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Assessing Groundwater Quality for Irrigation and Drinking in Seven Villages along Mara River - Tanzania

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ABSTRACT

In this study, the quality of groundwater is examined, and its appropriateness for irrigation and drinking is evaluated. Seven samples from S1 to S7 villages were gathered and examined for several physicochemical and heavy metal characteristics. Chemical data were assessed using US salinity diagrams, Wilcox and the water quality index, and a comparison was made with respect to WHO & TBS criteria. The results revealed that pH levels in two villages, S4 (pH 5.74) and S5 (pH 5.71) fell below the recommended WHO/TBS. The salinity measurements (EC: 696–938 µS/cm; TDS: 295 – 359 mgL^{-1}) indicated moderate salinity (C2 class), which is appropriate for irrigation with little control. The recorded value of nutrient concentrations was NO^{3-} (1.22 – 1.82 mgL^{-1}) and PO_4^{3-} (0.02 – 0.08 mgL^{-1}), which are within safe limits, while that of SO_4^{2-} (209 –258 mgL^{-1}) neared the 250 mg/L which is the regulatory threshold value. The Ca^{2+} (70 – 78 mgL^{-1}) and Mg^{2+} (25 – 52 mgL^{-1}) complied with the standards, Na^{+} (40 – 58 mgL^{-1}) exceeded recommended levels for Na^{+}-sensitive populations. Organic pollution, reflected in COD (14 – 97 mgL^{-1}) and BOD (1.4 – 9.9 mgL^{-1}) values, showed substantial spatial variation, with S5 exhibiting severe contamination. Hydrochemical analysis revealed $Ca-Mg-HCO_3/SO_4$ water types, accentuating mixed geological and anthropogenic influences. At the same time, the SAR ranging between 0.8 – 1.2; Na%: 30 – 40% classified most samples as excellent to good. Similarly, most samples were suitable for irrigation based on the US salinity rating. Additionally, the analysis discovered extensive pollution from heavy metals. Iron, chromium, mercury, lead, arsenic, and arsenic concentrations were continuously above WHO drinking water guidelines. Several samples had high cadmium, while the amounts of manganese and copper were typically appropriate.

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1.0 Introduction

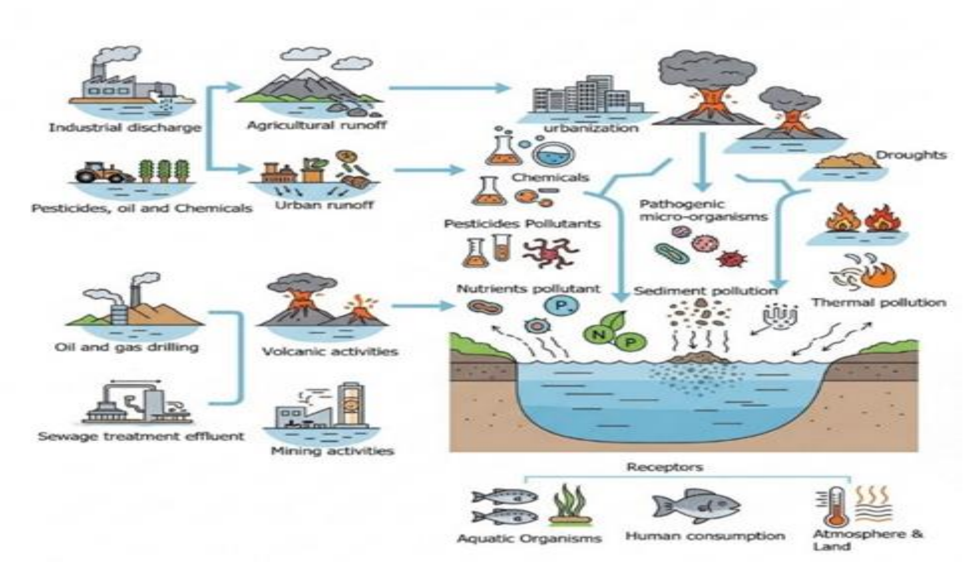
Water is a vital component of our environment, as all living creatures depend on it to exist. It is an indispensable requirement that plays a vital role in our daily life (Ahuja, 2017). From an ecological perspective, water is essential for preserving ecosystem equilibrium, which guarantees the existence of all living organisms (Zalewski, 2000). However, water supplies are becoming increasingly threatened by the world's rising population and faster development activities (du Plessis, 2019; Shan *et al.,* 2020). Activities that use a lot of water and increase pollution are associated with population expansion, going beyond the sustainable boundaries of these resources (Srivastav *et al.,* 2021; Zucca *et al*., 2021). The international community has put forth a lot of effort to guarantee that its residents have access to a sufficient and safe supply of water (Grönwall & Danert, 2020; Mishra *et al.,* 2021). Consumption of tainted water causes many illnesses and fatalities, especially in impoverished nations (Chowdhury *et al.,* 2016; Prüss-Ustün *et al*., 2014). Despite being a basic human right, many people in poor countries still do not have access to safe, clean water (Mullin, 2020). Groundwater is essential for agriculture and public water supply for both urban and rural people globally. A dip in the water table, land subsidence, saltwater intrusion, and a deterioration in water quality are only a few of the problems brought on by overuse of this resource (C. Singh *et al*., 2021). Land-based human activities, including urbanisation, agriculture, and industry, are the main drivers of declining water quality. Inadequate waste disposal and inappropriate chemical handling often lead to pollution (Painter *et al*., 2023). Rainfall, irrigation, or liquid waste can cause water-soluble wastes and other pollutants on the ground or in burial pits to seep into the soil and pollute groundwater (Painter *et al*., 2023). It is very difficult or impossible to restore groundwater quality after it has been contaminated. Therefore, preserving a consistent water supply requires safeguarding these resources against pollution (Boateng *et al*., 2016; Hairom *et al.,* 2021). Natural and man-made processes both have an impact on groundwater quality. Water quality is mostly determined by the kind and quantity of dissolved or suspended elements present as well as how they affect living things. The suitability of water for a certain purpose is ultimately determined by the concentration of these chemicals. Pollution from wastewater discharge is a major problem, and weather has a big impact on the seasonal runoff from these sources (Anh *et al.,* 2023; Gogoi *et al*., 2020). Pollutant discharge and concentration are greatly impacted by seasonal variations in precipitation, runoff, groundwater flow, interflow, and inflows and outflows (Wen *et al*., 2023; Zhu *et al*., 2022). A thorough grasp of the hydrological, biological, and chemical aspects of water quality metrics is required in order to handle this problem in an efficient manner over an extended period.

Analysis of several water quality measures is required under the EU's Water Framework Directive. These include heavy metals (Cd, Pb, Cu, Cr, and Ni), physicochemical factors (such as pH, conductivity, and total dissolved solids), ions associated with water hardness and treatment (Cl^{-}, Na^{+}, K^{+}, Ca^{2+}, and Mg^{2+}), other ions (F^{-}, NO^{2-}, NO^{3-}, Br^{-}, PO_4^{3-}, SO_4^{2-}, and NH_4^{+}), ions linked to water hardness and treatment (Mg^{2+}), and dissolved organic carbon (DOC) (Carvalho *et al*., 2019). Serious health effects may result from deficiencies or excessive use of these chemicals. Water contains naturally occurring nitrites (NO^{2-}) and nitrates (NO^{3-}). The body may convert nitrates into nitrites, which is why they are harmful. By oxidising haemoglobin, nitrites can lower the blood's capacity to provide oxygen to tissues, resulting in methemoglobinemia. When nitrate is consumed, this kind of condition is thought to be the main health danger (Brender, 2020). It is difficult to manage surface and groundwater effectively, and there is still a lot of unknown information on water quality. Beyond human activities, water quality is also influenced by the natural interactions between soil, rock, and water cycles (Hamid *et al.,* 2020). Both human and other organisms' health may suffer as a result of these natural changes. Both anthropogenic and geogenic sources can produce heavy metals (More & Dhakate, 2025). An increased risk of cancer is one of the negative health effects associated with excessive consumption of heavy metals such as Cd, Cr, Co, Hg, Ni, Pb, and Zn (More

& Dhakate, 2025). Mining, transportation, and industrial and agricultural operations are the main ways that heavy metals enter into groundwater (Sharafi & Salehi, 2025). Both soil and groundwater contamination are caused by these operations. Once present, these metals can move through the soil and water in a number of different ways. Any town must have access to clean water to prosper. Contaminated drinking water has been connected to several illness outbreaks and mortality in underdeveloped countries such as Tanzania. Groundwater is nevertheless vulnerable, even though it is frequently a preferred water source because of its inherent protection against pollution. The villages along the Mara River in Tanzania require a thorough assessment of the quality of the groundwater for drinking and farming. This is due to the mining and farming operations conducted near the river, which necessitate a proper investigation of the water quality. Thus, the present study reports on an examination of the heavy metal concentration and physicochemical characteristics of groundwater from boreholes taken from seven distinct villages: Nyiboko (S1), Buchanchali (S2), Baranga (S3), Nyansulumuti (S4), Wegero (S5), Kwisangura (S6), and Kongoto (S7). The results of this study will help stakeholders to better understand the quality of the drinking and irrigation water in these areas. And on the other hand, decision-makers may use this data to support the development of plans for managing and safeguarding the area's water resources and to establish evidence-based policies.

Figure 1

A Schematic Diagram Showing the Pathways, Receptors, and Other Forms of Pollution that Cause Water Contamination from Anthropogenic (Industrial, Agricultural, and Urban Activities) and Natural (Droughts and Floods) Sources



2.0 Materials and Methods

2.1 Description of the Research Area

The Mara River traverses three administrative districts: Tarime, Musoma Rural, and Serengeti. Tarime district, situated in the Mara region of northwest Tanzania, is a hub for both small- and large-scale gold mining operations, located approximately 20 kilometres south of the Kenyan border and 100 kilometres east of Lake Victoria. The Mara region itself is broadly located at a latitude of 1° 50′ 00′′ S and a longitude of 34° 25′ 00′′ E. The Mara Region has 2,356,255 residents, according to the 2022 Population and Housing Census. The region is characterised by pastoralism, small-scale agriculture, fishing and mining activities as the source of income. The region experiences an average annual temperature of about 28.50°C. Where the lowest temperature is around 27.68°C, while the highest is approximately 29.32°C.The current study area includes seven villages branded S1 to S7 located along the Mara River. The study sites are specifically positioned at the following coordinates:S1 is located at approximately 1° 35′ 38′′ S, 34° 03′ 00′′ E; S2 is at 1° 35′ 29′′ S, 34° 03′ 02′′ E; S3 is at 1° 42′ 16′′ S, 34° 18′ 33′′ E; S4 is at 1° 34′ 59′′ S, 34° 05′ 52′′ E; S5 is at 1° 38′ 22′′ S, 34° 20′ 05′′ E; S6 is at 1° 44′ 04′′ S, 34° 18′ 41′′ E; and S7 is at 1° 38′ 27′′ S, 34° 21′ 57′′ E. The specific sampling sites are visually represented on the map shown in Figure 2.

2.2 Sampling Techniques

Groundwater samples were taken from seven wells (samples S1–S7) in seven different villages situated along the Mara River that are used by the locals for irrigation and domestic purposes. The wells ranged in depth from 30 to 50 m below the ground. Figure 2 displays the locations of the sampling spots. Samples were collected using high-density polyethylene bottles. The bottles were filled to the top to ensure that there were no air bubbles caught in the water samples. To prevent evaporation and sample agitation during transit to the laboratory, bottles were sealed with plastic lids. Following that, the samples were promptly moved to the laboratory. Furthermore, in situ measurements of temperature, pH, dissolved oxygen, and electrical conductivity (EC) were made at the same settings as those of water samples. The on-site measurements were repeated three times to ensure consistent readings, and the average readings were recorded.

2.3 Laboratory Measurements

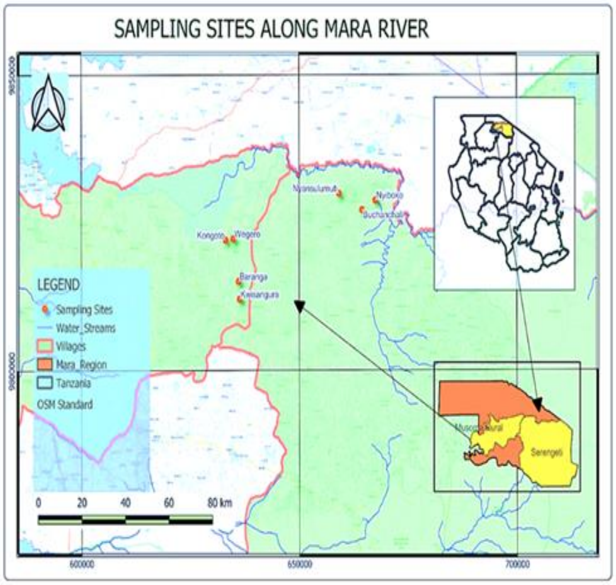
In the laboratory the glassware was cleaned thoroughly by treating it with 0.1 M HNO_3 and then rinsing it with distilled water. Then, the analyte stock solutions and standard solutions were prepared using deionised water. The water samples were measured after the analytical apparatus had been meticulously calibrated using standard solutions with known concentrations. The chemical composition measured included the measurement of the NO_3^-, HCO_3^-, free CO_2, total hardness, total alkalinity, PO_4^{3-}, NH_3^- and SO_4^{2-}, as well as K^+, Ca^{2+}, Mg^{2+}, and Na^+ ions. The chemical reagents used in this study were purchased from Sino Pharm Chemical Reagent Co., Ltd.

2.4 Analysis of Chemical Water Quality Parameters

The standard method investigations for water and wastewater were used to analyse the major ions in the samples (Apha A. WPCF, 1995). The pH concentration and electrical conductivity were measured with a portable turbidity meter ISO compliant at Mediray produced by Hanna Instruments (Model HI93703C) and the Water Quality Tester pH meter (Dr. meter model PH100 0.01, ATC, 0-14pH) produced by the Galleon. The electrical conductivity (EC), which was established based on the relative concentrations of ions present in the solution, was multiplied by a factor in order to calculate total dissolved solids (TDS) within the water samples (Golnabi, 2011; Marandi *et al.,* 2013). The concentration of SO_4^{2-} ions was measured using the Hanna HI96751 Sulfate Portable Photometer. Mohr's titration method was used to test the concentration of Cl^- ions, and a titration method was also used to evaluate alkalinity. The complexometric titration was used to measure total hardness in the current study. Additionally, within 48 hours following sample collection, the amounts of Ca^{2+}, Mg^{2+}, Na^+, and K^+ ions were measured using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP OES).

Figure 2

A Map Showing Water Sampling Sites along Mara River in Mara Region of Tanzania



2.5 Drinking Water Quality Index (DWQI)

The water quality assessment was carried out using the popular Water Quality Index (WQI), which is commonly used to evaluate the quality of drinking water (Uddin *et al.,* 2021a). The WQI is also applicable in the evaluation of groundwater quality, after being first presented by (Brown RM *et al.*, 1970) and then being modified by (Backman *et al.*, 1998). The WQI can assist in demonstrating how each indicator, including qualitative characteristics, interacts to influence the overall drinking water quality (Chidiac *et al.*, 2023; Fortes *et al.,* 2023). The value of each qualitative characteristic is determined by applying suggested standards and comparing it to other parameters (Uddin *et al.*, 2021b). To calculate the WQI, we use the specific equation to determine the relative significance of the physiochemical factors as presented in equation 1.

$$W_i = \sum \frac{w_e}{\sum_{i=1}^{n} w_e} \qquad 1$$

The relative weight of each parameter, denoted as Wi, is calculated by taking into account the weight (w_e) and the number of parameters (n). Table 1 displays the weight (w_e) and relative weight (Wi) for each chemical parameter. As per the guidelines set by the WHO in 2011, the quality rating (qi) is determined by comparing the concentration (Ci) of each chemical parameter in the samples (measured in mg/L) with the standard limit (Si) for that specific chemical parameter (also measured in mg/L) and then the result is multiplied by 100 as is displayed in equation 2.

$$q_i = \left(\frac{C_i}{S_i}\right) \times 100 \qquad 2$$

Each parameter's sub-index (SIi) is calculated to complete the WQI calculation. Then after, each sample's WQI is generated by averaging the SIi values as presented in **equation 3** (Choudhary *et al.*, 2025).

$$SI_i = W_i \times q_i \qquad 3$$

$$WQI = \sum_{i=1}^{n} SI_i \qquad 4$$

SIi, where 'n' is the number of parameters, is the symbol for the subindex, which represents the rating based on the concentration of a certain parameter. Table 1 presents the weight and relative weight per each chemical parameter calculated based on the standard values reported by WHO (WHO, 2017).

Table 1

The Weight (w_e) and Relative Weight (W_i) of each Chemical Parameter Calculated Based on the Standard Values Reported by the World Health Organisation

Parameter	WHO standards (mg/L)	Weight (w_e)	Relative weights (W_i)
K^+	12	2	0.056
Na^+	200	4	0.111
Mg^{2+}	50	3	0.083
Ca^{2+}	75	3	0.083
HCO_3^-	120	1	0.028
Cl^-	250	5	0.139
SO_4^{2-}	250	5	0.139
pH	8.5	3	0.083
T. D. S	500	5	0.139
NO_3^-	11	5	0.139

2.6 Water Quality Evaluation for Agricultural Irrigation

The water is undergoing a quality assessment to ascertain its suitability for usage in crop production and agricultural irrigation. The explicit investigation determines the level of pollutants in the water supply. The pH, electrical conductivity, turbidity, and mineral content are some of the variables that can be used to assess the quality of the water. This kind of assessment is especially important to ensure that irrigation water does not pose a risk to crops, the environment, or human health (Anyango *et al.,* 2024). Regular monitoring and analysis can identify any potential issues and take the necessary steps to maintain a high standard of water quality for agricultural applications.

To determine if groundwater is suitable for irrigation, researchers have used a number of indicators, such as the Sodium Adsorption Ratio (SAR), the proportion of sodium (Na%), the Magnesium Hazard, and the Permeability Index (Banyikwa, 2023; Selvakumar *et al.,* 2017). The following markers were used to determine whether groundwater could be used for irrigation, as displayed in equations 7-12. Geochemical software Diagrammes (v6.77) was used to study water quality data, making it easier to create a Piper trilinear diagram and Wilcox plots.

Sodium Adsorption Ratio (SAR):

$$\mathrm{SAR} = \frac{\mathrm{Na^+}}{\sqrt{\frac{\mathrm{Ca^{2+}+Mg^{2+}}}{2}}} \qquad 5$$

Sodium percentage (Na%):

$$\mathrm{Na\%} = \frac{(\mathrm{Na^+ + K^+})}{\mathrm{K^+ + Ca^{2+} + Mg^{2+} + Na^+}} \times 100 \qquad 6$$

Magnesium Hazard (MH):

$$\text{Mg adsorption ratio (MAR)} = \frac{\mathrm{Mg^{2+}}}{\mathrm{Ca^{2+}+Mg^{2+}}} \times 100 \qquad 7$$

Permeability index:

$$\mathrm{PI} = \frac{\left(\mathrm{Na^+} + \sqrt{\mathrm{CO_3^{2-}}}\right)}{\mathrm{Ca^{2+}+Mg^{2+}+Na^+}} \times 100 \qquad 8$$

Kelly Ratio (KR):

$$\mathrm{KR} = \frac{\mathrm{Na^+}}{(\mathrm{Ca^{2+}+Mg^{2+}})} \qquad 9$$

Residual Sodium Carbonate (RSC):

$$\mathrm{RSC} = (\mathrm{Na^+ - Cl^-}) - (\mathrm{Ca^{2-} + Mg^{2-}})/2 \qquad 10$$

The unit of concentration of ions maybe in milliequivalents per liter (meq/L) or milligram per liter (mg/L).

3.0 Results and Discussion

3.1 Physical and Chemical Water Quality Parameters

For every water sample, each parameter was measured three times, and the average outcome was noted. Table 2 displays the ranges and the arithmetic mean ± standard error for the seven groundwater samples evaluated in this study. The study found that the pH levels ranged from 5.71 ± 0.378 to 7.03 ± 0.536. It can be seen from the table that six groundwater samples (from S2 to S7) are slightly acidic, and the remaining sample, S1, displays neutral properties. AAccording to the guidelines established by TBS and WHO in 2017, the pH level of drinking water should ideally range between 6.5 and 8.5 (Banyikwa, 2023). The results of the current study, when compared to the recommendations set forth by the WHO in 2017, stress that almost all of the water samples analysed conform to the established standards, with the sole exceptions being S4 and S5, which failed to meet the necessary minimum pH level of 6.5 (WHO, 2017). The trend of acidic pH values observed in the groundwater of villages along the Mara River raises critical questions on whether the trend could be due to the interaction between natural and anthropogenic variables. Nevertheless, it can generally be concluded that prolonged exposure to such low pH levels may adversely affect the health of individuals exposed to it over time, despite the absence of any immediate health effects. In addition, the current study successfully measured the electrical conductivity of the groundwatersamples from all sampling sites.

The EC parameter measured is shown in the Table 2; the groundwater EC values in the studied area range from 696.4 ± 17.03 to 938.4 ± 12.630 µS $\mathrm{cm^{-1}}$. This variations in EC are perhaps attributed to the anthropogenic activities and geochemical processes that take place in the area, as supported by previous research (Narsimha & Sudarshan, 2017; Subba Rao *et al.,* 2017). Although the WHO has not set a precise standard for EC, but studies show that 30 to 1500 µS $\mathrm{cm^{-1}}$ is the appropriate range for drinking water (Alemu *et al.*, 2017; Udhayaku*mar et al.,* 2016). Water is generally considered to be of high drinking quality if its EC value is less than 300 $\mathrm{\mu Scm^{-1}}$ (Udhayakumar *et al.,* 2016). Using this range as a guide, our research provided fascinating information on the water in the villages that the Mara River flows through. While the EC measurements alone are insufficient to definitively assess water quality, they serve as a valuable preliminary indicator. Based on the EC values presented in the table, the sampled water from the site is unsuitable for drinking purposes. However, the same data suggests that the water from those sampling sites remains acceptable for irrigation use. The dissolved oxygen (DO) of the samples was measured, and the data obtained are presented in Table 2. Samples S1, S2, and S6 had DO concentrations of 2.15 ± 0.231 mg L^{-1}, 2.13 ± 0.176 mg L^{-1}, and 2.09 ± 0.241 mg L^{-1}, respectively. It is worthy of noting that there is a critical disparity in safe DO levels between humans and aquatic life, for instance, humans can drink water with a DO level of less than 2 mg L^{-1} without being harmed, while the same concentration constitutes a stressful environment, and prolonged exposure can be lethal to fish (Dickin & Gabrielsson, 2023; Ejiohuo *et al.,* 2025). Thus, the values from sampling site S1, S2, and S6 fall under the lowest threshold required for fish survival, below which survival of the fish isn't guaranteed. Samples S3, S4, S5, and S7, on the other hand, disclosed troublingly low DO levels of 1.97 ± 0.667 mg L^{-1}, 1.29 ± 0.290 mg L^{-1}, 1.25 ± 0.241 mg L^{-1}, and 1.53 ± 0.241 mg L^{-1} this level is typically lethal with potential mortality. Therefore, waters from S3, S4, S5 and S7 are generally unsuitable for sustaining aquatic life. On a serious note, the DO levels from the data presented in the table exhibit an inverse relationship with temperature; that is to say, higher temperatures correspond to lower DO concentrations, while cooler temperatures support more favourable oxygen levels (see Figure 3). This observation is consistent with other researchers' findings that warmer water saturates more quickly, demonstrating a definite inverse relationship between water temperature and DO levels; that is, as temperature rises, water's ability to hold onto dissolved oxygen decreases (Cassidy, 2018).

The chemical oxygen demand (COD) levels in the study ranged from 14.33 ± 1.667 to 97.33 ± 4.055 mg L^{-1}, with sample S5 exhibiting the highest concentration (97.33 ± 4.055 mg L^{-1}) and S1 the lowest (14.33 ± 1.667 mg L^{-1}). This substantial variation (approximately 14 to 100 mg L^{-1}) suggests considerable differences in organic contamination across sampling sites. The elevated COD in S5 indicates significant organic pollution, whereas the minimal COD in S1 reflects relatively uncontaminated conditions. A decrease in oxygen levels and increased stress on aquatic environments can result from microbial decomposition brought on by elevated levels of COD, which can eventually reach hazardous thresholds (Chowdhary *et al.,* 2018). Anthropogenic activities such as mining operations, industrial discharges of untreated or inadequately treated wastewater, agricultural runoff carrying fertilisers and pesticides, and sewage or wastewater contamination that introduces organic materials into groundwater are the main causes of this type of abrupt change in the COD level of the villages' underground water along the Mara River. Although much more research is required to reach a proper conclusion, the mining and agricultural operations that are occurring nearby this river may be the cause.

The current study also measured the Biochemical Oxygen Demand (BOD) values at the selected sampling sites. The outcome of the data obtained from sampling sites ranged between 1.40 ± 0.067 mg L^{-1} to 9.93 ± 0.133 mg L^{-1}. This range demonstrates the substantial variation in the quantity of organic matter in the water samples collected from different places. Out of all the samples examined, sample S5 has the highest BOD levels (9.93 ± 0.133 mg L^{-1}which indicates a larger amount organic pollutant in that sampling site. Such elevated BOD levels may have an impact on the aquatic ecology, possibly causing oxygen depletion and harming aquatic life (Mamun *et al.,* 2022). Sample S1, on the other hand, has the lowest BOD levels (1.40 ± 0.067 mg L^{-1}). This lower value might point to a comparatively cleaner ground water source with less organic pollution, indicating that the local ecosystem is better suited to sustaining higher DO levels (Abanyie *et al.,* 2023; Lapworth *et al.,* 2022; Mukherjee *et al.,* 2024). The content of free CO_2 varies between 67.33 ± 2.906 and 90.00 ± 3.464 mg L^{-1}, according to the results shown in Table 2. In particular, the concentration of free CO_2 is lower in the S1 sample and higher in the S5 sample. High levels of carbon dioxide are typically associated with reduced levels of DO (Rajendiran *et al.,* 2023). It is crucial to understand that the pH level falls in proportion to the increase in free CO_2 concentration presented in equation 11. The solubility of carbon dioxide in water, which leads to the formation of carbonic acid, is responsible for this pH drop (Boyd, 2015). This kind of changes lowers the water quality since it increases its corrosiveness.

This enhanced corrosiveness raises the possibility of hazardous materials, like lead, entering the water that is transported through these pipes as metals from plumbing systems and fixtures may leach into the water supply (Brossia, 2018).

$$H_2O + CO_2 \rightarrow H_2CO_3 = H^+ + HCO_3^- \qquad 11$$

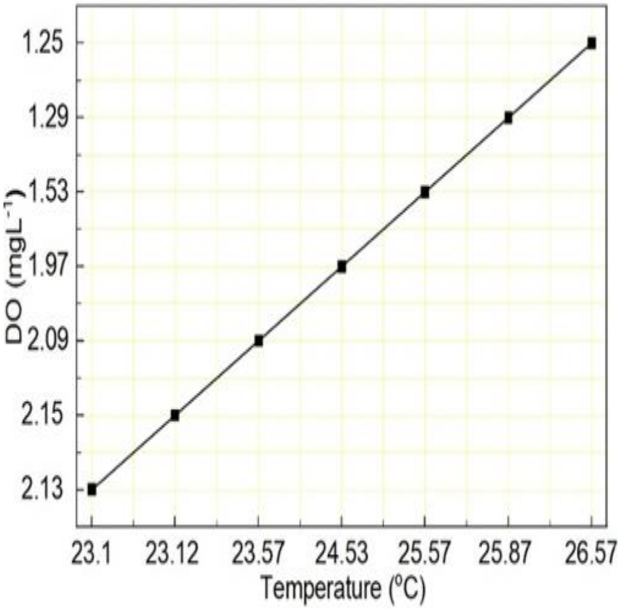
The total alkalinity across all samples results showed considerable variation, ranging from 19.99 ± 4.055 mg L^{-1} to 190.00 ± 4.163 mg L^{-1}, indicating substantial differences in alkalinity levels among the sampled sites. Sample from S1 in particular was the most alkaline, with a measured value that was close to 190 mg L^{-1}. The strong acid-neutralising ability of sample from S1 is shown by its elevated alkalinity, which may be advantageous for preserving steady pH values in aquatic situations (Shangguan *et al.,* 2021). However, sample from S5 was found to have the lowest alkalinity value, which could indicate a diminished capacity to buffer against pH variations (Somridhivej & Boyd, 2016). The chlorine concentrations showed relatively consistent values across measurements, indicating minimal temporal variation. Concentrations ranged from 0.31 ± 0.003 mg L^{-1} (S3) to 0.51 ± 0.005 mg L^{-1} (S1). The slightly wider error margin for S1's maximum value remained within acceptable limits of analytical variability. All measured chlorine concentrations in the samples complied with the WHO recommended range (0.2 – 0.5 mg L^{-1}) for drinking water.

Water hardness measurements, reflecting primarily dissolved calcium and magnesium ions, ranged from 78.67 ± 1.28 to 98.00 ± 1.15 mg L^{-1} (table 2). This variation suggests spatial or temporal differences in mineral concentrations, potentially influenced by water source characteristics, local geology, and environmental conditions. The hardness values offer a numerical evaluation of water hardness, which is a crucial metric for comprehending the quality of water and its appropriateness for a range of applications, such as drinking, irrigation, and industrial settings. The water's hardness in the current study is moderately hard since it typically falls between 60 and 120 mg L^{-1}, notwithstanding its variability. As per the current investigation, the samples had calcium ion (Ca^{2+}) concentrations up to 78.02 ± 2.67 mg L^{-1}, which is still regarded as safe. The TBS guideline states that 70 – 100 mg L^{-1} is the optimal range for Ca^{2+} levels in drinking water (Banyikwa, 2023b). All of the groundwater samples in this study had Ca^{2+} concentrations between 70.35 ± 1.76 and 78.02 ± 2.67 mg L^{-1}, which is within the permissible limit of 70 mg L^{-1}. The water sample had a magnesium concentration ranging from 25.37 ± 1.914 to 51.89 ± 6.693 mg L^{-1}. This range is within the acceptable and permitted range of Mg^{2+} in drinking water which is between 30 and 100 mg L^{-1}. Although only a tiny percentage of our samples had readings below 30 mg L^{-1}, this concentration is considered acceptable because it does not significantly endanger consumer health. As such, it can be considered safe.

The measured calcium concentrations in this study ranged from 70.35 ± 1.76 to 78.02 ± 2.67 mg L^{-1}, falling within the widely accepted permissible range (30 – 100 mg L^{-1}) established by most water quality standards organisationns (Ingin *et al.,* 2024). Magnesium is classified as a moderately hazardous metal due to its typically lower concentration in water compared to calcium. In drinking water, elevated magnesium levels particularly when combined with sulfate can induce laxative effects (Bothe *et al.,* 2017; Dupont & Hébert, 2020). Research indicates that individuals in hard-water areas exhibit significantly higher magnesium and potassium levels in cardiac muscle tissue compared to those in soft water regions, where the Mg^{2+} to K^+ ratio tends to be lower. Magnesium plays a critical role in calcium metabolism, and its deficiency may impair energy production and protein synthesis. The permissible range for Mg^{2+} in drinking water is established at 30 – 100 mg L^{-1} (Peng *et al.,* 2023). In this study, magnesium concentrations (25.37 ± 1.914 to 51.89 ± 6.693 mg L^{-1}) fell within this acceptable range. The measured sodium concentrations across sampling sites ranged from 39.97 ± 0.902 to 57.83 ± 1.167 mg L^{-1}. While these values comply with the WHO aesthetic guideline of ≤ 200 mg L^{-1} for drinking water, they exceed the recommended threshold of <20 mg L^{-1} for populations requiring sodium-restricted diets like hypertension patients. The potassium concentrations measured in this study ranged from 5.07 ± 0.220 to 10.33 ± 0.882 mg L^{-1}, well within the safe range for human consumption and posing no known health risks (Skowron *et al.,* 2018). Sulfate levels in samples S1 to S7 were generally within acceptable limits, though S4 and S5 exhibited slightly elevated concentrations. The TBS sets a maximum permissible sulfate level of 250 mg L^{-1}, while the WHO recommends an ideal limit of 250 mg L^{-1} but allows a higher tolerable threshold of up to 500 mg L^{-1} (Arellano-Sánchez *et al.*, 2025; Yiyen *et al.,* 2023). Parameters like that of ammonia, Nitrate and phosphate levels were within accepted levels as seen in table 2, the WHO recommended values are 0.2 to 1.5 mg L^{-1}, 10 to 50 mg L^{-1}, and ≤ 0.1 to 0.5 mg L^{-1} respectively (Isiuku & Enyoh, 2020; Mahmud *et al.,* 2020; Shen *et al.,* 2020). The TDS levels recorded from the samples obtained from sampling site (295 to 359 mg L^{-1} as is seen in table 2) are within the acceptable level of the TBS and WHO which is in between ≤ 300 mg L^{-1} for ideal to ≤ 1000 mg L^{-1} tolerable level (Nyagongo *et al.,* 2024).

Figure 3

The Relationship between DO and Temperatures



3.2 Ground Facies and Groundwater Types

The Piper trilinear diagram in Fig. 4 a provides a clear depiction of the hydrochemical composition of the studied water samples (Banyikwa, 2023b). In the cation triangle (labelled A), most data points cluster near the calcium (Ca^{2+}) and magnesium (Mg^{2+}) apex, confirming their dominance as primary cations (Saikrishna *et al.*, 2023). However, the partial distribution of points towards sodium (Na^{+}) and potassium (K^{+}) suggests their secondary involvement in the ionic composition (Karmegam *et al.,* 2011). Notably, magnesium's influence is relatively minor compared to calcium, as fewer points converge near its apex (Karmegam *et al.*, 2011). The anion triangle (labelled B) reveals greater variability, with data points distributed across sulfate (SO_4^{2-}), chloride (Cl^{-}), and nitrate (NO_3^{-}) regions. This pattern highlights sulphate's prominence in select samples, while chloride and nitrate trends may indicate localised contamination or mineral dissolution (Saikrishna *et al.,* 2023). Although carbonate (CO_3^{2-}) and bicarbonate (HCO_3^{-}) are present, their limited representation suggests alkalinity plays a secondary role in most cases (Zeebe, 2011).

The central diamond field (labelled C), combining cation and anion data, classifies the water as mixed hydrochemical facies. This classification implies that no one ion pair is dominating; rather, water quality is the result of complex interactions between multiple ions (Shelton *et al.*, 2018). Alkaline earth metals (Ca^{2+}, Mg^{2+}) outnumber alkali metals (Na^{+}, K^{+}), as seen by the clustering of dots in areas with high Ca^{2+}, Mg^{2+} ions this reflects the prevalence of hardness ions (Sajil Kumar *et al.,* 2014). Stronger acids (SO_4^{2-}, Cl^{-}, NO_3^{-}) have a greater impact than weaker acids (CO_3^{2-}, HCO_3^{-}), perhaps due to sulfate and chloride minerals or anthropogenic causes such fertilisers and industrial waste (Asif *et al.,* 2025). Furthermore, the subgroup with high amounts of weak acids indicates places where carbonate dissolution or natural buffering mechanisms are occurring.

Table 2

Mean ± Values of Different Physicochemical Parameters of Water Samples of the Given Areas

	Sampling sites							WHO/ TBS
Water Parameters	**S1 (Nyiboko)**	**S2 (Buchanchali)**	**S3 (Baranga)**	**S4 (Nyansulumuti)**	**S5 (Wegero)**	**S6 (Kwisangura)**	**S7 (Kongoto)**	**Ranges**
pH	7.03 ± 0.536	6.88 ± 0.174	6.53 ± 0.162	5.74 ± 0.303	5.71 ± 0.378	6.56 ± 0.378	6.50 ± 0.378	6.5 – 8.5
EC (µS cm^{-1})	696.4 ± 17.03	700.8 ± 8.667	728.2 ± 19.667	906 ± 9.233	938.4 ± 12.63	750.4 ± 12.630	760.4 ± 12.630	–
Temp.(˚C)	23.12 ± 0.536	23.1 ± 0.493	24.53 ± 0.481	25.87 ± 0.318	26.57 ± 0.318	23.57 ± 0.318	25.57 ± 0.318	–
DO (mg L^{-1})	2.15 ± 0.231	2.13 ± 0.176	1.97 ± 0.667	1.29 ± 0.290	1.25 ± 0.241	2.09 ± 0.241	1.53 ± 0.241	≥ 5
COD (mg L^{-1})	14.33 ± 1.667	15.33 ± 1.764	43.33 ± 2.905	95.33 ± 3.712	97.33 ± 4.055	67.33 ± 4.055	67.33 ± 4.055	–
BOD (mg L^{-1})	1.40 ± 0.067	1.47 ± 0.176	3.37 ± 0.145	8.67 ± 0.176	9.93 ± 0.133	4.93 ± 0.133	5.89 ± 0.133	1
Free CO_2 (mg L^{-1})	74.00 ± 4.163	76.00 ± 4.618	67.33 ± 2.906	84.67 ± 5.457	90.00 ± 3.464	70.00 ± 3.452	70.00 ± 3.365	50 – 200
T. Alkalinity (mg L^{-1})	190.00 ± 4.163	138.00 ± 8.326	101.33 ± 5.457	25.33 ± 5.457	19.99 ± 4.055	95.33 ± 4.055	54.33 ± 4.055	≥ 30
Chlorides (mg L^{-1})	0.51 ± 0.005	0.47 ± 0.006	0.31 ± 0.003	0.39 ± 0.291	0.42 ± 0.007	0.32 ± 0.002	0.41 ± 0.003	0.2 – 0.5
T. Hardness (mg L^{-1})	98.00 ± 1.15	93.33 ± 10.73	82.33 ± 2.40	78.67 ± 1.28	97.33 ± 1.71	86.33 ± 2.01	79.33 ± 3.712	–
Calcium (mg L^{-1})	71.64 ± 2.77	70.43 ± 1.97	74.00 ± 2.906	78.02 ± 2.67	70.35 ± 1.76	77.35 ± 1.06	75.35 ± 1.32	70 – 100
Magnesium (mg L^{-1})	51.89 ± 6.693	47.04 ± 0.963	29.27 ± 0.352	45.55 ± 3.417	25.37 ± 1.914	25.72 ± 1.414	27.37 ± 1.711	30 – 100
Sodium (mg L^{-1})	52.50 ± 0.764	49.00 ± 2.082	57.83 ± 1.167	39.97 ± 0.902	42.73 ± 0.536	41.03 ± 0.636	45.11 ± 0.332	≤ 200
Potassium (mg L^{-1})	8.67 ± 0.240	9.07 ± 1.485	10.33 ± 0.882	5.07 ± 0.220	6.13 ± 0.126	7.14 ± 0.176	8.12 ± 0.176	–
Sulfate (mg L^{-1})	209.5 ± 11.016	220.4 ± 11.311	235.93± 10.897	254.77 ± 10.267	258.23± 10.105	210.33± 19.102	245 ± 10.202	250 –500
Ammonia (mg L^{-1})	0.118 ± 0.011	0.124 ± 0.015	0.109 ± 0.012	0.139 ± 0.025	0.143 ± 0.012	0.143 ± 0.012	0.143 ± 0.012	0.2 – 1.5
Nitrate (mg L^{-1})	1.217 ± 0.146	1.328 ± 0.170	1.306 ± 0.134	1.351 ± 0.159	1.819 ± 0.097	1.819 ± 0.097	1.819 ± 0.097	10 –50
o-phosphate (mg L^{-1})	0.029 ± 0.009	0.035 ± 0.012	0.076 ± 0.006	0.022 ± 0.006	0.021 ± 0.007	0.022 ± 0.006	0.021 ± 0.007	0.1 – 0.5
TDS (mg L^{-1})	358.99 ± 20.213	340.0 ± 15.403	295.46 ± 11.178	336.81 ± 13.259	359.49 ± 20.04	359.49 ± 20.038	359.49 ± 20.038	300–1000

Fig. 4b provides an analysis of the relationship between sodium percentage (Na%) and electrical conductivity (µS/cm) across seven water samples (S1-S7). The y-axis represents Na% relative to total major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}), scaled from 0 to 100%, while the x-axis shows electrical conductivity (0-3500 µS/cm) as a measure of total dissolved salts (G. Singh *et al.,* 2024). All samples demonstrate low sodium content (30-40% Na) and moderate salinity (400-600 µS/cm). Samples S2, S3, S4, and S7, as seen in Fig. 4b, are within the 'Excellent to Good' range, indicating ideal irrigation suitability with minimal salinity/sodium risks, as supported by Gharaibeh *et al.* (2021). Sample S5 is classified as 'Good to Permissible', requiring some management for sensitive crops. Samples S1 and S6 border the 'Permissible to Doubtful' threshold, necessitating careful monitoring due to elevated (but not critical) salinity or sodium levels (G. Singh *et al.*, 2024). Importantly, no samples were deemed 'doubtful' or 'unsuitable', confirming overall water quality is appropriate for irrigation with minor precautions for selected sampling sites. According to the US Salinity Diagram presented in Fig. 4c, the seven studied water samples are primarily located in the C2 zone, indicating a medium salinity threat. This rating shows that, despite their moderate salinity, these waters are still suitable for irrigation, but with the need for mild leaching procedures (Diédhiou *et al.*, 2023). Furthermore, these samples are located in the S1 area (remember the S1 here isn't the sample site but the region in the US salinity diagram), suggesting a low sodium hazard, allowing for their use in irrigation across a wide variety of soil types with little risk of salt-related problems (Diédhiou *et al.,* 2023). Finally, the overall assessment of the water samples yields a C2-S1 grade, indicating their acceptability for irrigation with moderate leaching needs and a low risk of sodium-related soil issues.

3.3 Heavy Metal Analysis

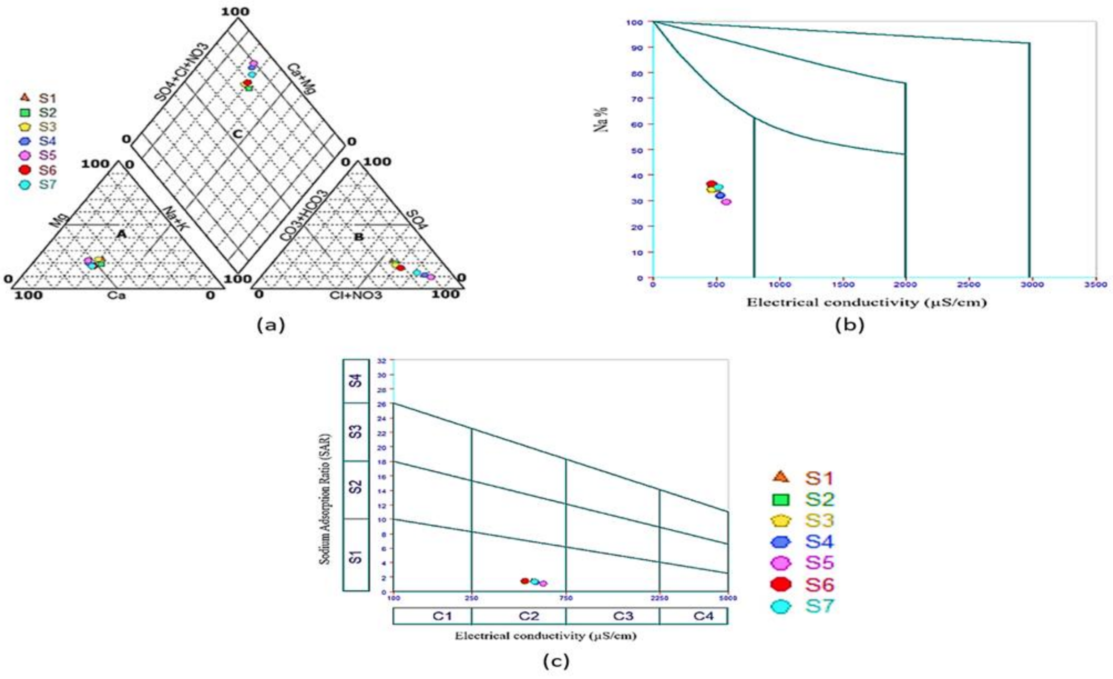
Table 3 summarises the levels of heavy metals at seven sample locations (S1–S7) and compares them to drinking water standards set by the WHO. According to the recorded data in the table, there is widespread heavy metal pollution, this is because all samples from every location had quantities of lead, arsenic, chromium, mercury, and iron that are higher than the WHO's recommended limits. In particular, lead contents are much higher than the 0.01 mg L^{-1} limit, ranging from 0.50 mg L^{-1} to 0.95 mg L^{-1}. Similarly, the Arsenic and mercury levels exceed the WHO recommended level, with levels as high as 0.073 mg L^{-1} and 0.014 mg L^{-1}, respectively, versus a norm of 0.01 mg L^{-1} and 0.006 mg L^{-1}. The levels of iron and chromium are significantly higher, with iron being especially high at 0.6 to 1.1 mg L^{-1} as opposed to the recommended 0.3 mg L^{-1}. While all sites meet WHO copper criteria, only S1, S2, and S7 have manganese levels within the permissible range; S3, S4, S5, and S6 have levels over the recommended range. All sites had cadmium levels that either meet or slightly above the WHO recommendation of 5 mg L^{-1}, with site S5 having the highest value at 5.9 mg L^{-1}. The villages along the Mara River face a significant public health risk due to the alarming amounts of many heavy metals in their groundwater, which makes it unsuitable for human consumption.

Figure 4

(a) Groundwater Hydrogeochemical Facies Plot of the Sampling Sites of S1, S2, S3, S4, S5, S6 and S7

(b) The Graph of Sodium Percentage (Na%) and Electrical Conductivity (µs/Cm)

(c) The US Salinity Diagram of the Samples from Selected Villages along Mara River



(a)

(b)

(c)

Table 3
Heavy Metal Analysis of Underground Water in Villages along Mara River

Parameter	**S1 (mg L^{-1})**	**S2 (mg L^{-1})**	**S3 (mg L^{-1})**	**S4 (mg L^{-1})**	**S5 (mg L^{-1})**	**S6 (mg L^{-1})**	**S7 (mg L^{-1})**	**WHO (mg L^{-1})**
Pb	0.50	0.7	0.65	0.90	0.95	0.91	0.8	0.01
AS	0.05	0.06	0.065	0.07	0.07	0.073	0.071	0.01
Cr	0.06	0.065	0.072	0.075	0.078	0.071	0.076	0.05
Cd	5	5	5.2	5.5	5.9	5.4	5	5
Hg	0.009	0.009	0.01	0.013	0.014	0.012	0.009	0.006
Cu	1.9	2	1.9	2	2	2	2	2
Fe	1.0	1.0	1.1	0.9	0.8	0.9	0.6	0.3
Mn	0.08	0.09	0.1	0.15	0.13	0.15	0.09	0.1

4.0 Recommendations

Implementing a thorough and long-term plan is necessary to solve the water quality challenge. The first step is to find and address the specific causes of pollution, which come from natural and man-made sources. A successful approach includes a public health campaign to inform locals about the risks of drinking the contaminated water, strict enforcement of environmental standards to stop more pollution, and a thorough long-term monitoring programme to track changes in water quality. The water's current condition presents a serious and immediate risk to human health, necessitating prompt action even though it may still be suitable for irrigation.

5.0 Conclusion

The evaluation of physicochemical and heavy metal contamination in seven villages along the Mara River in the Mara region has been successfully carried out to determine its suitability for drinking and irrigation. The results indicate that while most sites fell within the WHO's pH guidelines, some exhibited acidic properties. The EC and TDS were generally within acceptable ranges for irrigation but indicated unsuitability for drinking purposes. Also, the DO levels were critically low across all samples, suggesting the water is unsuitable for sustaining aquatic life, with an inverse relationship observed between DO and temperature. Moreover, the current study found widespread heavy metal contamination. Concentrations of lead, arsenic, chromium, mercury, and iron consistently exceeded WHO drinking water standards. Cadmium levels were higher in certain samples, although copper and manganese levels were typically acceptable. The water was categorised as a mixed hydrochemical facies via Piper diagram analysis, which accounted for both natural and man-made influences. Despite its potential for irrigation, the groundwater's heavy metal contamination and poor physicochemical qualities pose a significant public health concern.

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8.0 Declaration of Conflicting Interests

The author declares no conflict of interest.

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