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Assessment of Temporal Variations in Shallow Well Water Quality Using Graphical Analysis and Water Quality Index in Half-London Ward, Tunduma, Tanzania

Matungwa William* and Zacharia Katambara
Department of Civil Engineering
Mbeya University of Science and Technology, P.O Box 131, Mbeya, Tanzania

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ABSTRACT

Shallow wells are vital for water supply in regions lacking centralised systems, but they are highly susceptible to contamination from anthropogenic activities and natural processes. This study investigated seasonal variations in water quality from five shallow wells in Half-London Ward, Tunduma, Tanzania, over a 12-month period to assess biological, chemical, and physical parameters, to identify contamination drivers, and to propose sustainable management solutions. Using WHO and EPA guidelines, monthly water sampling was conducted for 12 months from June 2022 to May 2023. Parameters analysed included Faecal and Total Coliforms, Nitrate, Phosphate, Total Iron, Biological Oxygen Demand (BOD), pH, Electrical Conductivity (EC), Turbidity, Total Dissolved Solids (TDS), and Total Suspended Solids (TSS). The National Sanitation Foundation Water Quality Index (NSFWQI) was employed to classify seasonal variations in water quality. Results revealed significant seasonal trends. Microbial contamination peaked during the rainy season, with shallow well WW3 and WW5 recording faecal coliform levels of 5 CFU/100 ml and total coliforms of 18 CFU/100 ml, exceeding WHO and East African Standards. Phosphate levels in shallow well WW4 and WW5 exceeded the threshold of 2.2 mg/l, attributed to agricultural runoff. Elevated iron concentrations (1.85 mg/l) in WW4 reflected natural geological leaching. BOD and turbidity increased during wet periods due to organic pollutants and sediment influx, while physical parameters such as pH and TDS remained within permissible limits. The NSFWQI ranged from "Excellent" (18.6) in shallow well WW5 during winter to "Medium" (65.4) in shallow well WW3 during summer, highlighting contamination risks from surface runoff and poor land management. The study concludes that rainfall and proximity to pollution sources significantly impact shallow well water quality. It recommends implementing community-driven sanitation measures, protecting shallow wells, and conducting routine monitoring. These findings provide a framework for improving groundwater quality for domestic use in urbanising regions globally.

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*Corresponding author's e-mail address: matungwa.william@must.ac.tz (Matungwa, W)

1.0 Introduction

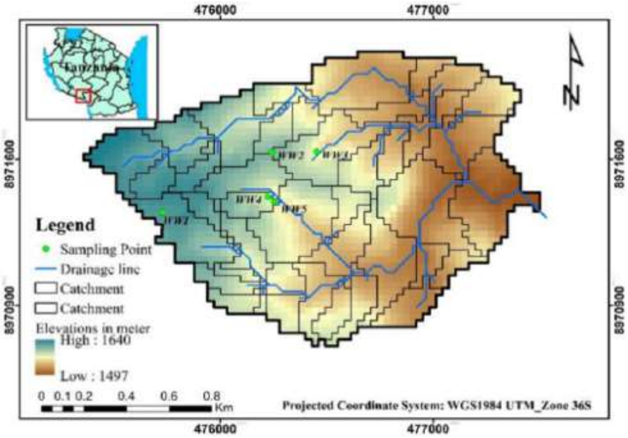
Groundwater serves as a critical water source for domestic and commercial use in many growing urban areas across Africa (Lapworth *et al*., 2017). This water can be accessed through shallow or deep wells, with shallow wells often being the preferred choice in regions where surface water supply systems are inadequate to meet growing domestic demand (Mbaka *et al*., 2017). Shallow wells are favoured due to their affordability, ease of construction, and accessibility to local communities (Graham & Polizzotto, 2013; Kimani-Murage & Ngindu, 2007). It is estimated that about 85% of water for public consumption in urban settings comes from groundwater (Ufoegbune *et al*., 2009).Groundwater, especially from deep wells in confined aquifers, is often perceived as clean and safe due to its natural filtration processes (Pandey *et al*., 2014; Schijven *et al.,* 2003). Additionally, groundwater systems respond more slowly to climate variability compared to surface water sources (Taylor et al., 2013). Despite these advantages, shallow wells are highly vulnerable to contamination, often situated close to point and non-point pollution sources such as pit latrines, small farms, and unmanaged solid waste. These pollutants, including physical, chemical, and microbial contaminants, can degrade water quality significantly (Mbaka *et al*., 2017; Howard *et al*., 2003).Studies conducted across African towns consistently report microbial contamination in groundwater sourced from shallow wells near pit latrines (Kanyerere *et al*., 2012; Pritchard *et al*., 2008). In unplanned settlements, shallow wells are often positioned adjacent to pit latrines located on nearby properties. High population density further increases the risk of contamination, particularly when pit latrines are situated at higher elevations than shallow wells (Dzwairo *et al*., 2006; Wright *et al*., 2012). Consequently, managing groundwater quality from shallow wells remains a significant challenge in both developing and developed urban areas. Water quality is defined by its physical, chemical, and biological characteristics, and its degradation is primarily caused by anthropogenic activities. These include land use changes associated with small-scale agriculture, urbanisation, and industrial activities (Cooper, 2010; Oki & Akana, 2016). Changes in climate and natural water flow have a big effect on groundwater quality by changing its chemistry, flow rates, and the ability of aquifers to let water through (Postolache *et al.,* 2012; MacDonald *et al*., 2011). The importance of analysing groundwater quality for sustainable management cannot be overstated (Kawo *et al*., 2018). This study evaluates the temporal variations in the quality of groundwater from shallow wells in the Half-London Ward of Tunduma Town, Tanzania.Half-London Ward in Tunduma was selected as the study area due to its unique combination of rapid urbanisation, reliance on shallow wells for water supplies, and significant vulnerability to groundwater contamination. The ward has a lot of people, not many places to collect wastewater, and people have settled there without planning to. This makes it more likely that pollution sources like pit latrines and agricultural runoff will be close to drinking water wells. Similar challenges have been documented in other urbanising areas across sub-Saharan Africa, where poor land use planning and inadequate waste management lead to groundwater contamination (Lapworth *et al*., 2017; Wright *et al*., 2012). Additionally, Tunduma's location near the border between Tanzania and Zambia makes it easier for a lot of business to happen, which raises the risk of contamination from uncontrolled solid and liquid wastes, as seen in other border towns in the region (Howard *et al.,* 2003). These factors, combined with the lack of centralised water supply systems and limited routine monitoring, align with studies that highlight that such areas face greater challenges in ensuring safe groundwater (Kanyerere *et al*., 2012; Kimani-Murage & Ngindu, 2007). This makes Half-London Ward an ideal case study for assessing seasonal variations in shallow well water quality and developing tailored interventions for sustainable groundwater management.This study addresses critical global water challenges by focusing on the vulnerability of shallow wells to contamination in urbanising areas like Half-London Ward, Tunduma, a scenario reflected in many regions worldwide. Globally, groundwater serves as a primary source of drinking water for nearly 2 billion people, particularly in developing regions where centralised supply systems are inadequate (UNICEF & WHO, 2021). Shallow wells, while accessible and affordable, are highly susceptible to contamination from inadequate sanitation, agricultural runoff, and unplanned urbanisation, as evidenced by studies in sub-Saharan Africa and South Asia (Lapworth *et al*., 2017; Pandey *et al*., 2014). Seasonal variations, driven by rainfall and climatic factors, exacerbate contamination risks, with studies globally demonstrating how increased surface runoff during rainy seasons introduces pathogens, nitrates, and other pollutants into groundwater systems (Taylor *et al.,* 2013; Howard *et al.,* 2003).This research builds on these global findings by integrating water quality indices and identifying specific contamination drivers, such as pit latrines and agricultural activities, to assess the dynamic risks faced by shallow wells in urbanising contexts. The actionable insights, including recommendations for sanitation improvements, community education, and affordable water treatment, align with strategies proposed in similar studies for improving water quality in low-resource settings (Kimani-Murage & Ngindu, 2007; Wright *et al.,* 2012). Moreover, the study's focus on sustainable groundwater management directly contributes to achieving Sustainable Development Goal 6 (SDG 6), which emphasises universal access to safe water and sustainable management practices by 2030. Thus, addressing local challenges, the research provides a scalable model for understanding and mitigating water quality risks, bridging gaps between local interventions and global water security efforts.

2.0 Materials and Methods

2.1 Description of the Study Area

Tunduma Town is located in the Southern Highlands of Tanzania's Songwe Region, near the border with Zambia (Figure 1). The town covers an area of 87.5 km², supporting a population of 219,309, with a rapid growth rate of 13% (United Republic of Tanzania Census, 2022). Elevations in the area range from slightly below 1500 m to above 1600 m above mean sea level, providing varied topography that influences water flow and aquifer recharge. The region experiences a unimodal rainy season from November to mid-May, with peak rainfall occurring in January and February. Annual average rainfall is 1006 mm, and the average temperature is 20.5°C, with extremes ranging from a minimum of 6.5°C in October to a maximum of 29.0°C in July (Tanzania Meteorological Agency, 2022). These climatic conditions play a significant role in the temporal variation of water quality.

Figure 1
Location Map of the Study Area (Half-London Ward) in Tunduma Town, Tanzania (William & Katambara, 2025)



2.2 Study Design

Water quality sampling was conducted by selecting five commonly used shallow wells from the Half-London Ward, Tunduma, Tanzania. The selection of the five wells was based on several critical criteria, including their high frequency of usage, ease of accessibility, and representation of different environmental and anthropogenic influences within the Half-London Ward. These wells are commonly used by local residents for domestic purposes, making them pivotal for understanding the community's concerns about water quality. They were placed in a way that took into account different types of possible contamination sources, like being close to pit latrines, farmland, and urban runoff zones. This made sure that the study area's groundwater quality was fully evaluated. Additionally, the wells were selected to align with EPA guidelines recommending a minimum of five to a maximum of 10 sampling points for community-level groundwater studies (EPA, 2009), thereby providing a robust dataset for analysing temporal variations in water quality. This approach ensures that the findings are representative of the broader water quality challenges facing the ward and similar urbanising contexts. These wells were labelled as Ward Wells and coded as WW1, WW2, WW3, WW4, and WW5. To capture temporal variations influenced by rainfall patterns, water sampling was carried out monthly over 12 months, from June 2022 to May 2023. Water samples were collected from the identified shallow wells at the geographic locations indicated in Figure 1. The Global Positioning System (GPS) was used to determine the position and elevation of the wells, while their depths were manually measured as indicated in Table 1. Water analysis focusses on biological, physical, and chemical parameters essential for public water consumption, as prioritised by Ambica *et al.* (2012) and Vousta (2012). Biological parameters included faecal and total coliform counts, while physical parameters encompassed pH, electrical conductivity, turbidity, total suspended solids (TSS), total dissolved solids (TDS), and colour. Chemical parameters included nitrate, phosphate, total iron, and biological oxygen demand (BOD).

Table 1
Shallow Well Depth, Elevation and GPS of the Sampling Points

Site Sampling Points	**Depth (m)**	**Elevation (m)**	**Latitude**	**Longitude**
WW1	9	1502	9° 18'11.61612" S	32° 47'17.3040"E
WW2	7	1573	9° 18'11.11000" S	32° 47'16.9860"E
WW3	6	1565	9° 18'10.95804" S	32° 47'8.09376"E
WW4	8	1579	9° 18'18.54100" S	32° 47'1.27800"E
WW5	7	1601	9° 18'18.51004" S	32° 47'1.27788"E

2.3 Sampling Framework

To capture the seasonal variation in groundwater quality, water sampling was conducted monthly over a 12-month period from June 2022 to May 2023. This approach accounted for both the dry and wet seasons, which significantly influence recharge, pollutant infiltration, and water chemistry in shallow wells. Sampling times were consistent each month to minimize diurnal variations in water quality parameters.

2.4 Sampling Procedures on Water Samples

The water sampling procedures adhered to both local and international standards, including the World Health Organisation (WHO) Guidelines for Drinking-Water Quality and the United States Environmental Protection Agency (EPA) Manual for Groundwater Sampling. These standards emphasise the proper sterilisation of sampling equipment, the collection of representative samples at consistent depths, and the use of cooled containers to preserve sample integrity during transportation. Furthermore, duplicate samples and field blanks were routinely collected to validate the sampling process and ensure that no contamination occurred during collection, handling, or transportation. By following these established protocols, the study ensured that the water quality data collected was accurate, reproducible, and suitable for analysis, aligning with global best practices for groundwater quality assessment.

The following standardised procedures were employed to ensure the collection of high-quality and uncontaminated samples:

2.4.1 Preparation and Sterilization

Before water sample collection, bottles were rinsed three times with the source water to minimise potential external contamination, as advised in the WHO Guidelines for Drinking-Water Quality (2017).

The sampling bottles were sterilised using an autoclave at 121°C for 15 minutes, following the methods outlined by APHA, AWWA, and WEF (2017) in the Standard Methods for the Examination of Water and Wastewater.

2.4.2 Collection Depth and Transportation

Water samples were collected at a consistent depth of 0.4 m below the surface to avoid floating debris and surface contaminants, as recommended in the US EPA Groundwater Sampling Guidelines (2009). Samples were transported in insulated containers maintained at 4°C, in accordance with the ISO 5667-3:2018 Standard for Water Quality Sampling, to preserve their integrity during transportation.

2.4.3 Replicates and Blanks

Duplicate samples and field blanks were periodically collected to verify consistency and rule out contamination during sampling or handling, aligning with best practices outlined by the EPA.

2.5 Determination of Water Quality Index

According to Brown *et al.* (1970), the National Sanitation Foundation Water Quality Index (NSF-WQI) was used to turn complicated data about water quality into a single score that water resource managers and decision-makers could easily understand. The calculation process included:

(i) Selecting the most significant water quality parameters;
(ii) Converting water quality parameter values to a common scale;
(iii) Assigning parameter weights; and
(iv) Aggregating the scores to a single numerical value (see Table 2).

The following equations were used in calculating NSFWQI:

$$\text{NFWQI} \sum_{i=1}^{n}(wi * qi) \qquad \textit{(Equation 1)}$$

Where:

- *n*: Number of water quality parameters considered,
- *wi*: Weight assigned to the *i-th* parameter based on its relative importance to overall water quality, and

qi: Quality rating for the *i-th* parameter, typically calculated as indicated below:

$$qi = \frac{\text{Observed Value-Ideal Value}}{\text{Standard Value-Ideal Value}} \times 100 \qquad \textit{(Equation 2)}$$

Where:

- Observed Value: Measured value of the parameter.
- Ideal Value: Value considered ideal for the parameter (often 0 for pollutants).
- Standard Value: Maximum permissible value of the parameter as per guidelines.

Table 2

Water Quality rating as per National Sanitation Foundation Water Quality Index (NSFWQI) Method

S/N	Water Quality Value	Water Quality Rating
1	0-25	Excellent Water Quality
2	26-50	Good Water Quality
3	51-75	Medium Water Quality
4	76-100	Bad Water Quality
5	Above 100	Very Bad Water Quality

Source: (Brown *et al.,* 1970)

2.6 Analysis of Data

Descriptive statistical analysis was performed using JAMOVI and spreadsheet application software to explore the relationships between water quality parameters across the 12 months. Parameters were summarised using statistical measures such as the minimum, maximum, mean, standard deviation, and standard error. These descriptive statistics provided insights into monthly variations in water quality and allowed for a more profound understanding of temporal trends.

3.0 Results and Discussion

This section presents a comprehensive analysis of water quality data collected over 12 months, focusing on biological, physical, and chemical parameters from five shallow wells in Half-London Ward, Tunduma. The findings highlight seasonal trends, potential contamination sources, and their implications for water quality management.

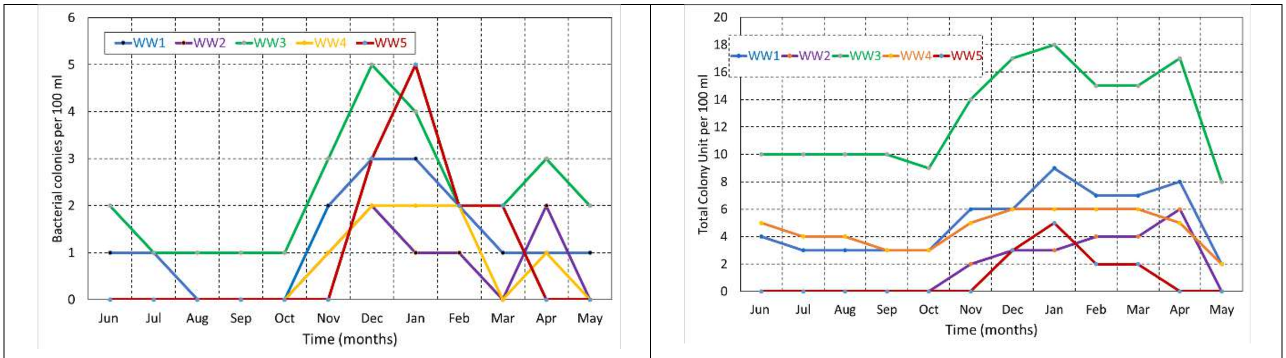
3.1 Biological Parameters (Faecal Coliform and Total Coliform)

The results indicate elevated levels of faecal and total coliform in shallow wells during the rainy season (November to April), with WW3 and WW5 recording peak counts of 5 CFU/100 ml in December and January, respectively, as indicated in Figure 2a and Figure 2b. Total coliform in WW3 reached 18 CFU/100 ml, exceeding the WHO (2006) and East African Standard (2022, ISO 9308-

1,2) permissible limit of 0 CFU/100 ml for drinking water. The proximity of these wells to pollution sources, such as pit latrines, is a significant factor. WW3, for instance, is situated only 8 meters from a pit latrine, falling well within the 30-meter radius of influence commonly cited in sanitation studies (Morgan, 2001). This proximity facilitates microbial infiltration into groundwater, especially during the rainy season when surface runoff and leaching are intensified. Interestingly, while Morgan (2001) highlights distance as a key determinant, Graham and Polizzotto (2013) argue that factors such as pit latrine design, maintenance, and usage frequency may have a more substantial impact. Properly sealed and lined latrines, for instance, can significantly reduce contamination risks even when located closer to water sources. This discrepancy underscores the complexity of groundwater contamination dynamics, where both spatial and structural factors interact. Poor hygiene practices, such as using unclean containers and dipping them directly into wells, further exacerbate microbial contamination, as explained by Kanyerere *et al.* (2012). Wright *et al.* (2012) similarly linked open wells and improper usage to higher microbial loads, emphasising the importance of proper water withdrawal methods. The findings align with studies in rural areas in Uganda and Malawi, where high coliform counts during rainy seasons were attributed to pit latrines, unlined wells, and surface runoff (Howard *et al.,* 2003; Pritchard *et al.*, 2008). The observed seasonal pattern suggests that coliform levels are strongly influenced by rainfall, which accelerates the transport of pathogens from surface sources into groundwater. This is consistent with findings in Kenya, where heavy rains increased bacterial contamination in shallow wells near latrines and agricultural fields (Kimani-Murage & Ngindu, 2007). Similar trends were reported in Nigeria, where coliform counts peaked during wet seasons due to higher infiltration and leaching rates (Kawo & Karuppannan, 2018). In Malawi, Kanyerere *et al.* (2012) observed microbial contamination in wells within 10 meters of latrines, with levels declining sharply beyond 20 meters, reinforcing the need for adequate spacing. In India, Pandey *et al.* (2014) reported that contamination depended not only on distance but also on soil permeability and aquifer characteristics, suggesting that regional geology plays a role in pathogen transport.

Figure 2

The Biological Parameters of Water Quality in the Shallow Wells for (A) Faecal Coliform and (B) Total Coliform



(a)

(b)

3.2 Chemical Parameters

The analysis of chemical parameters including nitrate, phosphate, total iron, and Biological Oxygen Demand (BOD) gave critical insights into the seasonal dynamics of water quality in the shallow wells. Seasonal trends are shown in Figures 3a-3d, indicating fluctuations linked to both anthropogenic activities and natural processes. These trends highlight the influence of environmental factors, such as rainfall and surface runoff, as well as human-induced activities, including agricultural practices, waste disposal, and sanitation systems.

3.2.1 Nitrate

The nitrate concentrations in the studied wells ranged from 0.5 mg/l (WW5, October) to 4.25 mg/l (WW1, December; WW2, January) as shown in Figure 3a, remaining acceptable below the WHO (2006) guideline of 10 mg/l and the East African Standard (2022) limit of 45 mg/l for drinking water. This evidence indicates that nitrate levels in the wells are suitable for consumption. However, the observed seasonal variations suggest a relationship between rainfall and nitrate contamination, as elevated concentrations were recorded during the rainy season (December and January). Nitrate contamination likely originates from sewage infiltration due to the proximity of pit latrines to the wells and nutrient leaching from nearby backyard gardens. Rainfall during the wet season exacerbates this issue by facilitating the transport of nitrates through surface runoff and infiltration into shallow wells. Similar findings were reported by Wright *et al.* (2012), who observed a direct correlation between rainfall and nitrate levels in wells located near pit latrines and agricultural fields. Pandey *et al.* (2014) found that nitrates in groundwater in rural India were mostly caused by agricultural runoff and organic waste leaching. The levels were highest during the rainy season. Likewise, studies in Malawi demonstrated that shallow wells near pit latrines and farming activities were vulnerable to nitrate contamination, particularly during periods of heavy rainfall (Kanyerere *et al.,* 2012). In Nigeria, Kawo and Karuppannan (2018) found nitrate concentrations ranging from 5 mg/l to 15 mg/l in shallow wells influenced by fertiliser application, higher than the levels observed in this study. This highlights the relatively moderate impact of agricultural activities in the Half-London Ward. Similarly, studies in Kenya (Kimani-Murage & Ngindu, 2007) reported nitrate levels exceeding 20 mg/l in wells near unregulated waste disposal sites, emphasising the importance of proper waste management practices. Although nitrate levels in the studied wells are within safe limits, prolonged exposure to elevated nitrate concentrations, even below regulatory thresholds, can lead to health risks such as methemoglobinemia (blue baby syndrome) in infants and other long-term health effects, as documented by Howard *et al.* (2003). This situation underscores the need for proactive monitoring, particularly during the rainy season when nitrate levels tend to increase.

3.2.2 Phosphate

Phosphate concentrations in the studied shallow wells, as shown in Figure 3b, displayed significant seasonal variation, with peaks recorded in WW4 (2.5 mg/l) and WW5 (2.25 mg/l) during December, exceeding the East African Standard (2022, ISO 15681) threshold of 2.2 mg/l. These elevated levels are primarily attributed to fertiliser runoff from nearby backyard gardens, particularly during the rainy season when increased surface runoff facilitates the transport of nutrients into groundwater. Elevated phosphate levels increase the complexity and cost of treating groundwater for domestic use. Removing phosphates requires advanced filtration systems that may not be accessible to resource-limited communities. By contrast, WW1 consistently exhibited minimal phosphate levels (0.1 mg/l), likely due to its location being relatively distant from agricultural activities and other phosphate sources. The major source of phosphate in WW4 and WW5 is the fertilisers used in the nearby backyard gardens. During the rainy season, surface runoff transports these nutrients into the shallow wells, a pattern widely observed in agricultural areas globally. Studies by Mbaka *et al.* (2017) revealed similar spikes in phosphate levels during the wet season, directly linked to fertiliser use. Also, heavy rains can erode phosphate-rich topsoil, leading to increased phosphate levels in surface runoff. This process has been documented in Malawi, where seasonal rains carried significant amounts of phosphate into shallow wells (Kanyerere *et al.,* 2012). In addition, improperly maintained or unsealed septic systems and latrines near WW4 contribute to elevated phosphate levels, particularly during rainy periods. This source has been found in Uganda and India, where groundwater with higher phosphate levels was found to be closer to systems that handle household waste (Howard *et al*., 2003; Pandey *et al.,* 2014). Organic waste from domestic activities and decaying plant material near these wells adds to phosphate levels. In poorly managed areas, decomposition of organic matter releases phosphates, which are further mobilised by rainfall.

3.2.3 Total Iron

Total iron concentrations ranged from 0.2 mg/l (WW3, October) to 1.85 mg/l (WW4, December), with most values exceeding the WHO (2006) guideline of 0.3 mg/l for drinking water as shown in Figure 3c. Elevated iron concentrations, while not directly toxic, can have adverse health effects when consumed over prolonged periods. Excessive iron in drinking water can lead to hemochromatosis (iron overload) and gastrointestinal irritation. It also imparts a metallic taste, making the water unpalatable. Only WW4 approached levels considerably higher than the acceptable threshold during the rainy season. These elevated concentrations are primarily attributed to natural geological processes, including the dissolution of iron-rich minerals within the aquifer. The pattern observed differs from findings by Ogunribido (2017), where iron contamination in groundwater was primarily linked to industrial and agricultural sources. The aquifer for the shallow wells' geological composition, characterised by iron-bearing minerals, is the most probable source of high iron concentrations. Heavy rainfall during the w*et* season accelerates the leaching of these minerals, dissolving iron into groundwater. This matches research done in places like Zimbabwe and Nigeria with similar hydrogeological conditions. In those places, higher iron levels were linked to lateritic soils and aquifer material (Dzwairo *et al.,* 2006; Kawo & Karuppannan, 2018). Also, increased infiltration during the rainy season introduces dissolved oxygen into the shallow wells, promoting the oxidation and dissolution of iron minerals. Studies by Pandey *et al.* (2014) and Mbaka *et al.* (2017) have reported similar seasonal spikes in total iron concentrations due to enhanced aquifer recharge during monsoon and rainy seasons. In contrast, studies in Nigeria (Ogunribido, 2017) and parts of Europe have linked total iron contamination to industrial runoff and the improper disposal of agricultural waste. In Half-London Ward, the lack of these kinds of human activities makes it clear where the pollution is coming from, highlighting how important geological factors are. While no significant industrial activities were identified in the study area, natural iron dissolution remains the dominant factor in the observed iron concentrations from the shallow wells.

3.2.4 BOD

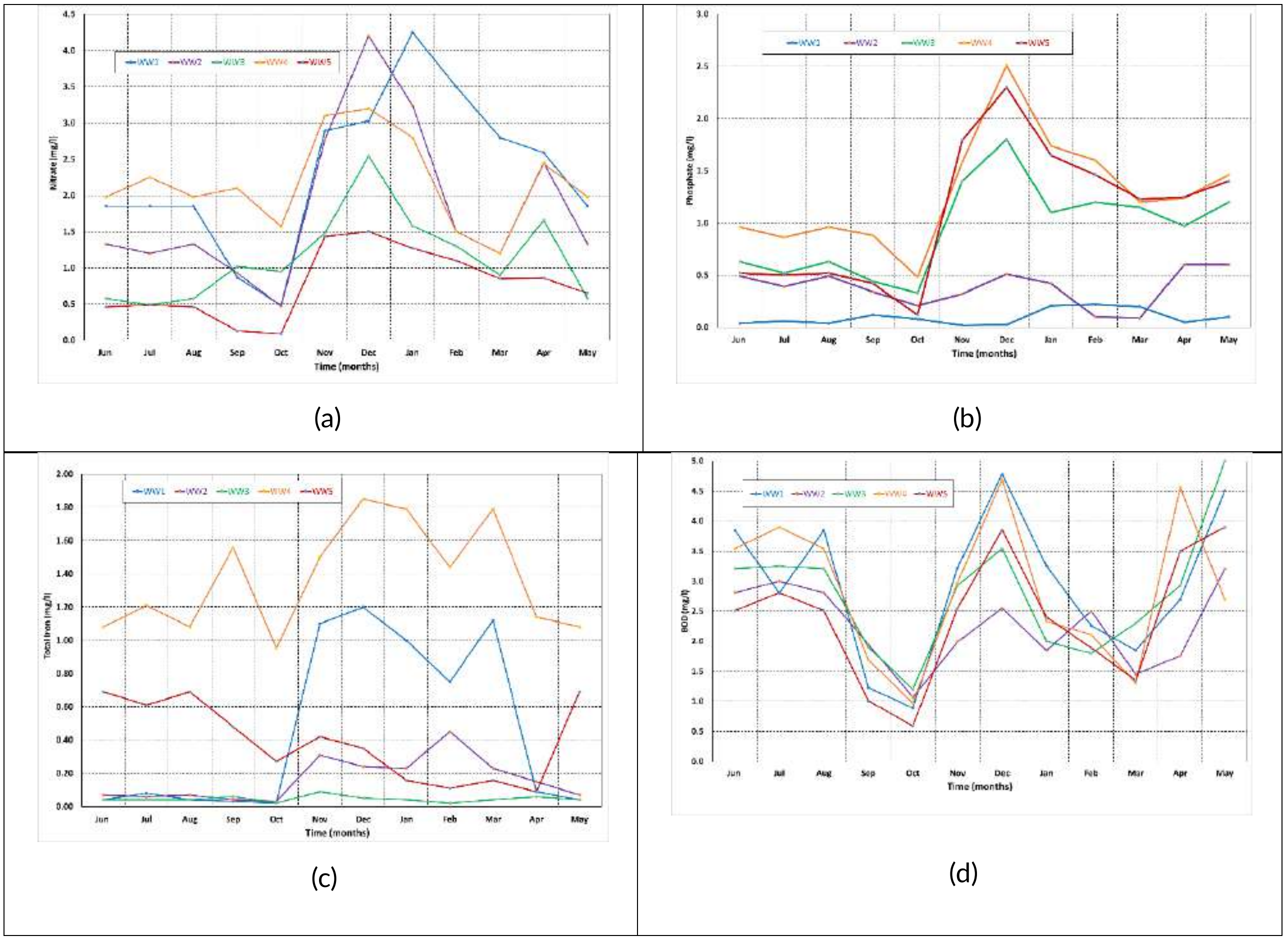
BOD levels displayed a rising trend throughout the study period, with significant increases observed in WW3 (4.9 mg/l) in May and WW1 and WW2 (4.75 mg/l) in December, as shown in Figure 3d. These values are below the permissible limit for untreated surface water, typically 6 mg/l as per WHO (2006) and East African Standards (2022). However, there is an indication of moderate organic pollution, which can compromise water quality if not managed effectively. The sharp rises during these times are mostly due to surface runoff and the movement of organic pollutants into shallow wells during the rainy season. These pollutants include dead plants, household trash, and farm residues. The rainy season increases the transport of organic matter into shallow wells.

Elevated BOD levels are indicative of increased microbial activity, which may lead to the proliferation of pathogens. While BOD itself is not a direct health risk, the associated microbial contamination poses significant risks, particularly for vulnerable populations. Rainwater mobilises decaying vegetation, animal waste, and organic residues from agricultural fields in the aquifer. Similar findings were reported by Howard *et al.* (2003), where BOD levels rose during heavy rains due to increased organic runoff. Proximity to poorly managed waste disposal sites and pit latrines can result in organic contaminants infiltrating the water table. Also, this phenomenon was also observed in other studies, where slum settlements near wells exhibited high BOD levels due to domestic wastewater intrusion (Kimani-Murage & Ngindu, 2007). In addition, organic fertiliser and crop residues contribute significantly to the organic load in water sources, as revealed by findings from Mbaka *et al.* (2017), who showed a direct correlation between agricultural runoff and increased BOD levels in shallow wells during rainy periods.

However, the BOD levels seen are similar to what was found in Malawi by Kanyerere *et al.* (2012), who found that peak BOD levels were 5 mg/l during the rainy seasons in wells that were close to farms and homes. Similar trends were noted in Nigeria by Kawo and Karuppannan (2018), where BOD levels increased with rainfall due to organic waste runoff. Furthermore, studies in the USA and Europe reported similar seasonal spikes, particularly in areas with intensive agricultural practices and poor waste management (Lapworth *et al.,* 2017).

Figure 3

The Chemical Parameters of Water Quality in the Shallow Wells for (a) Nitrate, (b) Phosphate, (c) Total Iron and (d) BOD



(a)

(b)

(c)

(d)

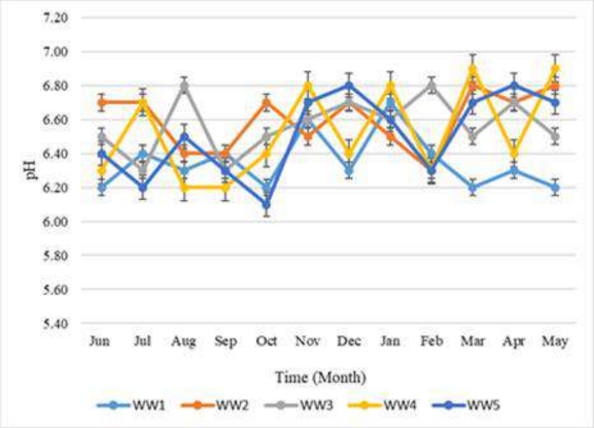
3.3 Physical Parameters

Physical parameters, including pH, electrical conductivity (EC), turbidity, total suspended solids (TSS), total dissolved solids (TDS), and colour, provide critical insights into the suitability of water for drinking and other domestic purposes. These parameters serve as indicators of the physical quality of water and are influenced by natural geological processes, land use, and anthropogenic activities.

3.3.1 pH

The pH levels of the shallow wells in Half-London Ward ranged from 6.10 (WW5, October) to 6.90 (WW4, March and May), as shown in Figure 4. All of these levels were within the acceptable range of 5.5 to 9.0 for drinking water, as s*et* by the East African Standard (2022, ISO 10523) and WHO (2006). This consistency suggests that the groundwater is neutral to slightly acidic and suitable for consumption and other domestic purposes. The fact that the pH stays the same throughout the year shows that acidifying or alkalising pollutants don't have much of an effect, which is a reflection of the aquifer's natural ability to buffer. The aquifer’s buffering capacity, due to carbonate and silicate minerals, likely maintains the stability of pH levels. Similar stability has been reported in Kenya and Uganda, where groundwater in weathered rock aquifers showed pH levels within the neutral to slightly acidic range (Howard *et al.,* 2003; Mbaka *et al.,* 2017). Furthermore, rainwater, with a natural pH of around 5.6 due to dissolved carbon dioxide, may slightly acidify the groundwater. However, the lack of significant variation between the wet and dry seasons suggests that the aquifer's buffering properties effectively neutralise such inputs. Furthermore, the absence of industrial activities and controlled agricultural practices in the area minimises the introduction of acidifying agents such as nitrates and sulphates from fertilisers, which have been observed to lower pH levels in regions with intensive agriculture, such as parts of India and Malawi (Pandey *et al.,* 2014; Kanyerere *et al.,* 2012). The pH stability observed in Half-London Ward aligns with findings from similar studies in sub-Saharan Africa. For example, in Uganda, Howard et al. (2003) reported pH values ranging from 6.0 to 7.5 in shallow wells, with minimal seasonal variation.

Figure 4
The Physical Parameters in the Shallow Wells for pH



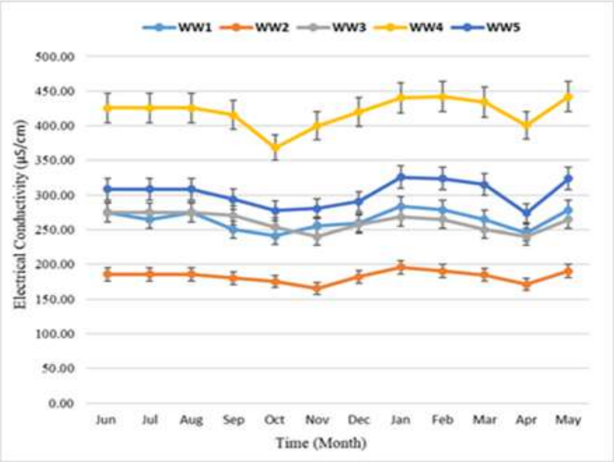
In contrast, studies in industrialised regions, such as parts of China, have documented significant pH fluctuations, often dipping below 5.5 due to industrial discharges, acid rain, and extensive fertiliser use (Lapworth *et al.,* 2017; Pandey *et al.*, 2014), where acidic pH levels pose challenges for water quality and infrastructure.

3.3.2 Electrical Conductivity (EC)

The EC levels in the shallow wells that were studied ranged from 165.3 µS/cm (WW2, November) to 442.0 µS/cm (WW3, May). All of these levels were well below the 2500 µS/cm limit set by the East African Standard (2022, ISO 7888) for potable water. This range indicates low levels of dissolved ionic substances in groundwater, suggesting limited mineralisation and minimal contamination from anthropogenic sources. There were seasonal changes, with slightly higher EC values during the rainy season (e.g., WW3, May), which means that more ions are leaching from the soil and aquifer material because of the higher recharge.

The dissolution of minerals from aquifer rocks is the primary contributor to EC. Low values in Half-London Ward point to aquifer materials that aren't very soluble, which fits with the type of weathered rock formations that are common in sub-Saharan Africa (Howard *et al*., 2003). During the rainy season, increased infiltration dissolves salts and minerals from the soil and aquifer, temporarily raising EC levels. This trend aligns with studies in Uganda, where EC levels peaked during wet periods due to ionic mobilisation (Mbaka *et al.,* 2017; Howard *et al*., 2003). The absence of significant agricultural runoff or industrial effluents contributes to the relatively low EC levels. In contrast, regions with intensive farming or industrial activities often report EC values exceeding 1000 µS/cm due to fertiliser use and effluent discharge (Pandey *et al.,* 2014; Kawo & Karuppannan, 2018). The EC values in Half-London Ward are consistent with groundwater trends in sub-Saharan Africa. For instance, Kanyerere *et al.* (2012) found that EC levels in shallow wells ranged from 200 to 600 µS/cm and were affected by the same geological and seasonal factors. In industrialised regions, such as parts of India and the USA, EC levels frequently exceed 1000 µS/cm due to extensive agricultural runoff and industrial discharges (Lapworth *et al*., 2017; Pandey *et al.,* 2014). These comparisons highlight the minimal anthropogenic impact in Half-London Ward.

Figure 5
The Physical Parameters in the Shallow Wells for Electrical Conductivity



3.3.3 Turbidity

Turbidity values in the shallow wells ranged from 4.0 NTU (WW3, March) to 19.0 NTU (WW2, November), with most values exceeding the WHO (2006) recommended limit of 5.0 NTU for drinking water as shown in Figure 6a. However, all values remained within the East African Standard (2022, ISO 7027) limit of 25 NTU. The higher turbidity levels during the rainy season, particularly in November, are primarily attributed to increased surface runoff and soil erosion. Rainfall mobilises fine particles, organic matter, and debris from surrounding catchments into the shallow wells, reflecting the influence of unprotected water sources and land management practices. Heavy rains in the wet season transport suspended particles, including silt, clay, and organic debris, into the wells. This process is exacerbated by poor vegetation cover and unprotected well structures. Similar findings were reported by Mbaka *et al.* (2017), where turbidity levels in shallow wells peaked during rainy periods due to soil erosion and unmanaged runoff. Furthermore, shallow wells near agricultural zones, such as WW2, may experience higher turbidity due to runoff carrying soil particles and agricultural residues into the aquifer. This trend is consistent with observations in Malawi, where agricultural runoff significantly increased turbidity levels in groundwater (Kanyerere *et al.,* 2012). Poor sanitation practices and proximity to pit latrines can contribute to organic matter infiltration, further elevating turbidity. Studies in Uganda by Howard *et al.* (2003) highlighted similar challenges, where unlined wells near waste disposal areas exhibited elevated turbidity during wet periods. Turbidity levels in Half-London Ward align with those reported in other parts of sub-Saharan Africa. For instance, in Uganda, Howard *et al.* (2003) recorded turbidity values exceeding 15 NTU during rainy seasons due to inadequate well protection and surface runoff. Similarly, in Central Kenya, Mbaka *et al.* (2017) found turbidity levels ranging from 10 to 20 NTU in wells exposed to agricultural and domestic runoff. Globally, turbidity issues are often more pronounced in developing regions with unprotected water sources. In India, Pandey *et al.* (2014) reported turbidity values of up to 25 NTU during monsoon seasons due to extensive agricultural activities and poor watershed management. In contrast, well-protected groundwater systems in developed regions typically exhibit turbidity levels below 1 NTU, emphasising the role of infrastructure and land-use practices in water quality management.

The seasonal variation in turbidity, with peaks during the rainy season (e.g., WW2, 19.0 NTU in November), highlights the significant role of rainfall in transporting particulates into the wells. Spatially, wells located near erosion-prone areas or agricultural lands exhibit higher turbidity levels. For example, WW2, surrounded by agricultural activities and poor drainage, consistently showed higher turbidity compared to shallow wells located in less disturbed areas.

3.3.4 Total Suspended Solids (TSS)

TSS levels observed in the shallow wells peaked at 7.2 mg/l in WW4 during July, corresponding to the dry season and likely due to dust deposition, as shown in Figure 6b. Additionally, surface runoff during the rainy season, especially in November, contributed to elevated TSS levels across the wells, albeit at lower levels compared to July. While the recorded TSS values remain below the WHO (2006) and East African Standards (2022) thresholds of 10 mg/l for drinking water, these findings highlight seasonal influences on groundwater quality. During the dry season, reduced vegetation cover and increased dust particles in the atmosphere contribute to higher TSS levels in uncovered wells. Wind erosion and the deposition of airborne particulates into open water sources are common in semi-arid and tropical regions. Similar trends were observed in Kenya, where TSS levels during the dry season were attributed to dust and windborne sediment deposition (Mbaka *et al.,* 2017). Also, heavy rainfall mobilises soil particles, organic debris, and other suspended materials, washing them into unprotected wells. In November, the onset of the rainy season increased TSS levels through erosion and runoff, consistent with findings in Malawi and Uganda, where TSS levels in shallow wells peaked during wet periods due to sediment influx (Kanyerere *et al.*, 2012; Howard *et al.*, 2003). WW4's high TSS levels are likely influenced by its proximity to unpaved areas and small-scale agricultural plots. Disturbed soil in such regions contributes to higher sediment loads in runoff, particularly after the first rains, as observed in rural regions of Nigeria (Kawo & Karuppannan, 2018). The observed TSS levels in Half-London Ward align with findings from sub-Saharan Africa. In Malawi, Kanyerere *et al.* (2012) reported TSS levels ranging from 5 to 15 mg/l in wells affected by seasonal runoff and soil erosion. Similar observations were made in Uganda, where unprotected wells near erosion-prone areas exhibited TSS values exceeding 8 mg/l during rainy periods (Howard *et al.,* 2003). In contrast, studies in industrialised regions often report significantly lower TSS levels, typically below 2 mg/l, due to the widespread use of protective well covers and sediment filtration systems (Lapworth *et al.,* 2017). However, in regions of Pakistan, TSS values frequently exceed 10 mg/l during monsoon seasons due to intense agricultural runoff and poor land management practices (Pandey *et al.,* 2014).

3.3.5 Total Dissolved Solids (TDS)

TDS concentrations in the studied shallow wells ranged from 60 mg/l (WW1, October) to 390 mg/l (WW5, December), as shown in Figure 6c. These values are well below the WHO (2006) recommended limit of 500 mg/l and the East African Standard (2022) permissible limit of 1500 mg/l for drinking water. The observed variability in TDS levels reflects natural geochemical processes, land use practices, and seasonal influences on groundwater recharge.

The mineral composition of the aquifer where the shallow wells are located is a key determinant of TDS levels. In the Half-London Ward, the dissolution of soluble minerals, such as calcium, magnesium, and bicarbonates, contributes to moderate TDS levels. Similar findings were reported in an East African country—Kenya, where TDS levels remained below 400 mg/l due to low salinity in the aquifers (Mbaka *et al.,* 2017). Rainfall and recharge Increased TDS levels during the rainy season, such as the peak observed in December (WW5), can be attributed to the dissolution of minerals during aquifer recharge. Rainwater infiltrates the soil, leaching ions from both natural and anthropogenic sources into the groundwater. This aligns with trends observed in Uganda and Malawi, where TDS levels increased during wet periods due to enhanced ionic mobilisation (Howard *et al.,* 2003; Kanyerere *et al.,* 2012).

While anthropogenic contributions appear minimal in Half-London Ward, activities such as the use of fertilisers, improper waste disposal, and agricultural runoff can increase TDS. WW5, surrounded by residential areas and agricultural plots, exhibited the highest TDS levels, reflecting localised human influence. This trend is consistent with studies in Nigeria, where agricultural and domestic activities contributed significantly to elevated TDS levels (Kawo & Karuppannan, 2018).

The TDS levels in Half-London Ward are comparable to those in sub-Saharan Africa, where values typically range between 50 mg/l and 600 mg/l. For instance, Howard *et al.* (2003) reported TDS values of 80–450 mg/l in Uganda, influenced by geological and seasonal factors. Similarly, in Malawi, Kanyerere *et al.* (2012) observed values below 500 mg/l in wells with limited anthropogenic impact. In industrialised regions, TDS levels are often influenced by higher anthropogenic activity, such as industrial effluent and urban runoff. For example, in India, TDS levels frequently exceed 1000 mg/l in agricultural areas due to extensive fertiliser use (Pandey *et al.,* 2014). Europe and the USA, on the other hand, have developed water protection systems that keep TDS levels below 250 mg/l. This is because land use is controlled and pollution is kept to a minimum (Lapworth *et al.,* 2017).

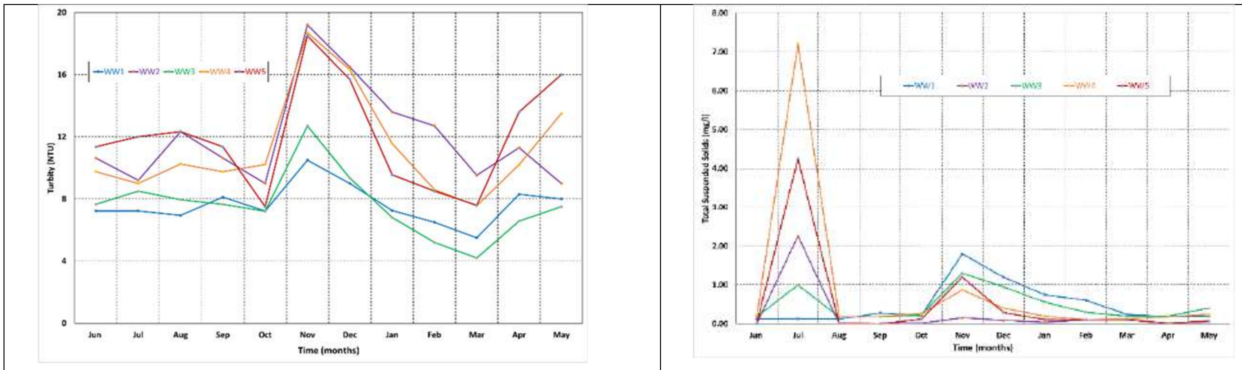
3.3.6 Colour

The colour of the shallow well water in Half-London Ward ranged from 0.25 TCU (True Colour Unit) in WW5 (March) to 4.25 TCU in WW4 (November), as indicated in Figure 6d. These values remained significantly below the acceptable limit of 50 TCU set by the East African Standard (2022, ISO 7887) and WHO (2006) guidelines for drinking water. The low levels of colour in the water indicate minimal organic and inorganic contamination, suggesting the groundwater in this area has high aesthetic quality and is suitable for domestic use. The presence of natural organic matter, such as humic and fulvic acids from decaying vegetation, can contribute to the colour of water. However, the low levels observed in this study indicate limited infiltration of such substances into the aquifer. Similar trends were noted in Kenya, where groundwater in less-forested areas exhibited low colour levels due to minimal organic input (Mbaka *et al.,* 2017). Furthermore, the dissolution of iron and manganese compounds from the aquifer can cause colouration in water. However, the low colour values in Half-London Ward suggest limited geochemical leaching of these elements, aligning with findings in Malawi, where wells with a lower mineral content exhibited colour levels below 5 TCU (Kanyerere *et al.,* 2012). Furthermore, the slightly higher colour levels in November (WW4) reflect the influence of surface runoff during the rainy season, which may introduce small amounts of organic and mineral debris to the water. This seasonal variation is consistent with studies in Uganda and Tanzania, where colour levels increased during wet periods due to organic and clay particle infiltration (Howard *et al.,* 2003; Kawo & Karuppannan, 2018). The low colour values in Half-London Ward are consistent with findings from Howard *et al.* (2003), who reported colour values below 10 TCU in protected shallow wells, while unprotected wells exhibited higher values due to runoff contamination. Globally, groundwater colour levels are influenced by land use, geological composition, and water source protection. In industrialised regions, colour values are typically lower than 1 TCU due to advanced protection systems and minimal organic input. In contrast, regions with dense vegetation or mining activities often exhibit higher colour levels, as observed in parts of India, where groundwater near mining zones reached up to 25 TCU due to dissolved iron oxides and clay particles (Pandey *et al.,* 2014).

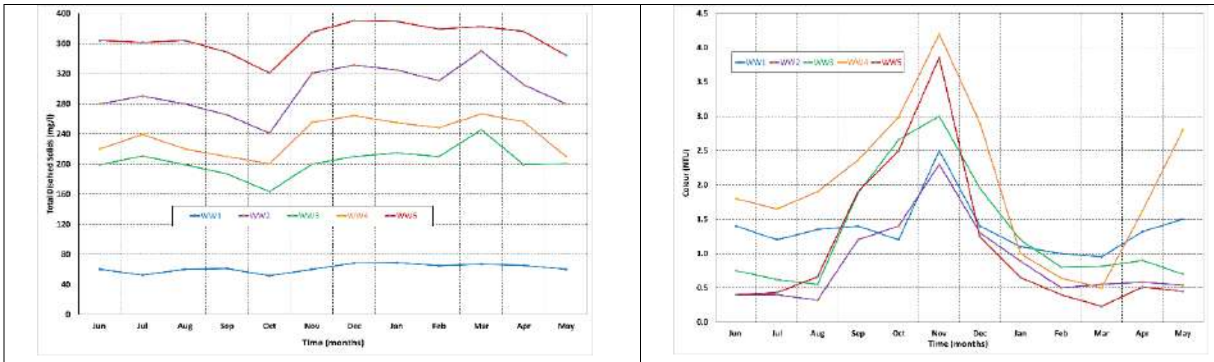
3.4 National Sanitation Foundation Water Quality Index (NSFWQI)

NSFWQI for the studied shallow wells exhibited notable seasonal variations, ranging from 18.6 ("Excellent") in WW5 during winter to 65.4 ("Medium") in WW3 during summer, as seen in Table 6. These variations highlight the complex interplay of natural and anthropogenic factors influencing groundwater quality. While most shallow wells maintained "Good" to "Excellent" water quality throughout the year, WW3 showed periodic degradation to the "Medium" category, particularly during the summer and autumn seasons. The summer season, characterised by increased rainfall and surface runoff, contributed significantly to the observed NSFWQI degradation in WW3. Heavy rains mobilise pollutants, including nitrates, phosphates, and microbial contaminants, from agricultural fields and nearby pit latrines, leading to higher pollutant loads in shallow wells. Similar seasonal patterns were seen in Malawi, where NSFWQI scores went down when it rained because more pollutants got into the groundwater (Kanyerere *et al.,* 2012; Howard *et al.,* 2003). The proximity of WW3 to unprotected agricultural and residential areas exacerbates its vulnerability to contamination. The introduction of fertilisers and improper waste disposal contribute to elevated nutrient loads and reduce water quality. Comparable findings were observed in Kenya, where wells near agricultural zones exhibited lower NSFWQI values due to nitrate and phosphate contamination (Mbaka *et al.,* 2017). Shallow wells such as WW5, with "excellent" WQI throughout the year, are likely located in areas with well-buffered aquifers and minimal exposure to surface contamination. The natural filtration capacity of these aquifers where these shallow wells are located helps to maintain water quality, consistent with trends observed in Tanzania's Dodoma region, where geologically protected wells maintained higher WQI scores year-round (Kawo & Karuppannan, 2018). NSFWQI values observed in Half-London Ward align with those in other sub-Saharan regions. For instance, NSFWQI in Malawi's rural wells ranged from "Good" to "Poor" depending on proximity to pollution sources and seasonal variations, highlighting similar patterns of seasonal and anthropogenic influence (Kanyerere *et al.,* 2012). In industrialised regions with advanced water management systems, NSFWQI values tend to remain in the "excellent" category year-round due to strict pollution controls and advanced treatment processes. However, in agricultural regions of South Asia, WQI values frequently dip into the "Medium" or "Poor" categories during wet seasons due to intense fertiliser runoff and poor waste management practices (Pandey *et al.,* 2014; Lapworth *et al.,* 2017). NSFWQI values in the "Medium" category, as observed in WW3 during summer and autumn, indicate potential health risks from microbial and chemical contaminants, including nitrates, phosphates, and coliform bacteria. Consumption of such water without treatment could lead to waterborne diseases and other health issues.

Figure 6
The Physical Parameters in the Shallow Well for (A) Turbidity, (B) Total Suspended Solids, (C) Total Dissolved Solids and (d) Colou



(a) (b)



(c)

(d)

Table 1

The Water Quality Index for Shallow Wells in Four Seasons of the Year

Shallow Wells	Winter Season		Spring Season		Summer Season		Autumn Season	
	WQI	Water Status	WQI	Water Status	WQI	Water Status	WQI	Water Status
WW1	25.00	Excellent	19.50	Excellent	40.00	Good	37.00	Good
WW2	22.30	Excellent	23.00	Excellent	26.10	Excellent	24.90	Excellent
WW3	36.20	Good	45.00	Good	65.40	Medium	57.00	Medium
WW4	24.60	Excellent	25.00	Excellent	27.44	Excellent	26.50	Excellent
WW5	20.80	Excellent	18.60	Excellent	20.50	Excellent	23.40	Excellent

4.0 Conclusions

The comprehensive assessment of water quality in shallow wells in Half-London Ward over 12 months reveals significant seasonal variations influenced by both natural and anthropogenic factors.

Biological, chemical, and physical parameters, as well as the National Sanitation Foundation Water Quality Index (NSFWQI), highlight critical insights into groundwater quality dynamics and potential health risks. Elevated faecal and total coliform counts, particularly in WW3 and WW5 during the rainy season, underscore the vulnerability of wells to microbial contamination from nearby pit latrines, unprotected water sources, and improper hygiene practices. This aligns with regional findings where proximity to waste disposal systems exacerbates contamination risks. While nitrate levels remained below permissible thresholds, phosphate concentrations exceeded standards in WW4 and WW5 during the rainy season, reflecting the impact of agricultural runoff.

Similarly, high total iron concentrations in WW4 indicate natural geological leaching intensified by seasonal recharge, emphasising the interplay between aquifer composition and rainfall patterns. Biological Oxygen Demand (BOD) and turbidity levels peaked during wet periods, highlighting the influx of organic pollutants and suspended solids through surface runoff. The physical parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), and colour, remained within acceptable limits, demonstrating the aquifer's buffering capacity against seasonal variations. However, higher turbidity and total suspended solids (TSS) during the rainy season point to inadequate well protection and land-use challenges. The NSFWQI values, ranging from "Excellent" to "Medium," reflect the influence of rainfall on water quality, with WW3 showing consistent vulnerability due to its proximity to pollution sources.

5.0 Recommendations

Based on the findings of the study on shallow well water quality in Half-London Ward, Tunduma, the following recommendations are proposed to mitigate contamination risks and enhance water quality management:

- *Enhanced Sanitation Infrastructure*

Implement improved sanitation facilities, including lined and sealed pit latrines, positioned at least 30 meters away from shallow wells to minimise microbial contamination. Community education on the importance of pit latrine maintenance and proper waste disposal is essential in Tunduma town.

- *Protection of Water Sources*

Install well covers and fences around shallow wells to prevent direct contamination from runoff and debris. Vegetative buffers should also be planted around wells to reduce soil erosion and nutrient leaching.

- *Promotion of Hygiene Practices*

Conduct awareness campaigns to promote the use of clean water containers and proper water handling methods, discouraging practices such as dipping contaminated buckets into wells.

- *Agricultural Runoff Management*

Encourage the adoption of sustainable agricultural practices, including controlled use of fertilisers and the establishment of buffer zones between agricultural activities and water sources to reduce nitrate and phosphate leaching.

- *Routine Water Quality Monitoring*

Establish regular monitoring programs for biological, chemical, and physical water quality parameters to track seasonal variations and contamination trends. This will enable timely interventions and data-driven management decisions.

- *Introduction of Community-Level Water Treatment*

Provide affordable, community-based water treatment technologies, such as chlorination or bios and filtration, to ensure the microbial safety of water, particularly during the rainy season.

- *Policy Integration and Local Governance*

Collaborate with local authorities to integrate water quality management into urban planning and development policies by enforcing regulations on land use and waste disposal near water sources.

- *Climate Resilience Strategies*

Develop strategies to address climate-related impacts on groundwater, such as rainfall variability, by enhancing recharge areas and using climate-adaptive aquifer management practices.

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8.0 Declaration of Conflicting Interests

The authors declare no conflict of interest regarding the publication of this paper.

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