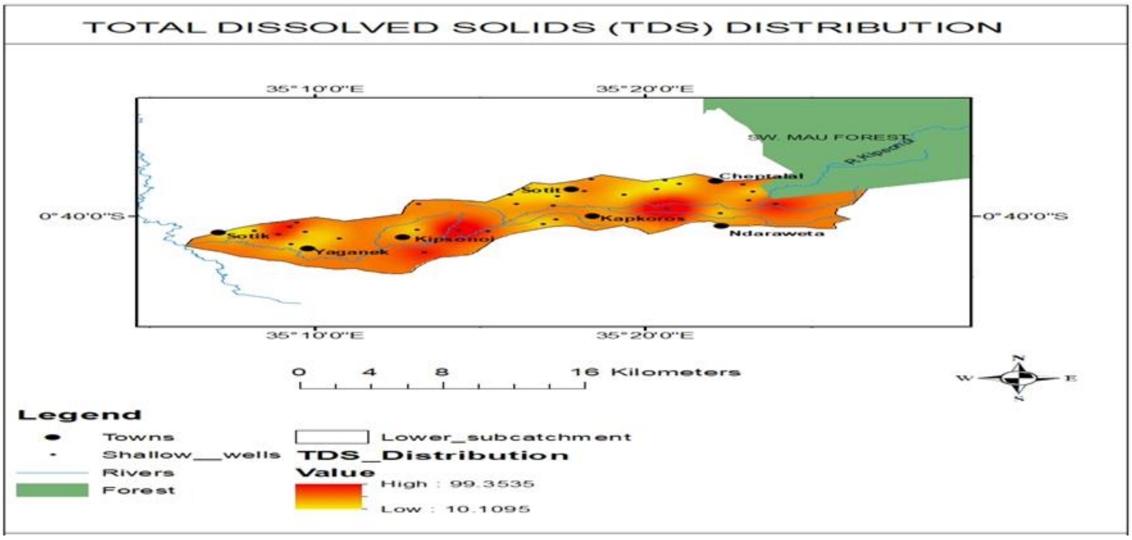

Figure 4.9: Spatial Distributions of Total Dissolved Solids in Kipsonoi Sub Catchment

4.3.1.5 Electrical Conductivity

The levels of electrical conductivity ranged from 21µS/cm to 200µS/cm (Figure 4.10). All recorded electrical conductivity values were below the World Health Organization's framework value of 1500 µS/cm for water (WHO, 2004). The lowest level of 21 was recorded in SW22, and this was because the well was protected with grass around it. While 200 was the highest levels recorded in SW1, which correlates with the TDS results and could be attributed to poor well construction. TDS and electrical conductivity levels showed the same trends, indicating that changes in total dissolved solids was likely the dominant factor influencing electrical conductivity (Figure 4.11).

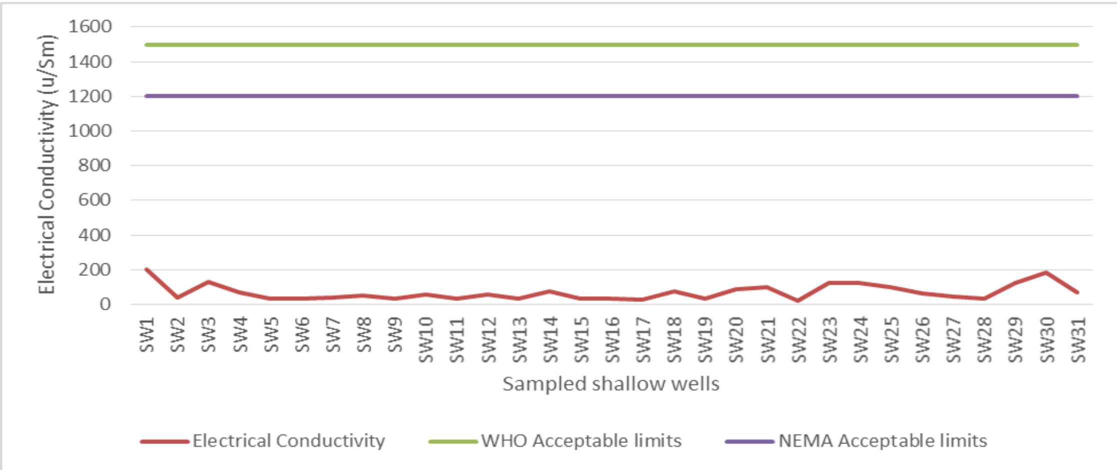

Figure 4.10: Levels of Electrical Conductivity of the sampled shallow wells

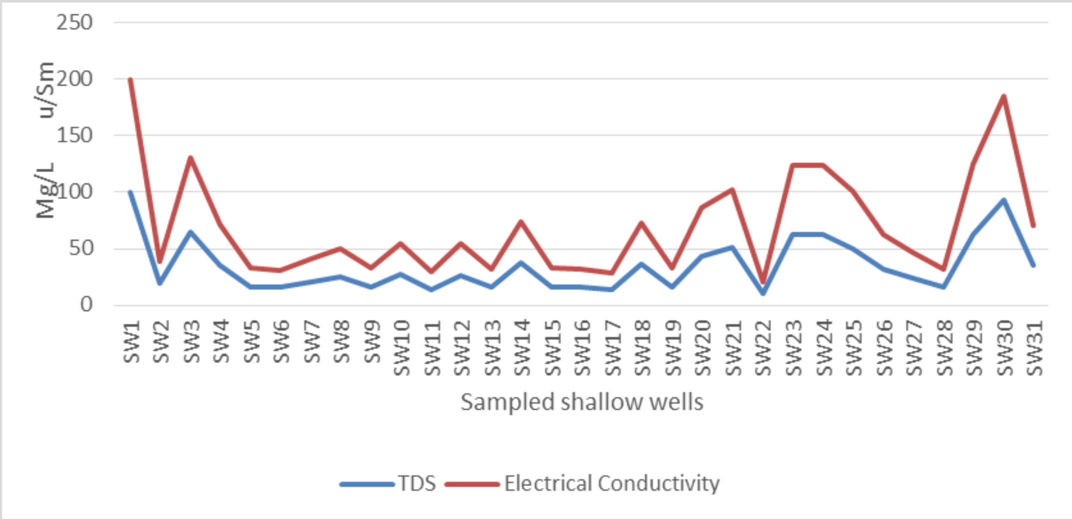

Figure 4.11: Levels of Electrical Conductivity and TDS of the sampled shallow Wells

Plate 4.6: A Protected shallow well (W22) with grass around it.

Plate 4.7: An unprotected shallow well (SW1) located near maize farm.

The thematic map generated for electrical conductivity was as seen in Figure 4.12.

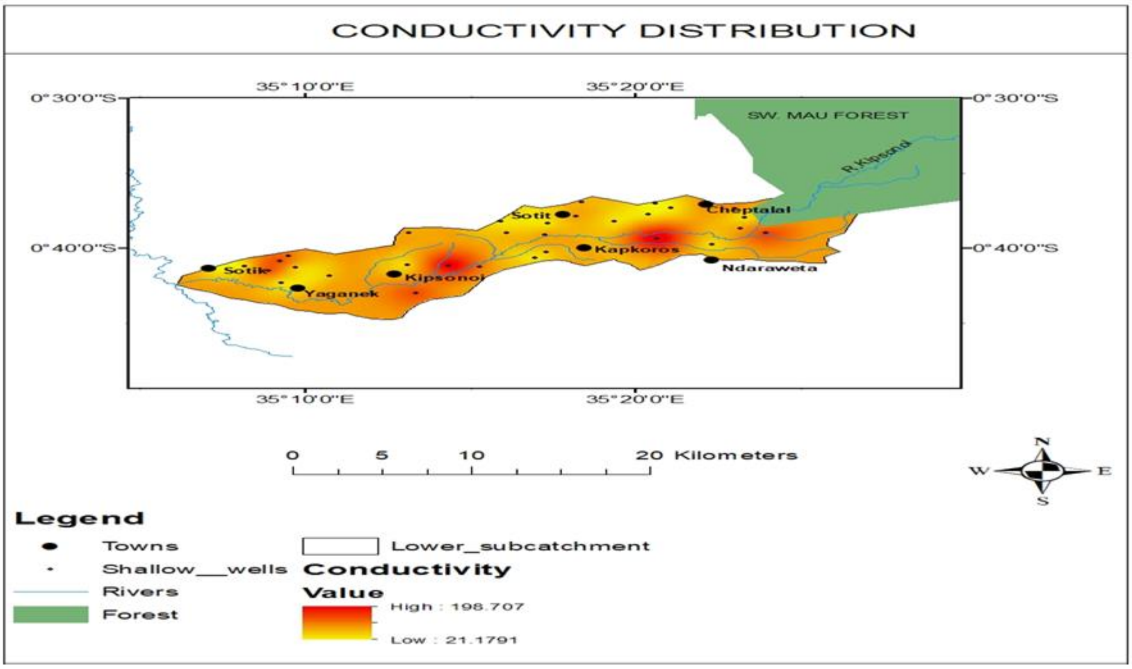

Figure 4.12: Spatial distribution of Electrical Conductivity in Kipsonoi Sub Catchment.

4.3.2 Chemical Parameters

4.3.2.1 Total Hardness

The concentration of total hardness within the Kipsonoi Sub-Catchment varied between 2 mg/L and 19 mg/L (Figure 4.13). All recorded levels of total hardness in the analyzed shallow wells remained well below the advised threshold of 500 mg/L for potable water, as concluded by NEMA (2006) and WHO (2004). The lowest levels were recorded in SW22 located in Bomet near a shopping centre and therefore is generally less likely to impact groundwater hardness directly, while the highest levels were recorded in SW1 and this is because the well was located near intensive agricultural fields and animal waste disposal systems. Intensive agricultural activities, such as the maximization of fertilizers and pesticides, can increase the concentration of calcium and magnesium ions in groundwater (Wang *et al.,* 2021). Industrial processes in the area could impact water quality, including hardness, but this is less likely in a shopping center compared to an industrial area (Akhtar *et al.,* 2021).

Water hardness is a natural phenomenon (inherent water quality characteristic) that reflects the concentration of divalent metal ions, primarily calcium (Ca^{2+}) and magnesium (Mg^{2+}), as well as associated anions like bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), and sulfate (SO_4^{2-}), dissolved in water (Kunjmon *et al.,* 2023). These naturally occurring minerals birthsource from the dissolution of geological formations, particularly limestone and dolomite, into the water system. According to WHO (2004), drinking water hardness can be classified based on its calcium carbonate ($CaCO_3$) equivalent concentrations, providing a standard framework for determining its suitability for human consumption.

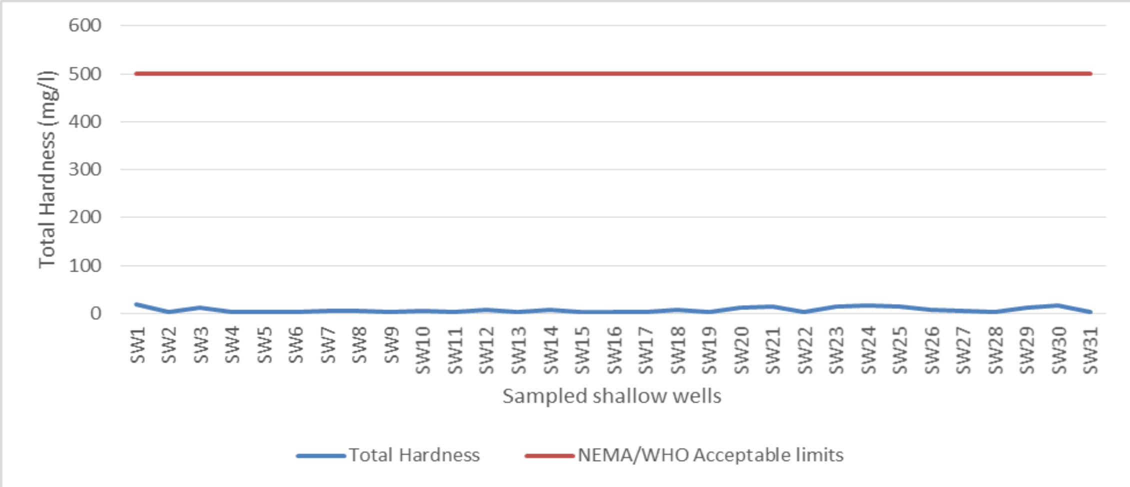

Figure 4.13: Levels of Total Hardness the sampled shallow wells.

The thematic map (Figure 4.14) illustrates the spatial arrangement of total hardness in Kipsonoi Sub Catchment. Sections that exhibited low total hardness levels could be attributed to low concentrations of hardness-causing minerals like calcium, magnesium and iron. These rocks (tertiary volcanics rocks, granites rocks, basement rocks and Bukoban rocks) present in the sub-catchment primarily contain silicate minerals like quartz, feldspars, and micas. Silicates do not release significant amounts of bicarbonates when they weather (Bhan *et al.,* 2023). Variations in the hardness levels in the Kipsonoi sub catchment could be due to the variations in the hardness causing minerals like iron. Because of magmatic differentiation, there can be variations in iron content. As magma cools and crystallizes, different minerals with varying iron concentrations solidify at different temperatures. This can lead to some areas within the formation being richer in iron-bearing minerals compared to others in areas with tertiary volcanic rocks (Williams *et al.,* 2018).

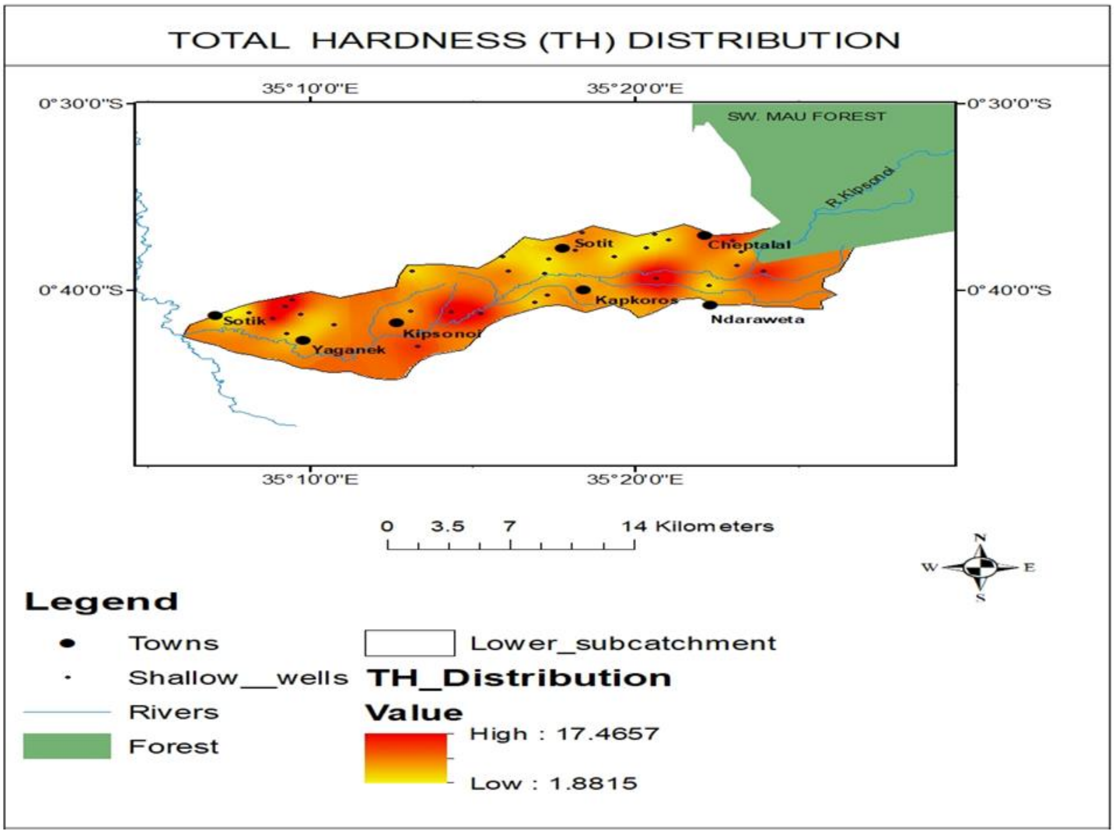

Figure 4.16: Spatial distribution of Total Hardness in Kipsonoi Sub Catchment.

4.3.2.3 Alkalinity

The alkalinity concentrations in the selected shallow wells within the Kipsonoi Sub-Catchment varied from 2 mg/L at sampling point SW24 to 15 mg/L at SW8 (Figure 4.15). All measured values fell well below the WHO (WHO, 2004) recommended threshold of 500 mg/L for potable water. Overall, low alkalinity levels observed in the Kipsonoi Sub-Catchment are likely influenced by dilution from surface runoff, which tends to be slightly acidic due to the application of acidic fertilizers such as NPK on surrounding tea farms. This runoff can dissolve and leach minerals from the soil, reducing their contribution to water alkalinity (Zeng *et al.,* 2020).

As noted by Nayar (2020), natural water alkalinity is predominantly shaped by the presence of carbonates, bicarbonates, and hydroxides. In this sub-catchment, the predominant bicarbonates are calcium carbonate and magnesium carbonate. The limited weathering of minerals such as feldspars known for their slow decomposition also restricts the release of calcium ions (Ca^{2+}), further minimizing their effect on alkalinity (Zhao *et al.,* 2020). Hence, manifestation of bicarbonates in groundwater is largely the result of chemical reactions occurring as water percolates through the soil, interacting with mineral components (Ram *et al.,* 2021).

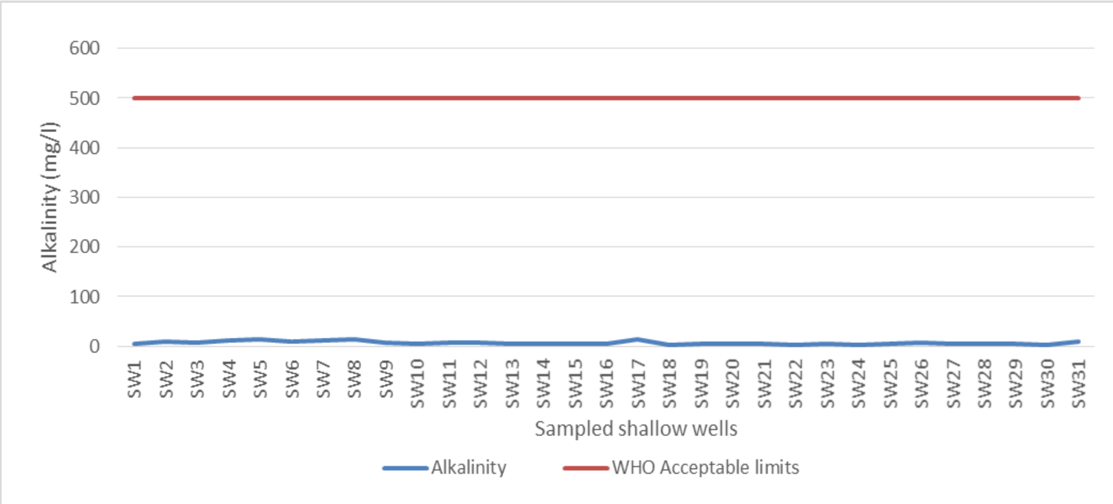

Figure 4.15: Levels of Alkalinity the sampled shallow wells.

Figure 4.16 is the thematic map displaying the distribution of alkalinity. Parts that exhibit high levels of alkalinity could be connected to human activities, for instance, the application of fertilizers. Some residents of the Kipsonoi sub-catchment apply DAP (diammonium phosphate), which is an ammonium-based fertilizer. Fertilizers containing ammonia or urea can break down and release ammonium ions ($NH4^{+}$). These can be converted to ammonium hydroxide (NH_4OH), which increases alkalinity (Wahyusi *et al.,* 2021). When fertilizers are applied, excess fertilizers could be carried to the shallow wells through surface runoff or leach through the soil and reach groundwater, particularly in areas with shallow wells. Improperly composted animal waste can also contribute to alkalinity if it leaches into groundwater, introducing ammonia and other alkalines (Kirchmann, 2020). This can also be carried to shallow wells through surface runoff or leaching through the soil and reaching groundwater. It could also be attributed to underlying geology rich in carbonate minerals like calcite (calcium carbonate) or dolomite. When rainwater dissolves these minerals, it increases the water's alkalinity. Sections that exhibit low levels of alkalinity could be attributed to distance from contaminant sources, as areas further away from agricultural fields, livestock operations, or naturally occurring rocks containing carbonate minerals like calcite (calcium carbonate) or dolomite would likely have lower alkalinity levels in the groundwater.

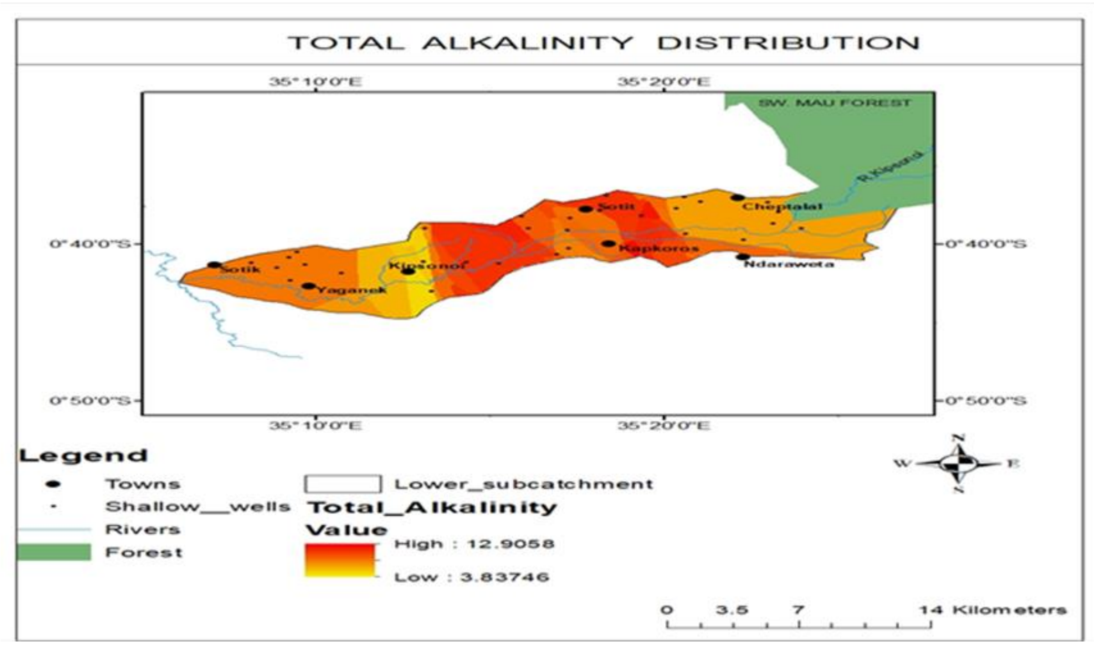

Figure 4.16: Spatial distribution of Alkalinity in Kipsonoi Sub Catchment.

4.3.2.3 Phosphates

The levels of phosphates in Kipsonoi Sub Catchment scaled from 0 mg/l to 4.9 mg/l (Figure 4.17). The lowest level of 0 was recorded in 0.1% shallow wells, while the highest/peak concentration of 4.9 mg/L was documented in SW1. All the recorded phosphate concentrations remained well beneath the prescribed thresholds of 30 mg/L for potable water as stipulated by WHO and NEMA. High levels of phosphates in SW1 could be attributed to the fact that the well was covered with timber planks and old tyres which do not protect the well from storm runoff, allowing it to be washed into the well during the rainy season, team with lack of vegetation cover around it to prevent runoff. Proximity to the maize farms and animal waste disposal systems could be another factor (Plate 4.2). Runoff and sewage discharges are significant contributors to phosphate contamination in groundwater (Bhat and Qayoom, 2021; Akhtar *et al.,* 2021).

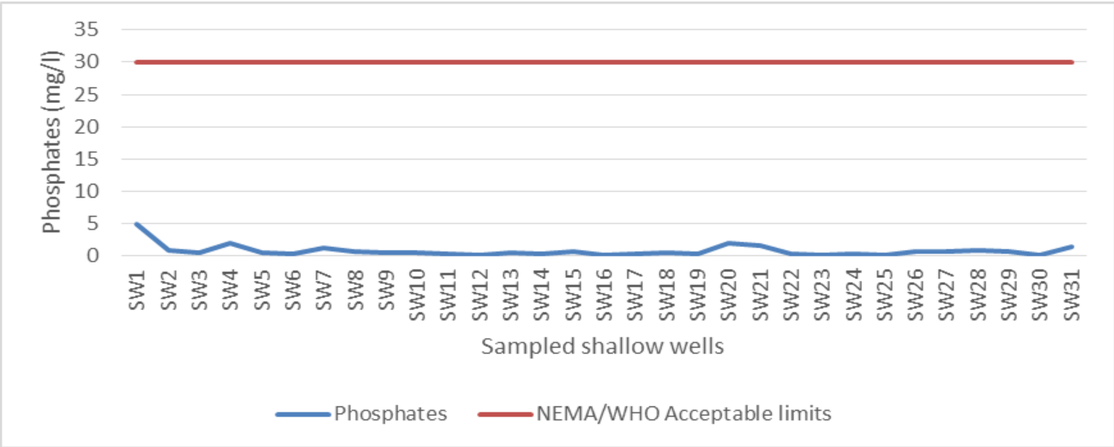

Figure 4.17: Levels of Phosphates the sampled shallow wells.

The thematic map for phosphates (Figure 4.18) displayed spatial distribution of phosphate in the Kipsonoi Sub Catchment. Parts that exhibited high levels of phosphates could be attributed to **a**gricultural activities, as areas with cultivated fields, especially

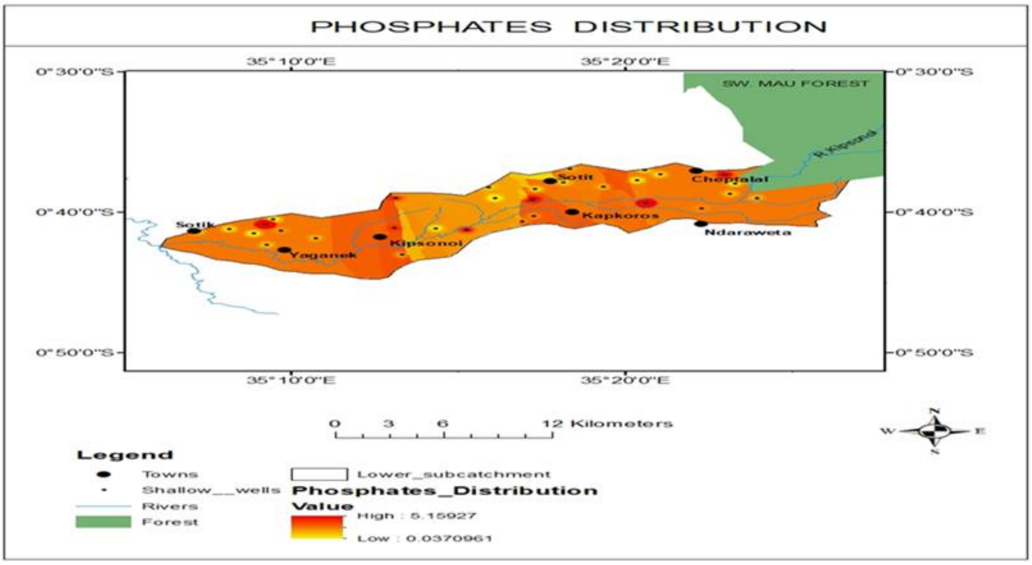

Figure 4.18: Spatial Distribution of Phosphates in Kipsonoi Sub Catchment.

4.3.2.4 Nitrates

Nitrate concentrations within the Kipsonoi Sub-Catchment ranging from 0 mg/L upto 66.3 mg/L (Figure 4.19). A significant proportion of the groundwater samples obtained from shallow wells exhibited nitrate levels surpassing the highest allowable limits for drinking water as established by regulatory bodies such as NEMA, USEPA, and WHO. The lowest/least concentration, 0 mg/L, was recorded at sampling points SW5 and SW6, while the highest concentration, 66.3 mg/L, was detected at SW8. The elevated nitrate concentration at SW8 is plausibly attributed to anthropogenic inputs, particularly the leaching of organic nitrogen from cattle kraals and nutrient-rich runoff originating from adjacent tea plantations. These land-use practices enhance nitrate loading into the shallow aquifer through infiltration and overland flow. The spatial proximity of potential point and non-point pollution sources including pit latrines, intensively cultivated fields, and livestock enclosures to the shallow wells further exacerbates nitrate contamination. These observations align with findings reported by Ashun (2014) in Kiambu County, specifically in Thiririka Sub-Catchment, where the intensification of agricultural activities and excessive application of nitrogen-based chemical fertilizers were identified as predominant contributors to raised nitrate levels in shallow groundwater resource. The presence of nitrates at concentrations exceeding safe limits raises substantial concerns regarding water safety and underscores the necessity for targeted mitigation strategies, including improved land management and protection of water sources.

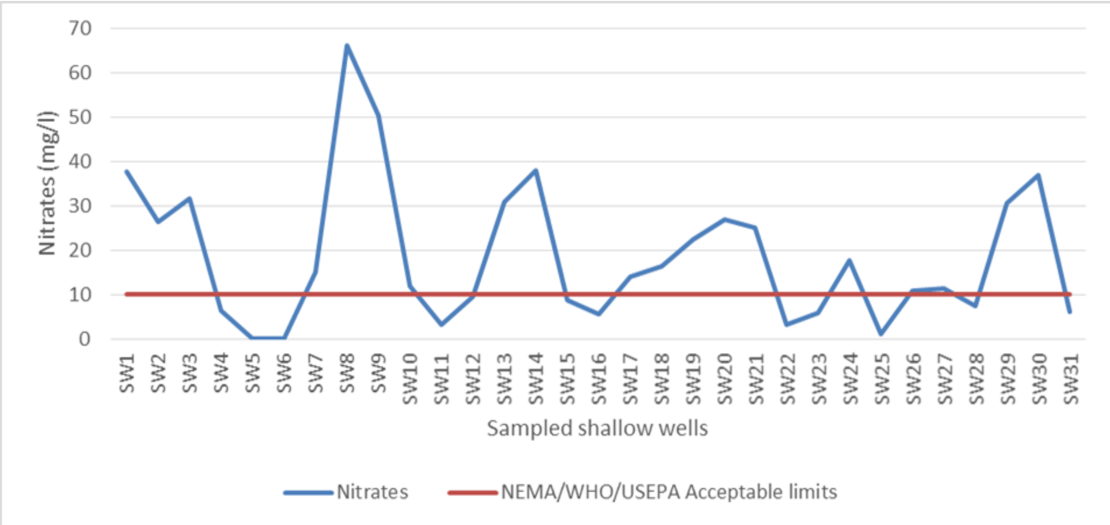

Figure 4.19: Levels of Nitrates of the sampled shallow wells

Figure 4.20 depicts thematic map for nitrates, showcasing spatial distribution of these nitrates, with some parts exhibiting high levels while others displayed low levels. This discrepancy could be attributed to proximity to pit latrines, cattle kraals and the farms, specifically the fields located around the wells. When livestock droppings and fertilizers are applied to crops (use synthetic fertilizers that are rich in nitrates), they dissolve and percolate down to the water table, contributing to nitrate contamination (Hubbard and Sheridan, 2020; Kitonga, 2018).

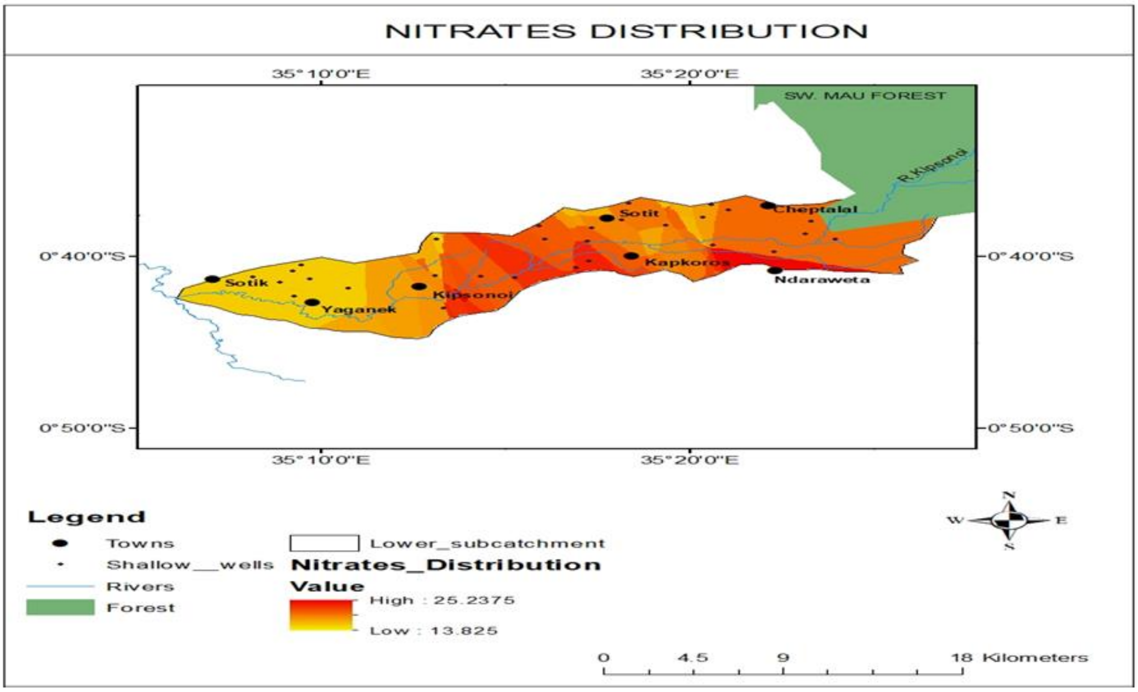

Figure 4.20: Spatial Distribution of Nitrates in Kipsonoi Sub Catchment

4.3.2.5 Potassium

Potassium concentrations was ranging from 1.35 mg/L at sampling location SW22 to optimum of 7.3 mg/L at site SW1 (Figure 4.21) among the assessed shallow wells. All phosphate values identified in the groundwater specimens remained below the optimum allowable threshold of 200 mg/L as stipulated by WHO (2004). The elevated potassium concentration at SW1 is likely attributable to the application of chemical fertilizers on nearby tea plantations. In contrast, the reduced potassium levels observed at SW22 may be linked to the presence of a protective drum barrier and well-established grass cover, both of which effectively mitigate contamination from surface runoff. These discoveries are reinforced by the outcomes of Sharma *et al.* (2018), who noted that cover vegetation is widely recognized for its capacity to prevent soil erosion and reduce nutrient leaching into water sources.

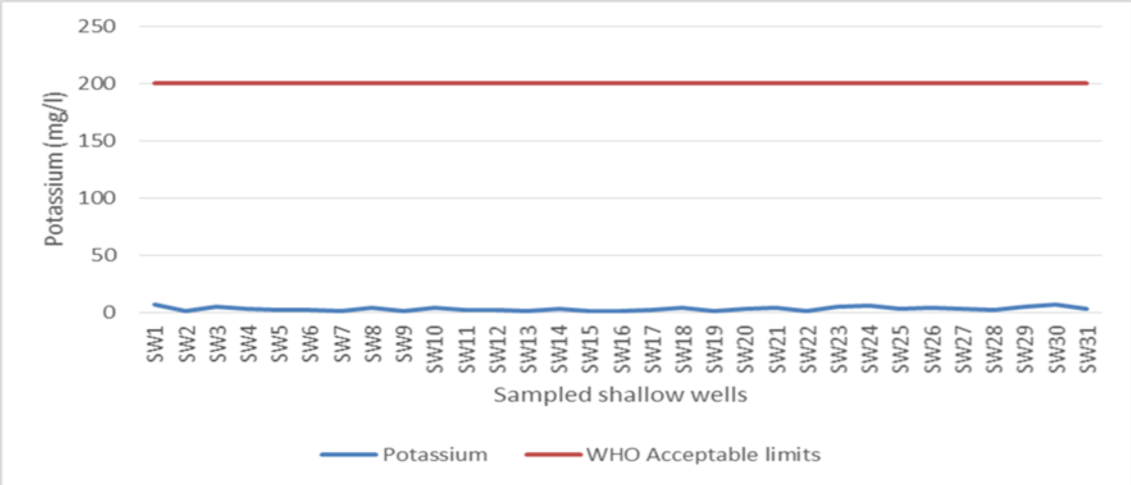

Figure 4.21: Levels of potassium of the sampled shallow wells.

(Figure 4.22) is thematic map for spatial distribution of phosphates. Parts that exhibit high potassium levels could be attributed to the application of fertilizers containing potassium (potash) for agriculture.

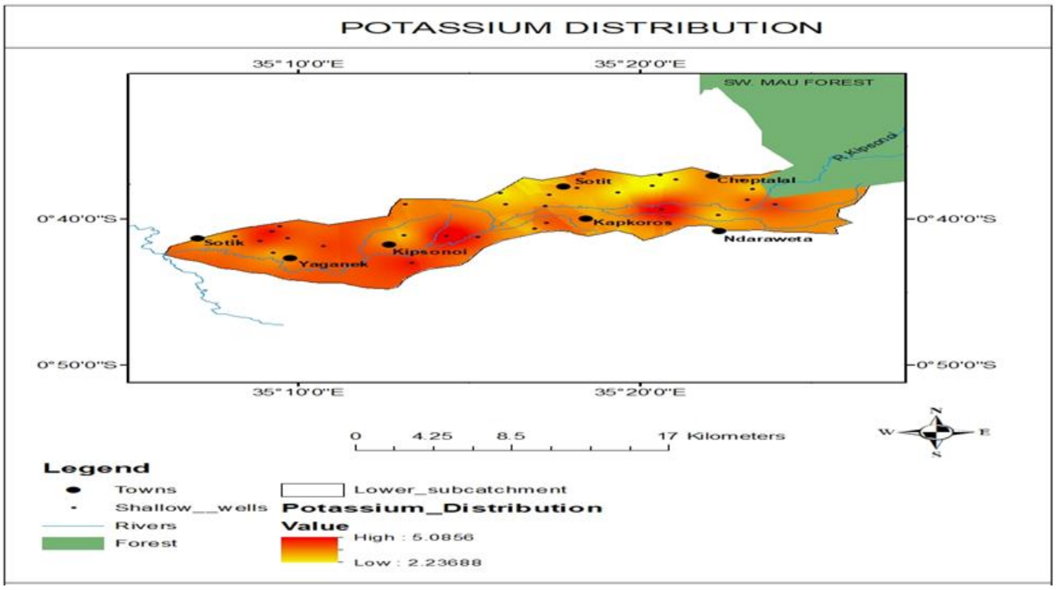

Figure 4.22: Spatial distribution of potassium in Kipsonoi Sub Catchment.

4.3.2.6 Sodium

Sodium (Na^+) concentrations in the sampled shallow wells exhibited variability, spanning from a minimum of 0.55 mg/L at sampling site SW28 to a peak of 27.5

mg/L at SW5 (Figure 4.23). All recorded sodium levels were within the accepted threshold of 200 mg/L as outlined by WHO (2004). The elevated sodium concentration at SW5 may be attributed to geogenic factors, as the well is situated in an area dominated by sodium-bearing lithologies such as granitic formations, which likely contribute to elevated Na^+ levels through mineral dissolution. Notably, sodium concentrations were lower during the rainy season, showing the impacts of dilution from precipitation. These findings align with those of Mohan and Krishnakumar (2021) and Mukaribu and Mu'azu (2023), who similarly observed reduced sodium levels during wet periods, affirming the rainwater's dilutive influence on groundwater chemistry.

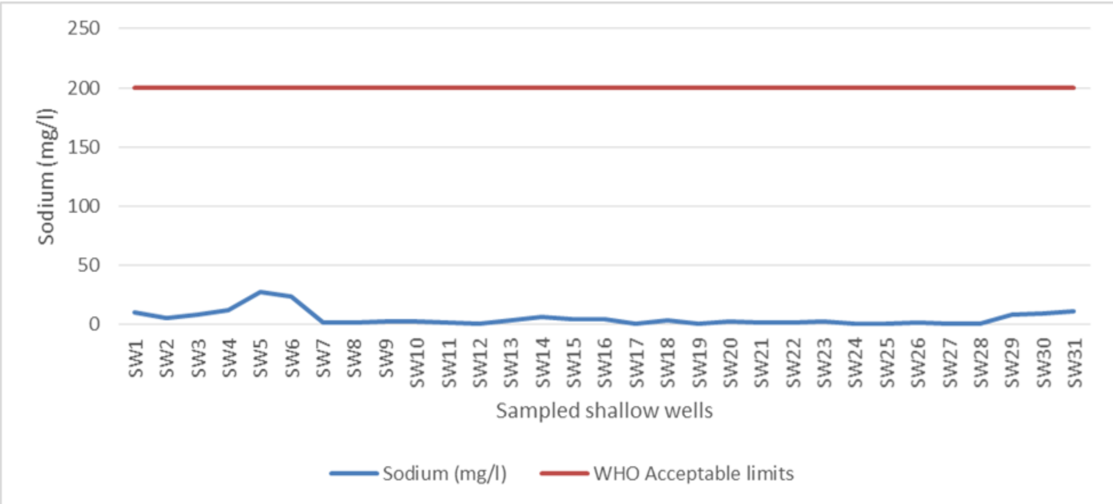

Figure 4.23: Levels of sodium of the sampled shallow wells.

The thematic map (Figure 4.24) gives the spatial arrangement of sodium. The levels of spatial distribution were connected to the geology of the underlying rocks; for instance, lower part of sub-catchment displayed high levels due to the presence of granite rocks.

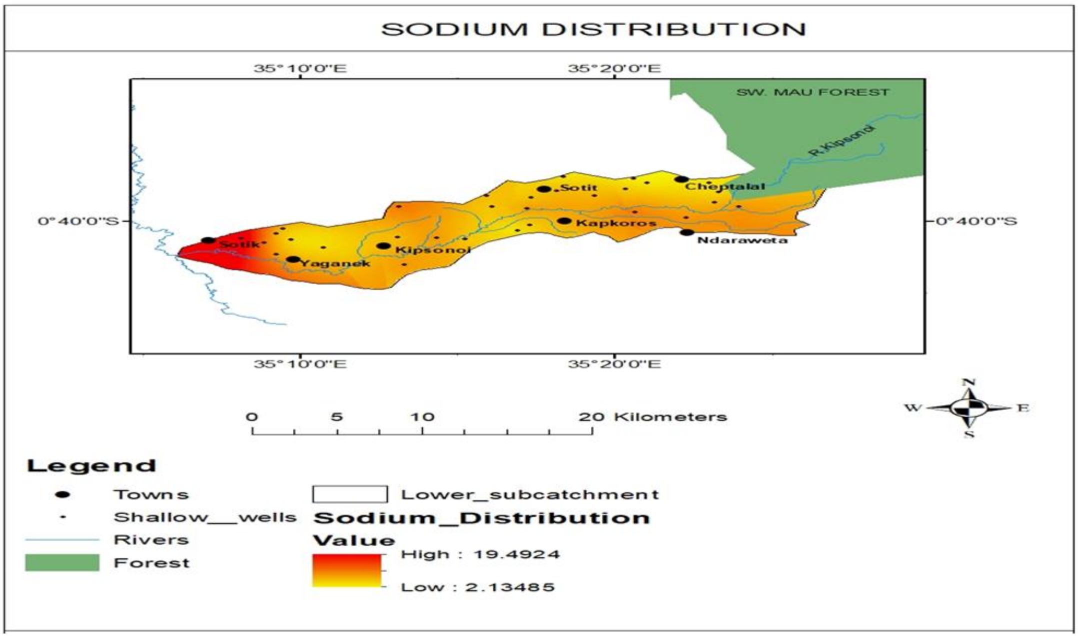

Figure 4.24: Spatial distribution of sodium in Kipsonoi Sub Catchment.

4.3.2.7 Fluorides

The fluorides in the shallow wells changed from 0.00 mg/L to 1.215 mg/L at sampling site SW20 (Figure 4.25). All the fluoride values gotten from the shallow wells were within the set standards of 1.5 mg/L outlined by WHO (2004) and NEMA (2006) and 2 mg/L recommended by USEPA (2012). The existence of fluorine in the natural waters depends on the geological composition of the area. High fluoride ion level in groundwater are typically due to fluoride minerals in the bedrock (Adimalla, 2020).

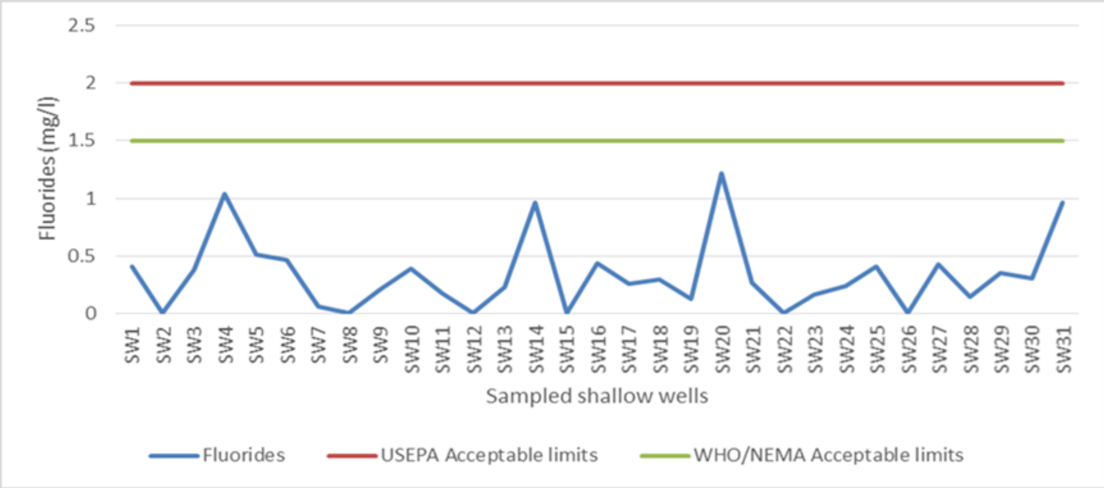

Figure 4.25: Levels of Fluorides of the sampled shallow wells.

The thematic map (Figure 4.26) gives the spatial distribution of fluoride. The presence of fluorides indicates the influence of geological rocks like fluorites on water quality.

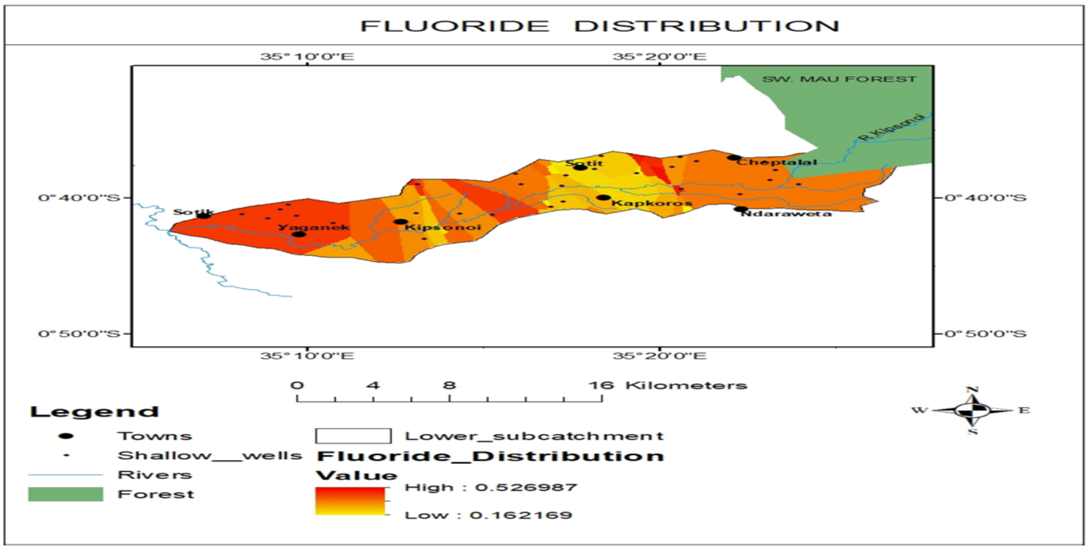

Figure 4.26: Spatial distribution of Fluorides in Kipsonoi Sub Catchment.

4.3.3 Levels of Biological Parameters (E. coli)

Faecal coliform concentrations (MNP/100 mL) observed in the assessment spanned from 0 MNP/100 mL at several sampling sites to a maximum of 1750 MNP/100 mL at SW2, SW7, and SW31 (Figure 4.27). The analysis revealed that 80.65% of examined shallow aquifers/wells exceeded the threshold of 0 MNP/100 mL outlined by NEMA (2006), USEPA (2012), and WHO (2004), rendering them non-compliant with established potable water standards.

The elevated presence of faecal coliforms is primarily linked to the proximity of these wells to anthropogenic sources such as cattle kraals, pit latrines, and areas designated for indiscriminate solid waste disposal. Substandard or improvised well covers further exacerbated vulnerability to contamination. Infiltration during the rainy season facilitates microbial mobility and proliferation due to increased surface runoff and leaching of organic and faecal matter into the groundwater (Hilili *et al.,* 2021).

Approximately 80.65% of the wells exhibited faecal coliform counts between 4 and above 2400 MNP/100 mL, signifying significant microbiological pollution and necessitating water treatment prior to human consumption to handle the hazards linked with pathogenic bacteria or viral agents (Some et al., 2021). Discharges from point origins like latrines and livestock enclosures have been consistently identified as critical contributors to aquifer contamination (Do *et al.,* 2022). Faecal coliforms, particularly *E. coli*, are widely acknowledged as dependable markers of faecal intrusion (Khan & Gupta, 2020), and their detection in drinking water is essential for assessing its hygienic integrity (Wen *et al.,* 2020). High coliform densities serve as a clear proxy for the microbiological compromise of the water source (Sarkar *et al.,* 2022).

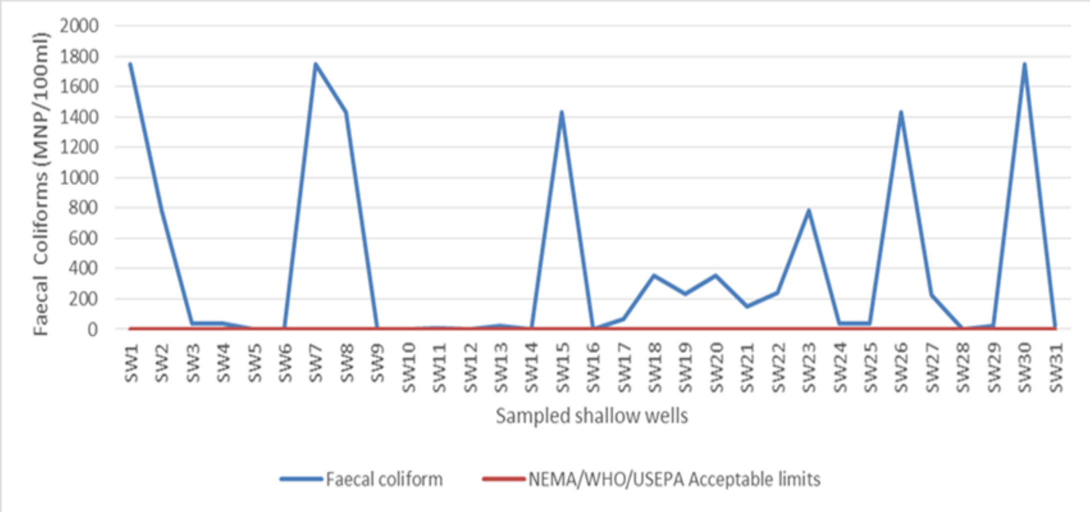

Figure 4.27: Levels of Faecal Coliforms of the sampled shallow wells.

The spatial distribution of faecal coliform concentrations across Kipsonoi Sub-Catchment is depicted in the thematic map (Figure 4.28).Sections with high faecal coliform levels were linked to human and livestock waste. Regions near urban settlements exhibited higher faecal coliform levels due to potential sewage and manure disposal.

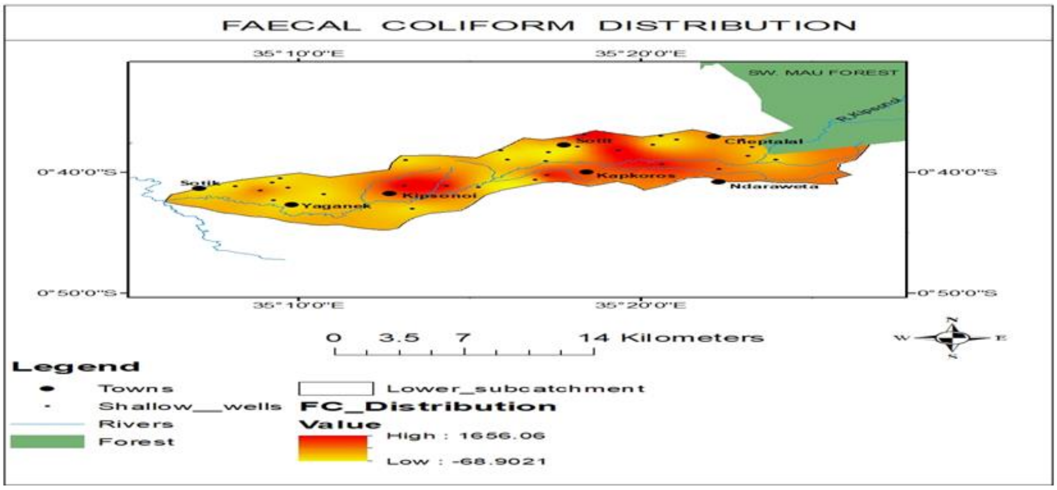

Figure 4.28: Spatial distribution of Faecal Coliforms in Kipsonoi Sub Catchment.

4.4 Mean differences for physico-chemical parameters and microbial parameters

The researcher's t-test conducted at a 95% confidence level indicated no statistically consequential variation ($p \geq 0.05$) in the average values of physical and chemical parameters of shallow well water between the two seasons, as detailed in Table 4.1. Temperature remained relatively stable, exhibiting only a marginal seasonal difference (22.30°C in the wet season versus 22.36°C in the dry season). Turbidity recorded a higher mean during the wet season (23.62 NTU) compared to the dry season (17.21 NTU); nevertheless, this variation9 was not statistically meaningful ($p = 0.321$).

Conductivity, TDS, and alkalinity exhibited minimal seasonal shifts, with slightly elevated values observed during wet season. These fluctuations may be connected to dilution from rainfall and enhanced leaching of soluble constituents and organic debris from the surrounding catchment, though observed differences lacked statistical significant ($p = 0.679$), ($p = 0.678$), and ($p = 0.169$), respectively. Concentrations of nitrates, phosphates, and potassium also showed non-significant increases in the wet season, presumably indicating diffuse contamination originating from agricultural runoff, including fertilizer residues and organic waste ($p = 0.830$), ($p = 0.577$), and ($p = 0.410$), respectively.

Sodium and fluoride concentrations were marginally lower during wet season (5.24 and 5.58 while dry season versus 0.32 and 0.35 in the wet season), likely reflecting dilution from precipitation, though the seasonal changes were not statistically significant ($p = 0.884$), ($p = 0.577$), and ($p = 0.766$), respectively. pH levels in both seasons were mildly acidic (6.23 in rainy season as well 6.16 in dry), suggesting that sampled water remains within the permissible pH range but trends slightly toward acidity.

A statistically significant difference (p = 0.033) was identified in E. coli concentrations between seasons, with a substantial elevation during the wet season (615.03 MNP/100 mL) compared to the dry season (220.45 MNP/100 mL). This pronounced increase is plausibly linked to intensified fecal contamination driven by surface runoff, overflow from sanitation facilities, and increased human or livestock interactions with water sources during the rainy period

Table 4.1: Mean differences for Physico-chemical parameters and E coli during the dry and wet season.

Water Quality Parameter	WET SEASON Mean ±Std. Error	DRY SEASON Mean ± Std. Error	p-values
Ph	6.23±0.138	6.16±0.135	.706
Temperature	22.30±0.043	22.36±0.054	.373
Turbidity	23.62±5.431	17.21±3.382	.321
Conductivity	71.71±8.500	66.77±8.294	.679
Sodium	5.24±1.125	5.58±1.181	.884
Potassium	3.59±0.301	3.24±0.288	.410
Total hardness	7.61±1.067	6.06±0.920	.276
Phosphates	0.97±0.233	0.79±0.214	.577
Fluoride	0.32±0.058	0.35±0.058	.766
Nitrates	19.15±2.891	18.28±2.846	.830
Alkalinity	7.03±0.662	5.81±0.582	.169
Total Dissolved Solids	35.77±4.256	33.29±4.157	.678
Faecal coliforms (*E.coli*)	615.03±167.424	220.45±60.597	.0.033*

*Significant at 95% confidence interval level.

4.5 Water Quality Index (WQI)

WQI is a numerical denoting transformation of extensive water characterization data into a single value (Banda and Kumarasamy, 2020). This metric reflects the degree to which water quality parameters conform to the established standards or targets designated for a specific area. It facilitates the examination of the water's appropriateness for multiple uses, including irrigation, recreational activities, and potable consumption (Adelagun *et al.,* 2021).

In this study, WQI values for 31 sampling wells (SW1 to SW31) within the Kipsonoi sub-catchment indices were determined using the expression SI = (WI × qi), and the water quality levels were subsequently categorized into four distinct classes; Excellent, Good, Poor, and Very Poor as stipulated under Table 4.2.

The WQI values varied between 17.76 at sampling station SW16 and 276.31 at sampling station SW1. Out of the 31 sampled sites, 7 wells (22.58%) exhibited excellent water quality (WQI < 50), 14 wells. Out of the total wells assessed, 45.16% were categorized as having good water quality, indicated by WQI values ranging from 50 to 100. Furthermore, 6 wells, representing 19.35% of the total, were identified as having poor quality, with WQI scores falling between 100 and 200. In addition, 4 wells, equating to 12.90%, were found to be in the very poor category, with their WQI values exceeding the threshold of 200, signaling significant contamination concerns.

The wells with very poor water quality include SW1, SW7, SW8, and SW30, each with WQI values exceeding 230. The primary reason for the high WQI values observed in these wells could be connected to the negative effect of agricultural tasks such as tea farming, maize farming, potato farming, and cattle waste from kraals on these wells. Similarly, wells such as SW20, SW21, SW22, and SW25 fall in the poor category, and could be exhibiting early signs of degradation.

On the other hand, wells such as SW16, SW10, SW5, and SW6 show excellent water quality, with WQI values as low as 17.76. These wells are well protected from the effect of human activities.

Table 4.2: Water Quality Index for the Kipsonoi Sub Catchment.

Well s/n no	SI=(WI*qi)	Status of water quality
SW1	276.31	Very poor water quality
SW2	85.21	Good water quality
SW3	95.86	Good water quality
SW4	69.14	Good water quality
SW5	38.28	Excellent water quality
SW6	45.37	Excellent water quality
SW7	238.93	Very poor water quality
SW8	230.45	Very poor water quality
SW9	143.47	Poor water quality
SW10	32.38	Excellent water quality
SW11	43.44	Excellent water quality
SW12	38.66	Excellent water quality
SW13	85.36	Good water quality
SW14	100.39	Poor water quality
SW15	94.18	Good water quality
SW16	17.76	Excellent water quality

Well s/n no	**SI=(WI*qi)**	**Status of water quality**
SW17	75.52	Good water quality
SW18	58.43	Good water quality
SW19	45.06	Excellent water quality
SW20	110.75	Poor water quality
SW21	143.91	Poor water quality
SW22	222.70	Poor water quality
SW23	63.47	Good water quality
SW24	78.90	Good water quality
SW25	166.84	Poor water quality
SW26	93.77	Good water quality
SW27	89.56	Good water quality
SW28	56.19	Good water quality
SW29	94.54	Good water quality
SW30	250.38	Very poor water quality
SW31	66.28	Good water quality

CHAPTER FIVE: CONCLUSIONS AND RECOMENDATIONS

5.1 Introduction

The main goal of this research was to assess the quality of groundwater in the Kipsonoi Sub Catchment area, specifically to determine its alignment with outlined drinking water standards. Additionally, the study employed GIS techniques to spatially visualize the distribution and changes of groundwater quality factors, thereby enhancing the interpretability and decision-making capacity regarding the region's water resource management.

5.2 Conclusions

Shallow well distribution in Kipsonoi Sub-Catchment is uneven, 64% of drinking water wells are concentrated in the upper region, while only 36% are in the lower region.

The predominant physical, chemical and biological parameters were nitrates, turbidity and fecal coliform. P values were significant at 0.05 for the faecal coliform, indicating that animal and human wastes were primary contributors to contamination, especially during the rainy season.

The water quality index (WQI) indicates that more than 60% of the shallow wells had suitable water for drinking. while 32.2% had poor water quality and were unsuitable for drinking purposes.

5.3 Recommendations

It is recommended that the government, through relevant agencies such as the Ministry of Water, Sanitation and Irrigation, water resources Authority (WRA}, and the Geological Survey Department should assist in conducting geological surveys that will identify suitable locations with

Potential aquifer for constructing deeper wells in the Kipsonoi potential within the Kipsonoi Sub-Catchment despite the clay layer.

The wells in Kipsonoi Sub-Catchment should be constructed with proper sealing to prevent contamination from surface runoff and debris.

Water from Kipsonoi Sub-Catchment requires treatment to reduce turbidity, nitrates, and faecal coliform to safe levels. While advanced methods like ion exchange are costly and unaffordable for local residents, simpler and more accessible home-based techniques such as filtration, boiling or chlorination can be effectively used.

To improve groundwater quality in the Kipsonoi Sub-Catchment, shallow wells exhibiting excellent water quality should be protected, while those exhibiting poor and very poor quality require urgent interventions like better farming practices and waste management.

5.4 Further Research

Additional investigation is needed in the specified domains within the Kipsonoi Sub Catchment. There is a need to investigate the potential aquifer mapping by conducting geophysical surveys to map potential aquifer zones within the Kipsonoi Sub Catchment, considering the presence of the clay layer.

Future studies should expand the water quality monitoring program to include a longer timeframe and more frequent sampling throughout the year in Kipsonoi Sub-Catchment.

Future studies should expand the water quality monitoring program to include a longer timeframe and more frequent sampling throughout the year in Kipsonoi Sub-Catchment.

Further investigation should explore correlations between groundwater quality and public health outcomes within Kipsonoi Sub-Catchment.

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APPENDICES

Appendix I: WHO and NEMA Drinking Water Guidelines

Source: WHO, 2004, NEMA, 2006 and USEPA 2012)

S/N	PARAMETERS	Unit	WHO Guidelines	USEPA Guidelines	NEMA Guidelines	Method used	Type of analysis
1	Temperature	^0C	20 -35	-	20 - 35	Universal Meter	Onsite
2	PH	-	6.5 – 9.2	6.5 – 8.5	6.5 - 8.5	Universal Meter	Onsite
3	**Conductivity (25^0 C)** (EC)	µS/cm	1500	-	1200	Universal Meter	Onsite
4	Total Dissolved Solids (TDS)	mg/L	1000	500	1000	Universal Meter	Onsite
5	Total Hardness (TH)	$mgCaCO_3$ /l	500	-	500		Laboratory
6	Total Alkalinity	$mgCaCO_3$ /l	500	-	-		Laboratory
7	Nitrates (NO3-)	$mgNO_{3-}$ N/l	10	10	10	Colorimetric method	Laboratory
8	Fluoride (F-)	mg/L	1.5	2	1.5	Colorimetric method	Laboratory
9	Turbidity	NTU	5	5	5	Universal Meter	Onsite
10	Sodium (Na^+)	mg/L	200	-		The Flame Photometric Method	Laboratory
11	Potassium (K^+)	mg/L	200	-		The Flame Photometric Method	Laboratory
12	Phosphates (PO_4^{3-})	$mgPO_4$/l	30	-	30	Colorimetric method	Laboratory
13	E. coli	MPN /100ml	Nil	Nil	Nil	Multi-tube fermentation technique	Laboratory

Appendix II: Results of Physico Chemical and Biological Analysis of Shallow Wells in Kipsonoi Sub Catchment.

WELL ID	Longitude	Latitude	pH	Temperature	Turbidity	Conductivity (250 C)	Sodium	Potassium	T Hardness	Phosphates	Fluoride	Nitrate	T Alk	TDS	Faecal Coliforms (E. Coli)
1	**35.343889**	**-0.65573**	5.715	22.43	71	200	9.95	7.3	19	4.9	0.41	37.9	4	100	1430
2	**35.371389**	**-0.66208**	7.83	22.415	26	38.5	5.65	2	2	0.765	0	26.6	9	19.5	780
3	**35.398889**	**-0.64972**	5.93	22.45	5.7	130	8.65	4.99	13	0.47	0.375	31.7	7	64.5	41
4	**35.287222**	**-0.65147**	5.385	21.55	2.65	71.5	12	3.2	2	1.9	1.04	6.35	11	35.5	41
5	**35.11998**	**-0.68977**	6.35	22.095	6.3	32.5	27.5	2.55	2	0.425	0.515	0	13	16	0
6	**35.135765**	**-0.6865**	6.45	22.405	10.45	30.5	24	2.5	2	0.19	0.465	0	9	15.5	2
7	**35.21812**	**-0.68527**	5.955	22.4	75.5	40.5	1.55	1.55	5	1.25	0.06	15.25	12	20	1750
8	**35.288**	**-0.671**	7.845	22.31	59.3	49.5	2.1	4.5	5	0.7	0	66.3	15	25	1430
9	**35.15448**	**-0.70529**	6.03	22.4	15	32.5	2.3	2	3	0.41	0.205	50.55	7	16.5	0
10	**35.178878**	**-0.69718**	7.595	22.405	9.9	54	2.25	4.4	5	0.52	0.39	11.9	5	27	0
11	**35.288733**	**-0.63911**	6.45	22.425	8.95	30	1.65	2.65	2	0.245	0.175	3.2	7	14	4
12	**35.268135**	**-0.64968**	6.75	22.415	6.6	54	1.05	2.8	7	0	0	9.7	7	26.5	2
13	**35.265212**	**-0.63679**	6.035	22.425	3.95	31.5	4.1	1.4	2	0.51	0.23	30.9	5	15.5	21.5
14	**35.302845**	**-0.63131**	6.14	22.3	3.15	74	6.45	3.45	7	0.34	0.965	38.15	5	37	0
15	**35.32258**	**-0.63635**	7.46	22.34	36.45	33	4.45	1.6	2	0.56	0	8.85	4	16	1750
16	**35.339297**	**-0.6286**	7.225	22.38	3.78	31.5	4.3	1.6	2	0.065	0.435	5.6	5	16	0
17	**35.350563**	**-0.62178**	6.015	22.3	10.35	28	0.6	2.6	3	0.25	0.26	14	13	14	68
18	**35.385792**	**-0.64444**	6.4	22.41	5.4	72.5	4.1	4.35	7	0.385	0.29	16.45	3	36	350
19	**35.387892**	**-0.63234**	7.125	22.85	4.5	33	0.85	1.4	3	0.175	0.125	22.5	4	16.5	232
20	**35.382992**	**-0.62205**	5.465	22.475	6.45	86.5	2.75	3.9	12	1.925	1.215	26.95	6	43	350
21	**35.254167**	**-0.68745**	5.325	22.5	23.3	102	2	4.3	14	1.6	0.27	25.2	4	51	151.5
22	**35.343275**	**-0.61654**	5.86	22.425	75.55	21	1.85	1.35	2	0.34	0	3.15	3	10	240
23	**35.147917**	**-0.69187**	5.28	22.405	3.05	124	3.05	5.25	15	0	0.165	6	4	62	780
24	**35.153945**	**-0.68089**	5.255	22.4	1.15	124	0.85	5.9	17	5.3	0.24	17.85	2	62	39
25	**35.157808**	**-0.67514**	5.52	22.25	49	101	0.8	3.05	14	0	0.405	1.15	4	50.5	41
26	**35.305924**	**-0.61491**	6.025	22.3	20.5	62.5	1.3	4.25	7	0.6	0	11	7	31.5	1750
27	**35.16177**	**-0.68824**	5.805	22.405	14.7	46.5	0.65	3.45	5	0.7	0.43	11.35	4	23.5	225
28	**35.282053**	**-0.67744**	5.75	22.24	4.5	32	0.55	2.15	3	0.72	0.14	7.5	4	16	0
29	**35.222**	**-0.717**	5.92	22.425	5.45	125	8.35	5.15	11	0.555	0.355	30.8	5	62	21.5
30	**35.23894**	**-0.68567**	5.745	22.315	62	185	9.35	7.15	17	0.155	0.305	37.1	2	93	1430
31	**35.219056**	**-0.64979**	5.45	21.42	2.4	70	11.1	3.2	2	1.355	0.965	6.3	9	35	20.5

Appendix III: Determination of Water Quality Index

WELL ID	Conductivity(qiwi)	Potasium(qiwi)	Phosphate (qiwi)	TH(qiwi)	Ph(qiwi)	sodium(qiwi)	Turbidity(qiwi)	TDS(qiwi)	Nitrates (qiwi)	Fluoride (qiwi)	∑(qiwi) WQI	
1	0.520833	0.114063	0.510417	0.2375	31.75	0.62188	177.5	1.5625	59.2188	4.270833	276.307	Very poor water quality
2	0.10026	0.03125	0.07969	0.025	-22.25	0.35313	65	0.30469	41.5625	0	85.2065	Good water quality
3	0.3385	0.078	0.049	0.1625	26	0.5406	14.25	1.0078	49.531	3.9063	95.864	Good water quality
4	0.1862	0.05	0.1979	0.025	40	0.75	6.625	0.5547	9.9219	10.833	69.144	Good water quality
5	0.0846	0.0398	0.0443	0.025	15	1.7188	15.75	0.25	0	5.3646	38.277	Excellent water quality
6	0.0794	0.0391	0.0198	0.025	12.5	1.5	26.125	0.2422	0	4.8438	45.374	Excellent water quality
7	0.1055	0.0242	0.1302	0.0625	25	0.0969	188.75	0.3125	23.828	0.625	238.93	Very poor water quality
8	0.129	0.07	0.073	0.063	-22.25	0.131	148.3	0.391	103.6	0	230.5	Very poor water quality
9	0.08464	0.03125	0.04271	0.0375	24.25	0.14375	37.5	0.25781	78.9844	2.13542	143.467	Poor water quality
10	0.1406	0.0688	0.0542	0.0625	-15.5	0.1406	24.75	0.4219	18.594	3.6458	32.378	Excellent water quality
11	0.07813	0.04141	0.02552	0.025	13.75	0.10313	22.375	0.21875	5	1.82292	43.4398	Excellent water quality
12	0.14063	0.04375	0	0.0875	6.25	0.06563	16.5	16.5	15.1563	0	38.6578	Excellent water quality
13	0.08203	0.02188	0.05313	0.025	24.125	0.25625	9.875	0.24219	48.2813	2.39583	85.3576	Good water quality
14	0.1927	0.0539	0.0354	0.0875	21.5	0.4031	7.875	0.5781	59.609	10.052	100.39	Poor water quality
15	0.08594	0.025	0.05833	0.025	-11.5	0.27813	91.125	0.25	13.8281	0	94.1755	Good water quality
16	0.08203	0.025	0.00677	0.025	-5.625	0.26875	9.45	0.25	8.75	4.53125	17.7638	Excellent water quality
17	0.07292	0.04063	0.02604	0.0375	24.625	0.0375	25.875	0.21875	21.875	2.70833	75.5167	Good water quality
18	0.1888	0.06797	0.0401	0.0875	15	0.25625	13.5	0.5625	25.7031	3.02083	58.4271	Good water quality
19	0.0859	0.0219	0.0182	0.0375	-3.125	0.0531	11.25	0.2578	35.156	1.3021	45.058	Excellent water quality
20	0.2253	0.0609	0.2005	0.15	38.375	0.1719	16.125	0.6719	42.109	12.656	110.75	Poor water quality
21	0.266	0.067	0.167	0.175	41.88	0.125	58.25	0.797	39.38	2.813	143.9	Poor water quality
22	0.0547	0.0211	0.0354	0.025	28.5	0.1156	188.88	0.1563	4.9219	0	222.7	Very poor water quality
23	0.32292	0.08203	0	0.1875	43	0.19063	7.625	0.96875	9.375	1.71875	63.4706	Good water quality
24	0.3229	0.0922	0.5521	0.0213	43.625	0.0531	2.875	0.9688	27.891	2.5	78.901	Good water quality
25	0.26302	0.04766	0	0.175	37	0.05	122.5	0.78906	1.79688	4.21875	166.84	Poor water quality
26	0.163	0.066	0.063	0.088	24.38	0.081	51.25	0.492	17.19	0	93.77	Good water quality
27	0.1211	0.0539	0.0729	0.0625	29.875	0.0406	36.75	0.3672	17.734	4.4792	89.557	Good water quality
28	0.08333	0.03359	0.075	0.0375	31.25	0.03438	11.25	0.25	11.7188	1.45833	56.1909	Good water quality
29	0.3255	0.0805	0.0578	0.1375	27	0.5219	13.625	0.9688	48.125	3.6979	94.54	Good water quality
30	0.4818	0.1117	0.0161	0.2125	31.375	0.5844	155	1.4531	57.969	3.1771	250.38	very poor water quality
31	0.18229	0.05	0.14115	0.025	38.75	0.69375	6	0.54688	9.84375	10.0521	66.2849	Good water quality

Appendix IV: Research Approval

KENYATTA UNIVERSITY
GRADUATE SCHOOL

E-mail: dean-graduate@ku.ac.ke
Website: www.ku.ac.ke

P.O. Box 43844, 00100
NAIROBI, KENYA
Tel. 020-8704150

Internal Memo

FROM: Dean, Graduate School **DATE:** 31st August, 2022

TO: **Ms. Janeth Chelangat Segut** **REF:**156/CE/34857/2016
Department of Geography

SUBJECT: APPROVAL OF RESEARCH PROPOSAL

We acknowledge receipt of your Research Proposal after fulfilling recommendations raised by the Graduate School Board of 20th June, 2022.

You may now proceed with your Data collection, subject to clearance with the Director General, National Commission for Science, Technology & Innovation.

As you embark on your data collection, please note that you will be required to submit to Graduate School completed Supervision Tracking and Progress Report Forms per semester. The Forms are available at the University's Website under Graduate School webpage downloads.

Also, please ensure that you publish article(s) from your thesis before submitting it to Graduate School for examination as per the Commission for University Education and Kenyatta University guidelines.

Thank you.

JULIA GITU
FOR: DEAN, GRADUATE SCHOOL

CC. Chairman, Department of Geography

Supervisors:

1. Dr. Mary Makokha
   C/o Department of Geography
   Kenyatta University

2. Dr. Kennedy Obiero
   C/o Department of Geography
   Kenyatta University

Appendix V: Research Authorization

KENYATTA UNIVERSITY
GRADUATE SCHOOL

E-mail: dean-graduate@ku.ac.ke

Website: www.ku.ac.ke

P.O. Box 43844, 00100
NAIROBI, KENYA
Tel. 020-8704150

Our Ref: I56/CE/34857/2016 **DATE: 31st August, 2022**

Director General,
National Commission for Science, Technology
and Innovation
P.O. Box 30623-00100
NAIROBI

Dear Sir/Madam,

RE: RESEARCH AUTHORIZATION FOR MS. JANETH CHELANGAT SEGUT REG. NO. I56/CE/34857/2016

I write to introduce Ms. Janeth Chelangat Segut who is a Postgraduate Student of this University. She is registered for M.Sc. degree programme in the **Department of Geography.**

Ms. Segut intends to conduct research for a M.Sc. thesis Proposal entitled, **"Drinking Water Quality in Shallow Wells in Kipsonoi Subcatchment in Bomet County, Kenya."**

Any assistance given will be highly appreciated.

Yours faithfully,

PROF. ELISHIBA KIMANI
DEAN, GRADUATE SCHOOL

Appendix VI: NACOSTI Permit

REPUBLIC OF KENYA

NATIONAL COMMISSION FOR SCIENCE, TECHNOLOGY & INNOVATION

Ref No: 158760

Date of Issue: 01/May/2023

RESEARCH LICENSE

This is to Certify that Miss.. JANETH CHELANGAT SEGUT of Kenyatta University, has been licensed to conduct research as per the provision of the Science, Technology and Innovation Act, 2013 (Rev.2014) in Bomet on the topic: DRINKING WATER QUALITY IN SHALLOW WELLS IN KIPSONOI SUBCATCHMENT IN BOMET COUNTY, KENYA. for the period ending : 01/May/2024.

License No: NACOSTI/P/23/25565

158760

Applicant Identification Number

Director General

NATIONAL COMMISSION FOR SCIENCE,TECHNOLOGY & INNOVATION

Verification QR Code

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See overleaf for conditions