Discover Water

Research

Domestic and irrigation water quality on the southern slopes of Mount Kilimanjaro

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Abstract

This study assessed the water quality for drinking and irrigation purposes on the southern slopes of Mt. Kilimanjaro during the dry season under low flow conditions. Fifty-one samples covering eight different water sources (i.e., stream water from natural and anthropogenic impacted streams, domestic water, spring water, rainfall, groundwater, lake water and water from irrigation canals) were collected in a snapshot sampling campaign over 10 days in February 2023. First, physical, chemical and biological parameters were analysed and compared with Tanzanian and international drinking and irrigation water quality requirements. The samples were then ranked according to their suitability for drinking and/or irrigation using water quality indices (WQI). All drinking water quality parameters except for *E. coli* and turbidity were within the permissible limits. A generalised problem of faecal contamination was found in the study area, including in domestic water, highlighting the need to identify sources of contamination and remediate them before distribution. The drinking water quality index (DWQI) classified 89% of the samples as unsuitable and 11% as excellent for drinking. Irrigation water quality parameters were within the guidelines of restriction of use except for pH in 5 samples. In contrast to the DWQI, the vast majority of the water samples (88%) can be used for irrigation without restrictions according to the irrigation water quality index (IWQI). The suitability of water for irrigation was also assessed using three indices, i.e., Kelley's Index, Soluble Sodium Percentage and Magnesium Ratio, which indicated potential problems with excess of sodium (about 30% of the samples) and magnesium (about 20%). Further studies combining suitability indices, soil characteristics and crop types are recommended to assess water quality for irrigation use.

Article Highlights

- The southern slopes of Mt. Kilimanjaro act as a water tower, providing drinking water and irrigation resources for surrounding communities.
- The drinking water quality was found to be compromised by a widespread presence of *E. coli* bacteria, which indicates faecal contamination.
- The irrigation water quality was generally good, although there were indications of sodium and magnesium excess in the central and eastern parts of the study area, respectively.

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1 Introduction

"Maji ni uhai", Swahili for "water is life", is the motto that appears along the highway when approaching Moshi town, the capital of the Kilimanjaro Region, Tanzania. Its strong relationship with water is not surprising as Mt. Kilimanjaro acts as a water tower, generating and supplying water resources along its slopes and the adjacent lowlands, as well as to the Pangani River Basin [1, 2]. According to Komakech et al. [3], approximately 80% of the population in the Pangani River Basin depends on agriculture for livelihoods and export, and 80% of the water from the Kilimanjaro Region is used for irrigation. On the fertile and densely populated southern slopes of Africa's highest mountain, the Chagga people have lived and shaped the upper part of the territory for more than 400 years with their small-scale "homegarden" farming, while the lower part is characterised by intensive agriculture and urbanised areas, particularly around Moshi [2, 4]. Global dynamics, including the growing human population [5, 6], evidence of climate change [7, 8] and changes in land use and land cover on the slopes [6, 9–13] have impacted the people, their livelihoods and the environment, with water resources being highly affected.

Concerns regarding water quality at Mt. Kilimanjaro and in the Pangani River Basin are related to elevated nutrient concentrations in groundwater [14], rivers and sediments with increasing concentrations closer to intensive agricultural, horticultural and livestock activities [15, 16]. Pesticide residues from agricultural applications have been found in the Kikafu River flowing in the lowlands near sugarcane plantations [17]. Furthermore, trace elements such as aluminium, iron, vanadium and manganese have been found in surface waters of the Pangani River Basin at concentrations exceeding the recommended drinking water permissible limits. This is likely due to rock weathering and human activities [18]. In the nearby Meru District Council, widespread faecal contamination was found in groundwater and rivers [19, 20]. In addition, there have been cases of anthropogenic pollution, including high concentrations of nutrients and chlorine [21, 22].

There are different approaches that can be used to assess water quality, including multivariate factor analysis, water quality indices (WQI) and the use of fuzzy logic [21, 23, 24]. The WQI is one of the most commonly used and accepted methods for effectively summarising, interpreting and communicating large datasets of water quality data to the general public and decision-makers in a simple and informative way [23, 25, 26]. The steps to calculate the WQI include: parameter selection, calculation of a dimensionless index for each parameter, weight assignment, aggregation of the calculated subindices in a single-value WQI, and, finally, the ranking of the WQI in qualitative classes. Since the first WQI was developed in the 1960s, several approaches have been implemented to aggregate quantitative variables into qualitative values using different mathematical methods, with the aim of eliminating subjectivity and expert bias. A number of reviews have been published with the objective of describing, classifying and evaluating the advantages and disadvantages of the most popular WQIs [23, 26–30]. It is widely accepted that a universal WQI cannot be defined, as the selection and the weighting of parameters must be adapted to each application and context [23, 24, 29]. Parameter weighting is a crucial step to obtain the accuracy of a result and to determine the relative importance of the settings. The Weighted Arithmetic Water Quality Index, for example, is based on the permissible limits of water quality parameters for a targeted use, which helps to reduce the risk of subjectivity [23, 27, 31].

While there have been several studies conducted on the water quality of the Kilimanjaro Region and the Pangani River Basin, the suitability of water specifically for drinking and irrigation use on the southern slopes of Mt. Kilimanjaro has not been assessed. Given the crucial role water resources play locally in the densely populated slopes, the objective of this study is to provide insights into the quality of various water sources (i.e., stream water, domestic water, spring water, rainfall, groundwater, lake water and water from irrigation canals) for drinking and irrigation purposes. Moreover, the study uses water quality indices as a user-friendly tool to facilitate the communication of the findings to stakeholders and the public.

2 Materials and methods

2.1 Study area

This research was conducted on the southern slopes of Mt. Kilimanjaro in Tanzania. The spatial extent of the study area ranges from elevations of 700 m a.s.l. to 1900 m a.s.l. and from the Kikafu River in the west to Lake Chala in the east (Fig. 1). It represents the densely populated area below the Kilimanjaro National Park boundary, where human settlements and agricultural activities are located around Moshi town.

According to Hemp [4], this section of the southern slopes can be divided into two main ecological zones. The lower zone, situated below approximately 1000 m a.s.l., is characterised by colline savannah. The upper zone, located above 1000 m a.s.l. and up to the national park boundary, is dominated by agricultural and horticultural activities. The colline savannah zone is characterised by hot and dry conditions and by intensive crop production, particularly of maize, beans and sunflowers as well as grazing. Additionally, there are patches of former savannah vegetation around Lake Chala in the eastern zone. The upper zone is characterised by traditional agroforestry systems (Chagga homegardens), as well as banana and coffee plantations. Here, the deepest valleys and gorges can still contain patches of former submontane forest.

Annual rainfall is distributed across two distinct rainy seasons, with the first lasting from March to May and the second around November. The periods between January and February and between June and September are characterised by reduced precipitation. The mean annual rainfall increases rather linearly from the lowlands, ranging from approximately 900 mm at 800 m a.s.l., to around 2700 mm at 2,200 m a.s.l. [8, 33, 34].

Mt. Kilimanjaro is located in the southern part of the East African Rift system. The lava that flowed down the southern slopes formed a range of rock types including olivine and alkali basalts, phonolites, trachytes, nephelinites and pyroclastic rocks [14, 35, 36]. The soils that have developed are highly fertile alkaline types, such as andosols [37, 38].

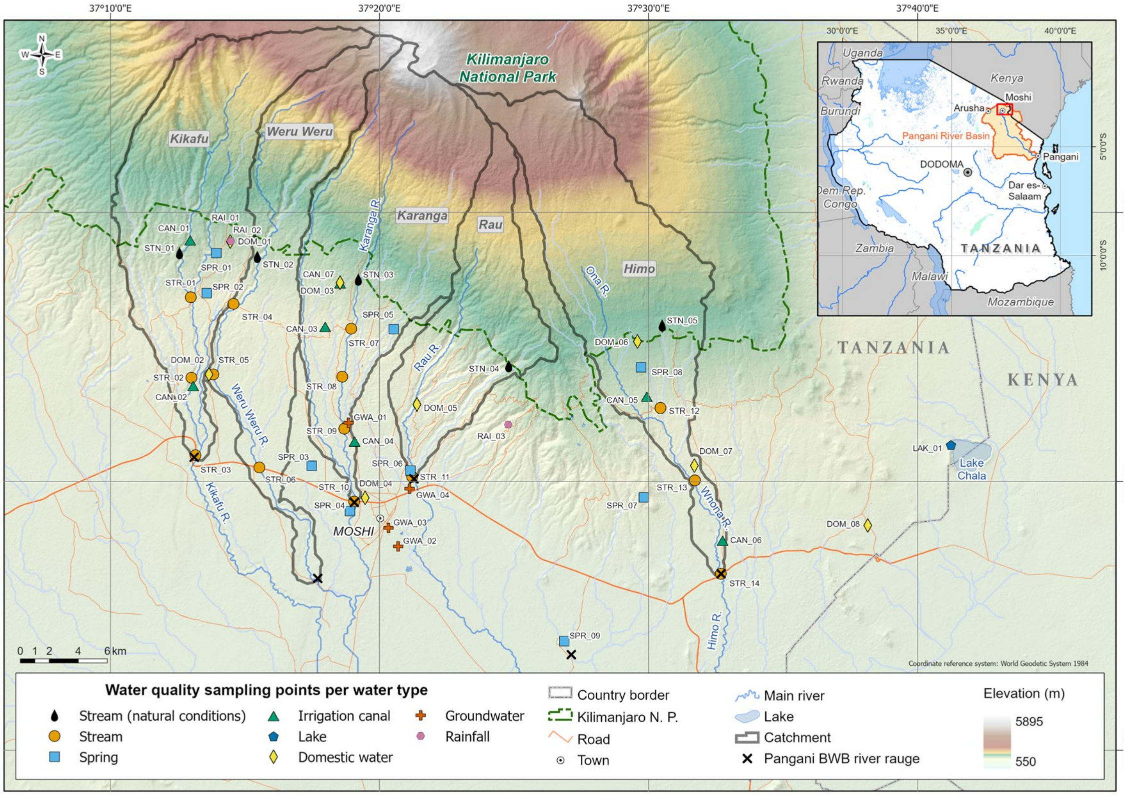


Fig. 1 Location of the study area and sampling sites on the southern slopes of Mt. Kilimanjaro. The catchments of the main rivers were delineated upstream from the Pangani Basin Water Board gauging stations, using the 30 m resolution Digital Elevation Model of Hemp et al. [32]. The abbreviations for the sampling sites are STN = stream in natural conditions, STR = stream, CAN = canal, DOM = domestic water, SPR = spring, LAK = lake, GWA = groundwater and RAI = rainfall

The combination of fertile soils and favourable climatic conditions has made the southern slopes area known as the "breadbasket" of Tanzania [39].

Mt. Kilimanjaro, together with Mt. Meru, is the primary source area of the Pangani River. The river network formed in this area flows to the Nyumba ya Mungu dam, which is an essential source for hydroelectric power generation and provides livelihoods such as fishing and water for irrigation. Permanent rivers, small seasonal streams and numerous springs originating on the southern slopes of Mt. Kilimanjaro are the primary sources of water for domestic and agricultural use. These sources are distributed through an extensive network of traditional furrows, or *mfongo* in the Chagga language, which overcomes the steep topography of the area [14, 40–44]. It should be noted that the glaciers on Mt. Kilimanjaro are considered to not currently play a substantial role in replenishing the region's water resources [9, 14, 34, 45].

2.2 Sampling design, measured parameters and analytics

To assess the water quality for drinking and irrigation purposes, water samples were collected from 51 sampling sites on the southern slopes of Mt. Kilimanjaro (Fig. 1, Table S1 in the Supplementary Material) during a 10-day snapshot sampling campaign [46, 47] in February 2023. Due to logistical limitations, we were only able to conduct a single campaign, which was conducted during the dry season to minimise the potential for sample dilution and therefore to ensure comparable conditions for all the samples. It is also important to acknowledge the challenging fieldwork conditions, which can make it difficult to ensure the comparability of the analytical results between samples taken on different days. Samples were collected from streams (STR, n = 19), irrigation canals (CAN, n = 7), domestic water (DOM, n = 8), springs (SPR, n = 9), lake (LAK, n = 1), groundwater (GWA, n = 4) and rainfall (RAI, n = 3). Five samples were collected from streams close to the Kilimanjaro National Park boundary. These streams with minimal anthropogenic impact were selected as being representative for streams in their natural conditions (STN). The drinking water quality was assessed using samples from streams, streams in natural conditions, irrigation canals, domestic water, springs and a lake. Samples from streams, streams in natural conditions, irrigation canals, springs, groundwater, a lake and rainfall were used to assess the irrigation water quality.

The surface water sampling sites (streams, canals and springs) were distributed along the altitudinal gradient and from the east to the west side of the southern slopes of Mt. Kilimanjaro to represent the water quality of the major rivers in the area. The study area included the Kikafu, Weru Weru, Karanga, Rau and Himo rivers, as well as two additional springs between the Rau and Himo river catchments, i.e., the Miwaleni and Mkongo springs. Domestic water samples were collected from private and public taps distributed along the altitudinal gradient and east–west extension of the study area. Groundwater is not a significant water source for drinking or irrigation on the southern slopes of Mt. Kilimanjaro. However, four groundwater samples were collected from boreholes within the study area, including one from a coffee plantation and three from monitoring boreholes in Moshi town. The three rainwater samples were collected at two different sites prior to the two-week sampling campaign. One sample was taken from Lake Chala on the eastern edge of the study area. The sample was collected at a lodge that pumps from approximately 4 m below the lake surface to a tank.

Electrical conductivity (EC), pH, total dissolved solids (TDS), turbidity and water temperature were measured in situ using a portable multiparameter meter (EC/temperature sensor WTW TetraCon 925-3 and pH/temperature sensor WTW Sentix 940 attached to a multimeter WTW MultiLine Multi 3630 IDS, Xylem, Germany; TSS/turbidity TSS Portable, HACH, USA).

All other parameters were analysed in laboratories. For this purpose, water samples were collected in 1-L PE plastic bottles for the analysis of total hardness (TH) and total alkalinity (ALK) through titrimetric methods. A second set of water samples was collected in 500 ml sterilised glass bottles for the analysis of *Escherichia coli* (*E. coli*) through membrane filtration. These three parameters were analysed within 24 h from sampling by the Ngurdoto Research Campus Water Laboratory based in Usa River, Arusha, Tanzania. A third set of water samples was collected, filtered (KX Syringe Filter, PP, 30 mm diameter, 0.45 µm, Kinesis Ltd., St. Neods, UK) and stored in 150 ml PE plastic bottles for the analysis of calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and sodium (Na^+) through inductively coupled plasma optical emission spectroscopy (ICP-OES) (Varian 720-ES ICP-OES, Varian (now Agilent), CA, USA), and for chloride (Cl^-), fluoride (F^-), nitrate (NO_3^-) and sulphate (SO_4^{2-}) through ion chromatography (DX-120, Dionex Corporation, CA, USA). These parameters were analysed at the Institute for Landscape, Ecology and Resource Management and the Department of Soil Science and Soil Conservation, Justus Liebig University of Giessen (Germany). To minimise chemical reactions between collection and analysis, all the samples were refrigerated in a cooler box with ice during fieldwork and frozen in the laboratory until analysis.

Standard operating procedures were adhered to by all participating laboratories to ensure the quality of the analytical data. Calibration coefficients for all parameters and instruments were above 0.97. In addition, a subset (n = 17) of water samples was re-analysed by an independent environmental analytical laboratory (Chemisches und Mikrobiologisches

Institut UEG GmbH, Wetzlar, Germany) to confirm the results of the ICP-OES and ion chromatography analyses. The accuracy of the analyses was verified by calculating the relative percentage difference (RPD) for each parameter with duplicate samples. The RPD was within the acceptable range of 30%, except for chloride. Additionally, we have calculated the charge balance error for our samples which was not satisfactory for the majority of the cases. The occurrence of a charge balance error in water quality monitoring is often attributed to the presence of titratable organic components, which can influence the calculation of carbonate contribution. The error may be also the result of other systematic errors, such as the determination of alkalinity from non-acidified samples or the failure to filter samples [48]. Despite the aforementioned potential systematic errors and lack of closed charge balance, we proceeded with the data analysis.

2.3 Water quality permissible limits and guidelines

2.3.1 Drinking water quality

Drinking water quality was evaluated based on EC, pH, TDS, turbidity, TH, *E. coli*, Cl^-, F^-, NO_3^- and SO_4^{2-} levels, and compared with Tanzanian and international permissible limits. The parameters were selected in accordance with the guidelines of the Ministry of Water and Irrigation [49] for routine monitoring at drinking water sources or intakes. The assessment of colour was conducted on a qualitative basis, while temperature and alkalinity were excluded due to the lack of permissible limits. Instead, F^-, Cl^- and SO_4^{2-} were included in the list because they are considered to be possible local specific water quality issues in the study area by the Ministry of Water and Irrigation [49]. Table 1 shows the permissible limits set by the Tanzania Bureau of Standards (TBS) [50] and those set by the World Health Organization [51], along with the potential effects on human health if these limits are exceeded. As the limits set by the TBS are equal to or more restrictive than those set by the WHO, the Tanzanian limits were selected as the reference. It should be noted that these limits distinguish between treated and natural drinking water. In this study, the former were used exclusively for domestic water, while the latter were used for all other water sources.

2.3.2 Irrigation water quality

The irrigation water quality was evaluated using a range of parameters, including EC, pH, TDS, Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, nitrate-nitrogen (NO_3-N), SO_4^{2-} and sodium adsorption ratio (SAR). The results were compared with Tanzanian and international guidelines. The SAR is a commonly used parameter to evaluate water for irrigation [52, 53], which represents the relative ratio of sodium to the sum of calcium and magnesium concentrations. It is calculated using the following equation (Eq. 1) [54]:

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+}+Mg^{2+}}{2}}} \tag{1}$$

with ion concentrations in meq/l. SAR is also known as the "sodicity hazard" because Na^+ is likely to replace Ca^{2+} and Mg^{2+} in the soil. This can lead to general degradation of the soil structure through compaction, a reduction in saturated hydraulic conductivity and aeration, and thus affecting crop production [53, 55].

Table 2 shows the guidelines for the assessment of water quality for irrigation (hereafter referred to as guidelines) established by the TBS [56] and by the Food and Agriculture Organization [57]. The guidelines include three degrees of restriction on use, which should not be taken as absolute values, as the guidelines are designed to cover a wide range of conditions [57]. In this study, we have applied the most rigorous guideline requirements for each parameter, which corresponds to the value for slight to moderate restriction. In addition, Table 2 provides a concise overview of the potential impacts on crops if the guidelines are exceeded [57, 58].

2.4 Water quality indices

We calculated WQIs in order to provide a qualitative description of drinking and irrigation water quality based on the parameters described (Tables 1 and 2 respectively). The WQI used to assess compliance with the regulations is an adapted version of the Weighted Arithmetic Water Quality Index (WAWQI) developed by Brown in 1972 [23]. The original index offers flexibility in terms of the number and type of parameters selected, as well as the water sources

Table 1 Permissible limits for drinking water according to the Tanzania Bureau of Standards (TBS) and the World Health Organization (WHO) and their potential health effects if the limits are exceeded

Parameter	Unit	TBS Potable water [50]		WHO Guidelines for drinking-water quality [51]	Potential effects on human health
		Treated potable water	Natural potable water		
EC	µS/cm	1500	2500	–	Indicator of pollution events (further studies are necessary to understand the causes)
pH	–	6.5–8.5	5.5–9.5	Not of health concern at levels found in drinking-water	Bitter taste of water, effects on mucous membrane, dry, itchy and irritated skin, possible mobilization of harmful chemical constituents (*e.g.* metals and nutrients)
TDS	mg/l	700	1500	Not of health concern at levels found in drinking-water	Unpalatability of water, scale deposition in the water treatment, storage and distribution system
Turbidity	NTU	5	25	Not defined	Unpalatability of water, indicator of potential pollution (*e.g.* metals and bacteria)
TH	mg $CaCO_3$/l	300	600	Not of health concern at levels found in drinking-water	Unpalatability of water, skin irritation, scale deposition in the water treatment, storage and distribution system
E. coli	CFU/100 ml	0	0	0	Meningitis, bacteraemia, urinary tract and intestinal infections
F^-	mg/l	1.5	1.5	1.5	Risk of dental and skeletal fluorosis
Cl^-	mg/l	250	250	No health-based guideline value is proposed	Unpalatability of water, corrosion of metals in the distribution system, increase the concentration of metals in the supply
NO_3^-	mg/l	45	45	50	Methaemoglobinaemia and thyroid effects in the most sensitive population
SO_4^{2-}	mg/l	400	400	Not of health concern at levels found in drinking-water	Possible laxative and gastrointestinal effects

Table 2 Tanzania Bureau of Standards (TBS) and Food and Agriculture Organization (FAO) guidelines for evaluation of water quality for irrigation and the potential impacts on crops if the guidelines are exceeded

Parameter	Unit	TBS Water for irrigation [56]			FAO Water quality for agriculture [57]			Potential impacts on crops
		Degree of restriction of use			Restriction on use			
		No problem	Increasing problem	Severe problem	No	Slight to Moderate	Severe	
EC	µS/cm	< 750	750–3000	> 3000	< 700	700–3000	> 3000	Increase of soil salinity causing physiological drought, reduction of plant growth and crop yield
pH	–	< 6.5	6.5–8.4	> 8.4	normal range 6.5–8.4			Effects on plant growth and irrigation equipment
TDS	mg/l	< 450	450–2000	> 2000	< 450	450–2000	> 2000	Increase of soil salinity causing physiological drought, reduction of plant growth and crop yield
Ca^{2+}	mg/l						> 400.8	Increase of pH, decreases nutrient availability for plants
Mg^{2+}	mg/l						> 60.8	Increase of pH, decreases nutrient availability for plants
Na^{+}	mg/l						> 920	Leaf burn, scorch and dead tissue along the outside edges of leaves, loss of soil structure, reduction of infiltration capacity and aeration
K^{+}	mg/l						> 78.2	Not a concern for plant growth. Indicator of contamination from fertilisers
Cl^{-}	mg/l	< 142	142–355	> 355	< 142	142–355	> 355	Inhibition of plant growth, reduction of phosphorus availability to plants, leaf burn and drying of leaf tip
NO_3-N	mg/l	< 5	5–30	> 30	< 5	5–30	> 30	Overstimulation of growth, delayed maturity and poor crop quality
SO_4^{2-}	mg/l						> 960.6	Reduction in phosphorus availability to plants
SAR	–	< 3	3–9	> 9	< 3	3–9	> 9	Loss of soil structure, reduction of infiltration capacity and aeration

included [23, 27, 31]. Furthermore, the index calculation is simple, comprising a single basic mathematical equation, and is reproducible, as each parameter weight is based on permissible limits. However, this approach also has some limitations. For example, the index may unduly emphasise the significance of parameters that exceed the permissible limits and, depending on the selected parameters, it may lack sufficient information about the actual quality of the water [23, 27, 31]. The adapted version of the WAWQI avoids giving undue importance to those parameters that exceed the permissible limits by adjusting the calculation of each parameter weight [30]. Several previous studies have adopted this version [53, 59, 60] and it was also identified by Lukahbi et al. [30] in their review of water quality indices as one of the most used for water quality monitoring in Africa.

The procedures for calculating the WQI for drinking water (DWQI) and irrigation (IWQI) are the same. The parameters and their respective permissible limits and guidelines selected for the calculation of the DWQI and the IWQI are presented in Tables 1 and 2. Four steps are involved in the calculation of the indices.

First, a weight (w_i) is assigned to each parameter (i). The range of w_i is 1 to 5, based on the percentage of samples within the permissible limits. The relative importance of a parameter is inversely proportional to the percentage of samples within the permissible limits for that parameter. Specifically, for a percentage of samples within the reference standards or guidelines between 0–20, 21–40, 41–60, 61–80 and 81–100%, the weights applied are 5, 4, 3, 2 and 1, respectively.

Second, a relative weight (Rw_i) for each parameter (i) is calculated using the equation Eq. 2 by dividing its weight (w_i) by the sum of the weights of all parameters:

$$Rw_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{2}$$

Third, a quality rating scale (q_i) for each parameter (i) for each sample is calculated using equation Eq. 3 by dividing the concentration (C_i) of parameter i in the water sample by the permissible limit (for drinking water) or the guideline (for irrigation water) of parameter i (S_i):

$$q_i = \frac{C_i}{S_i} * 100 \tag{3}$$

In the fourth and final step, the WQI for each sample is calculated according to equation Eq. 4 by summing the multiplication of the relative weights (Rw_i) and the quality rating scales (q_i) of the n parameters as follows:

$$WQI = \sum_{i=1}^{n} \left(Rw_i * q_i\right) \tag{4}$$

The calculated DWQI and IWQI are a numerical rating system that can be categorised to qualitatively describe the suitability of water for drinking and irrigation purposes, respectively [23, 27]. The indices are finally grouped into categories, 5 for the DWQI and 4 for the IWQI, as shown in Tables 3 and 4, respectively.

Following testing of the methodology, it was found that a sample could still be classified as good or excellent for drinking, or with no restriction for irrigation uses, despite one parameter slightly exceeded the permissible limit or guideline. A similar issue was identified by Kitalika et al. [20], who observed an "over-grading" with the WAWQI method, resulting in the index appearing to be excessively positive in comparison to another method. To address this issue, we have introduced an additional rule to the calculation of both indices. This involves adding the value of 100 for drinking water and 150 for irrigation use to the water quality subindex (Rw_i*q_i) for the parameter i of a

Table 3 Classification of the DWQI

DWQI value	Categories for DWQI
< 25	Excellent
25–50	Good
50–75	Poor
75–100	Very poor
> 100	Unsuitable
[23, 27]	

Table 4 Classification of the IWQI

IWQI value	Categories for IWQI
< 150	No restriction
150–300	Slight restriction
300–450	Moderate restriction
> 450	Severe restriction
[60, 61]	

Table 5 Description and classification of irrigation suitability indicators

Indicator	Equation	Classification	Irrigation suitability	Description
KI (-)	$\frac{Na^{+}}{Mg^{2+}+Ca^{2+}}$	< 1	Suitable	Excess sodium in water, soil permeability reduction
		> 1	Unsuitable	
SSP (%)	$\frac{Na^{+}+K^{+}}{Mg^{2+}+Ca^{2+}+Na^{+}+K^{+}} * 100$	< 20	Excellent	Reduction of water transport capacity resulting in hard and dry soil
		20–40	Good	
		40–60	Permissible	
		60–80	Doubtful	
		> 80	Unsuitable	
MR (%)	$\frac{Mg^{2+}}{Mg^{2+}+Ca^{2+}} * 100$	< 50	Suitable	Increase salinity, decrease phosphorus binding capacity of the soil, less friability of the soil
		> 50	Unsuitable	

The ion concentrations are expressed in meq/l. The abbreviations for the indicators are: Kelley's Index (KI), Soluble Sodium Percentage (SSP) and Magnesium Ratio (MR)

given water sample each time that the concentration C_i exceeds the permissible limit or guideline S_i. These values correspond to the threshold that would lead to the classification of the water sample as "unsuitable" (DWQI) or "slight restriction of use" (IWQI).

Furthermore, three indicators commonly used for assessing irrigation water quality were used to classify the suitability of water for irrigation use. These were Kelley's Index (KI), Soluble Sodium Percentage (SSP) also called sodium hazard (Na%) and Magnesium Ratio (MR) [22, 53, 60]. Table 5 describes the indicators, their classification and the irrigation suitability for each class.

3 Results and discussion

3.1 Drinking water quality

A total of 44 samples were analysed to assess drinking water quality. These were collected from streams (n = 19, including 5 streams in natural conditions), springs (n = 9), irrigation canals (n = 7), one lake and domestic water (n = 8). All the selected sources are used in the study area for both drinking water and other domestic uses. All the selected parameters were found to be within the permissible limits for drinking water (Table 1), with the exception of *E. coli* and turbidity (Fig. 2, Table S2 in the Supplementary Material).

E. coli is a bacterium that lives in the intestines of warm-blooded animals (i.e., mammals and birds) and is commonly found in human and animal faeces. Its presence is therefore an indicator of recent faecal contamination of water, as it generally does not survive for long periods outside its host. Although some strains can cause serious illnesses such as meningitis, bacteraemia (presence of bacteria in the blood), urinary tract and intestinal infections (which can cause nausea, vomiting and diarrhoea), the majority of *E. coli* strains are harmless. However, the detection of *E. coli* in water also indicates the possible presence of other disease-causing bacterial pathogens, such as *Salmonella* spp. and *Shigella* spp. [51]. A recent study revealed that *Shigella* and enteroinvasive *E. coli* were among the most common diarrhoea-associated pathogens identified in children under five years of age admitted to health facilities with diarrhoea in Moshi town [62]. Infection with these pathogens occurs through contact with animals and humans that host the bacteria and, more commonly, through consumption of contaminated food or water. *E. coli* can reach surface waters in a variety of ways, including leakage from sewage or septic systems; improper disposal of human waste; runoff from agricultural, grazing

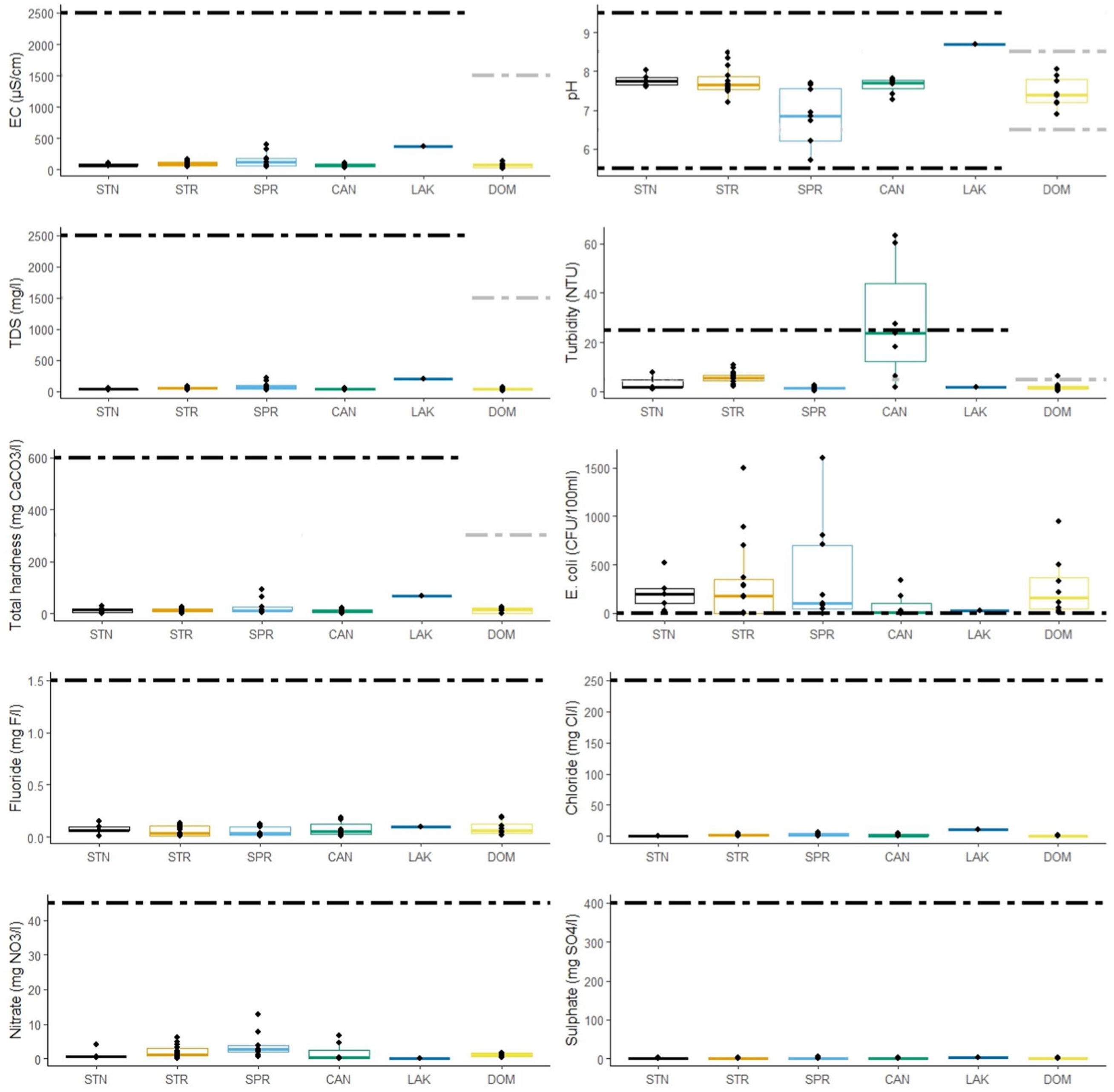


Fig. 2 Boxplots showing the analytical results of the 10 parameters analysed to assess drinking water quality for each water source. The black dashed line represents the permissible limit for natural water and the grey one for treated water [50]. If only the black dashed line is shown, it means that the two limits coincide. The water sources are coded as follows: STN = stream in natural conditions, STR = stream, SPR = spring, CAN = irrigation canal, LAK = lake and DOM = domestic water

and manure storage areas; effluent from wastewater treatment plants; and direct access to surface waters by livestock and wildlife. Previous studies carried out in the nearby Meru District Council, showed that a significant number of water samples from streams, springs and boreholes exceeded the drinking water quality standards for microbial contamination. The contamination levels were found to be greater during the wet season due to increased runoff, and at lower altitudes due to increased population and livelihood activities [19, 20].

According to the permissible limits set by the TBS and the WHO, water used for domestic purposes should be free of *E. coli*. The results show that one or more colonies were present in 86% of the water samples. The bacterial counts ranged from 0 to 1600 CFU/100 ml, with the highest average found in springs (393 CFU/100 ml), followed by streams (315 CFU/100 ml) and domestic water (275 CFU/100 ml). The widespread occurrence of *E. coli* in our surface water samples is not surprising. Kitalika et al. [20] and Elisante & Muzuka [19] also reported the presence of faecal coliform colonies with counts above 0 CFU/100 ml in rivers and groundwater in Meru District Council during the dry season. This may be due to animals congregating along the river as a primary source of drinking water during the dry season [20], or to the proximity of pit latrines, farms and animal sheds [19]. The domestic water supply system in the study area draws water from streams and springs located within the national park. In the upper land, the water supply can be either local, untreated, or managed by the Moshi Urban Water Supply and Sanitation Authority or by Community-based Water Supply Organizations, which treat the water with simple chlorination at the source and before distribution. However, the presence of *E. coli* in all the domestic waters sampled is a cause for concern, as most of these waters are collected within the national park boundaries, where livestock and human impacts are minimal. A possible explanation for this issue is a failure in the water distribution infrastructure in the area. Fingerprint analyses for source attribution are recommended to further identify sources of faecal contamination [63–65] and to develop WASH (water, sanitation and hygiene) strategies in the area. Community education on safe water practices, potential threats and appropriate household water treatment methods is essential to safeguard public health in the region.

Turbidity is an optical property of water and it describes its cloudiness due to suspended matter such as (organic) particles, chemical precipitates and organisms. Turbidity is not a direct indicator of health risk, but particles in the water can provide food and shelter for pathogens and protect them from the effects of disinfection. Particles can also provide a surface for other contaminants, such as metals, to adhere to, increasing the effort and relative cost of water treatment. Previous research has shown a strong positive correlation between *E. coli* and turbidity [66–68]. However, this is not reflected in the results of our campaign. In addition, high levels of turbidity can make water unattractive for drinking for aesthetic reasons [51, 69].

The measured turbidity values ranged from 0.4 to 63.2 nephelometric turbidity units (NTU). The stream turbidity results are in the same range as those found in rivers in Meru District [21, 70]. Only 4 out of the 44 samples exceeded the permissible limits of 25 and 5 NTU for natural and treated potable water, respectively [50]. These samples were collected from three irrigation canals and one domestic water (DOM_5) taken from a public tap in the village of Mnini (6.4 NTU). While the water from the irrigation canals is not intended for domestic use, and the population could be advised not to use it, for the public taps, regular testing and frequent visual checks are useful to detect an increase in turbidity and thus address possible failures in the distribution system.

3.1.1 Drinking water quality index (DWQI)

To provide an overall assessment of drinking water quality, a WQI was calculated for each drinking water sample (DWQI) based on the Tanzanian permissible limits (Table 6). The DWQI ranged from 3 to above 50,000 (Table S3 in the Supplementary Material). According to the classification shown in Table 3, 11% of the samples were classified as excellent quality and 89% as unsuitable for drinking. As shown in Fig. 3, all samples taken from domestic water,

Table 6 Permissible limits, weights and relative weights of the selected parameters used to calculate the DWQI

Parameter	Unit	Domestic water source (DOM)				All other water sources (STN, STR, SPR, CAN, LAK)			
		Treated potable water*	% of compliance	Weight (w_i)	Relative weight (Rw_i)	Natural potable water*	% of compliance	Weight (w_i)	Relative weight (Rw_i)
EC	μS/cm	1500	100	1	0.07	2500	100	1	0.07
pH	–	6.5–8.5	100	1	0.07	5.5–9.5	100	1	0.07
TDS	mg/l	700	100	1	0.07	1500	100	1	0.07
Turbidity	NTU	5	88	1	0.07	25	92	1	0.07
TH	mg $CaCO_3$/l	300	100	1	0.07	600	100	1	0.07
E. coli	CFU/100 ml	0	0	5	0.36	0	17	5	0.36
F^-	mg/l	1.5	100	1	0.07	1.5	100	1	0.07
Cl^-	mg/l	250	100	1	0.07	250	100	1	0.07
NO_3^-	mg/l	45	100	1	0.07	45	100	1	0.07
SO_4^{2-}	mg/l	400	100	1	0.07	400	100	1	0.07

*Permissible limits established by TBS [50]

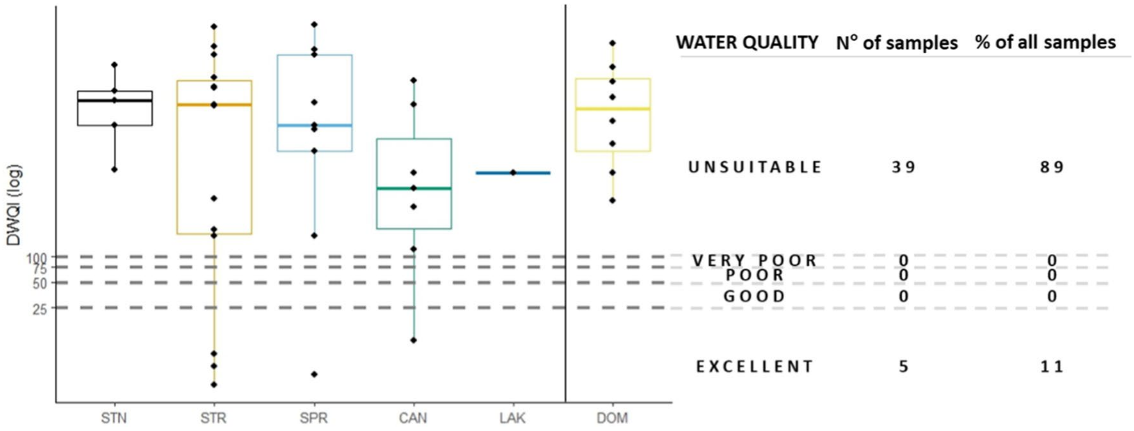


Fig. 3 Boxplots per water source showing the DWQI calculated for each sample (black dot) and the index classification into categories. The water sources are coded as follows: STN = stream in natural conditions, STR = stream, SPR = spring, CAN = irrigation canal, LAK = lake and DOM = domestic water

streams in natural conditions and Lake Chala were unsuitable for drinking, as were the majority of the streams, irrigation canals and springs. Surprisingly, water from streams situated further downstream from the national park boundary is of better quality than water from streams in "natural condition", located within or in close proximity to the national park. This is because of the number of *E. coli* colonies found in the water samples, which strongly influenced the calculation of the DWQI. In fact, the higher the number of colonies, the higher the quality rating scale for *E. coli* (q_{Ecoli}) (Eq. 3). Please note that for the calculation of the quality rating scale for *E. coli*, the permissible limit S_i in Eq. 3 was set to 1 CFU/100 ml even if it should be "absent" [50, 51]. Otherwise, the use of 0 CFU/100 ml would result in a division by zero.

3.2 Irrigation water quality

Forty-three samples from streams (n = 19, including 5 streams in natural conditions), springs (n = 9), irrigation canals (n = 7), groundwater (n = 4), rainfall (n = 3) and one lake were analysed to assess the irrigation water quality. All the selected parameters were within the guidelines of restriction of use for irrigation (Table 2) with the exception of pH (Fig. 4, Table S2 in the Supplementary Material).

pH values outside the range are rarely problematic [57, 71], but they can be a warning of abnormalities. High pH is often associated with high levels of bicarbonate and carbonate, which can cause Ca^{2+} and Mg^{2+} to precipitate as insoluble minerals, leaving Na^{+} as the dominant ion in the solution. An increase in water sodicity can lead to a decrease in the water infiltration rate and soil gas exchange by degrading the soil structure through swelling and dispersion of clays [71, 72]. The precipitation of Ca^{2+} and Mg^{2+} minerals can also cause problems with the irrigation equipment. It is important to consider both pH and alkalinity. Alkalinity is a measure of the ability of water to neutralise acidity [73]. The higher the alkalinity, the greater the resistance to pH change. Therefore, when high pH and high alkalinity occur together, the pH of the water is difficult to change, so the pH of the soil will also increase, leading to mineral and nutrient deficiencies [58, 72, 74]. Acidic water can mobilise trace elements, such as heavy metals, contribute to soil acidification and damage metal pipes and tanks through corrosion [71].

Seven percent of the samples (n = 5) exceeded the normal pH range of 6.5 to 8.4. The lowest values were found in three springs (5.7, 5.7 and 6.2) and the highest values in a stream (Kikafu) and Lake Chala (8.5 and 8.7, respectively). Only the water sample from Lake Chala had a high alkalinity (202 mg $CaCO_3$/l), so the remaining samples, which had low alkalinity, should not be a cause for concern. In agriculture, several water treatment techniques can be used to correct either the irrigation water or the substrate pH if highly alkaline water has to be used for irrigation. Proper fertiliser selection or acid injection are two common techniques, although they can be expensive and not environmentally friendly. Finding an alternative water source for irrigation may be the best solution in some cases [58].

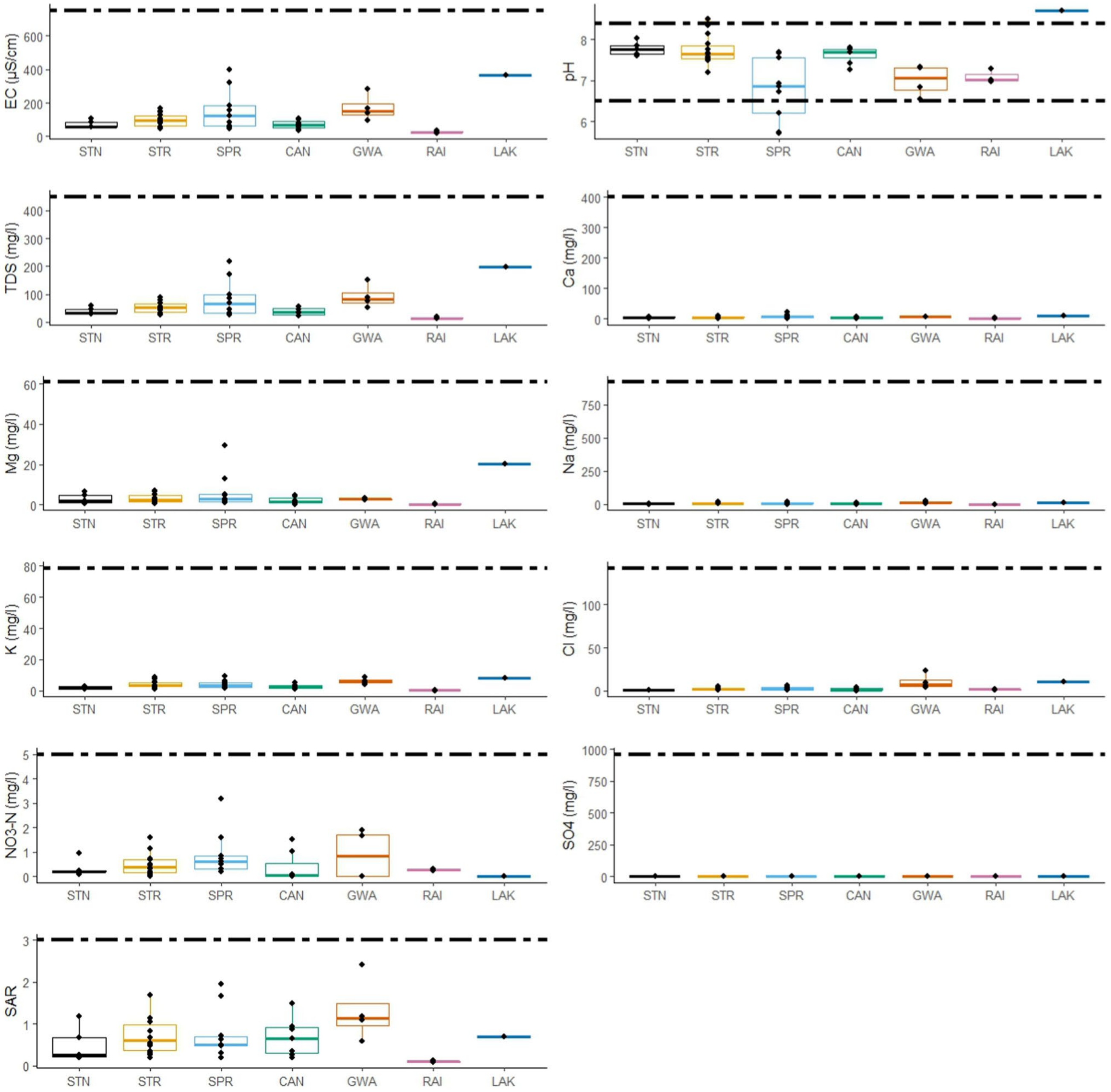


Fig. 4 Boxplots per water source representing the analytical results of the 11 parameters analysed to assess irrigation water quality. The black dashed line represents the guideline of restriction of water use for irrigation [56, 57]. The water sources are coded as follows: STN = stream in natural conditions, STR = stream, SPR = spring, CAN = irrigation canal, GWA = groundwater, RAI = rainfall and LAK = lake

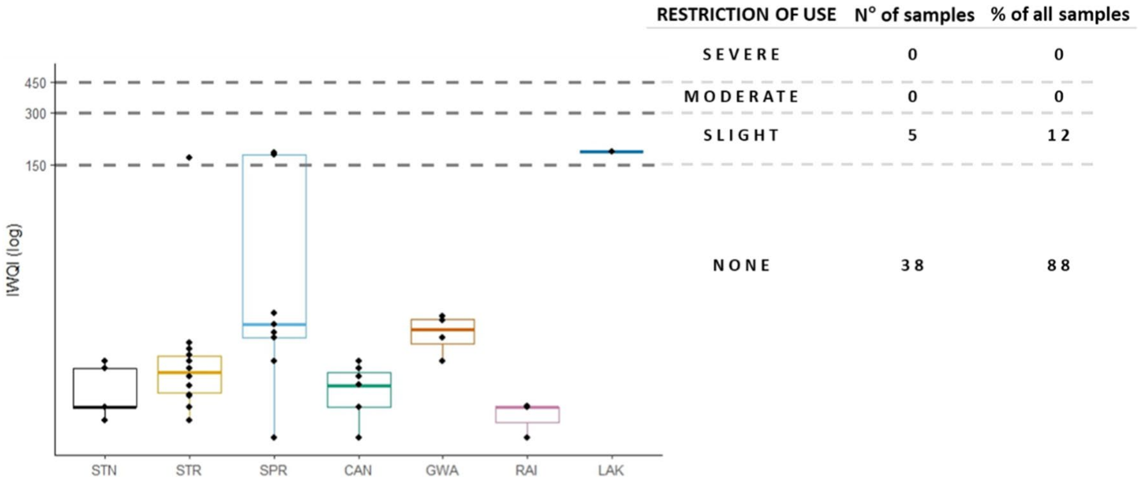
3.2.1 Irrigation water quality index (IWQI) and other irrigation indices

A WQI was also calculated for each sample to assess irrigation water quality (IWQI). The weight w_i and the relative weight Rw_i were assigned to each parameter based on the percentage of samples within the water use restriction guidelines (Table 7). The calculated IWQI ranged from 4 to 128 (Table S3 in the Supplementary Material). According to the classification shown in Table 4, the majority (88%) of the water samples can be used for irrigation without restrictions and 12% with a slight restriction of use (Fig. 5). The results highlight the generally good quality of water for irrigation use on the southern slopes of Mt. Kilimanjaro compared to water quality in nearby areas. In the Mwanga District, a district to the south-east of our study area, high concentrations of SO_4^{2-} were found in irrigation water for paddy rice, associated with intensive use of synthetic fertilisers [75]. In the Kikafu River, further south of the study area and downstream of Moshi

Table 7 Guidelines, weights and relative weights of the selected parameters used to calculate the IWQI

Parameter	Unit	Guidelines*	% of compliance	Weight (w_i)	Relative weight (Rw_i)
EC	µS/cm	750	100	1	0.09
pH	–	6.5–8.4	88	1	0.09
TDS	mg/l	450	100	1	0.09
NO_3-N	mg/l	5	100	1	0.09
Cl^-	mg/l	142	100	1	0.09
SO_4^{2-}	mg/l	960.6	100	1	0.09
Ca^{2+}	mg/l	400.8	100	1	0.09
K^+	mg/l	78.2	100	1	0.09
Mg^{2+}	mg/l	60.8	100	1	0.09
Na^+	mg/l	920	100	1	0.09
SAR	–	3	100	1	0.09

*Guidelines for slight to moderate restrictions in water use for irrigation established by TBS [56] and FAO [57]



RESTRICTION OF USE	N° of samples	% of all samples
SEVERE	0	0
MODERATE	0	0
SLIGHT	5	12
NONE	38	88

Fig. 5 Boxplots per water source showing the IWQI calculated for each sample (black dot) and the index classification into categories. The water sources are coded as follows: STN = stream in natural conditions, STR = stream, SPR = spring, CAN = irrigation canal, GWA = groundwater, RAI = rainfall and LAK = lake

Table 8 Number and percentage of water samples classified into each irrigation suitability indicator class

Indicator	Classification	Irrigation suitability	Nº samples	% samples
KI (-)	> 1	Unsuitable	14	32.6
	< 1	Suitable	29	67.4
SSP (%)	> 80	Unsuitable	1	2.3
	60–80	Doubtful	10	23.3
	40–60	Permissible	12	27.9
	20–40	Good	13	30.2
	< 20	Excellent	7	16.3
MR (%)	> 50	Unsuitable	9	20.9
	< 50	Suitable	34	79.1

The abbreviations for the indicators are as follows: Kelley's Index (KI), Soluble Sodium Percentage (SSP) and Magnesium Ratio (MR) town, high levels of EC, TDS and NO_3-N were found, exceeding the guidelines for irrigation use. These levels are likely to be the result of domestic waste and agrochemical run-off [15].

In addition to the IWQI, other indices were calculated to investigate the suitability of water for irrigation purposes. The number and percentage of water samples falling into each irrigation suitability indicator class are shown in Table 8. The classification of each water sample is available in the Supplementary Material (Table S3) and the boxplots per water source are shown in Fig. 6.

Natural waters with a Kelley's Index (KI) greater than 1 have an excess of Na^+ and are therefore considered unsuitable for irrigation. The KI values of the samples ranged from 0.12 to 4.66, of which 67.4% were suitable for irrigation. All the samples classified as unsuitable were found in the central part of the study area (Karanga and Rau catchments), with the highest value found in an irrigation canal in the upper part (CAN_07). This sample was also the only one classified as unsuitable for irrigation (SSP = 83.2%) based on the Soluble Sodium Percentage (SSP), which is also an indicator of the amount of Na^+ in the water that can cause an increase in soil salinity and therefore affect plant growth. The SSP values for the other samples in the study area ranged from 12.3% to 75.2%. With a similar distribution as for the KI, the samples classified as doubtful for the SSP (23.3%) belonged to the central part of the study area (Karanga and Rau catchments). The majority of the samples (about 74%) were classified as of permissible, good or excellent quality (SSP < 60%) for irrigation use. In contrast, most of the samples classified as unsuitable based on the Magnesium Ratio (MR) were found in the eastern part of the study area (Himo catchment, Miwaleni and Lake Chala). An imbalance between Ca^{2+} and Mg^{2+} concentrations towards higher levels of Mg^{2+} tends to deteriorate the soil structure by increasing soil alkalinity. Although the concentrations of Ca^{2+} and Mg^{2+} in the samples were within the reference guidelines (Sect. 3.2), the MR showed that 21% of the samples had an excess of Mg^{2+} relative to Ca^{2+} (MR > 50%). The range of MR was from 12.8% to 75.8% with the highest value found in Lake Chala. The majority of the samples (79%) were classified as suitable for irrigation according to the MR index.

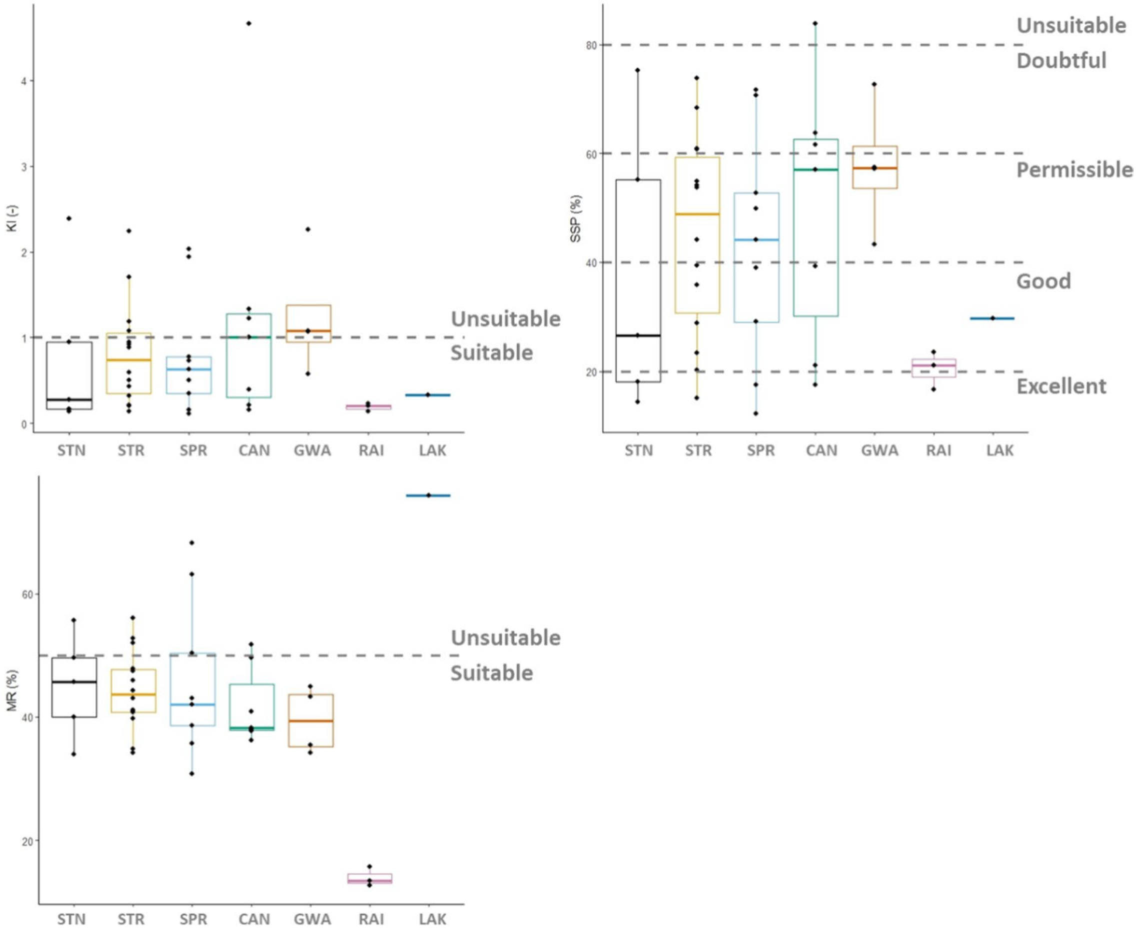


Fig. 6 Boxplots per water source for the irrigation water suitability indicators. The abbreviations of the indicators mean: Kelley's Index (KI), Soluble Sodium Percentage (SSP) and Magnesium Ratio (MR)

4 Conclusions

The results of this study provide an overview of the water quality for drinking and irrigation purposes on the southern slopes of Mt. Kilimanjaro. Water quality was found to be generally unsuitable for drinking due to the presence of faecal contamination in the majority of the samples, including all domestic water. It is recommended that domestic water be regularly monitored and treated for pathogenic bacteria prior to distribution. It would be beneficial to implement public awareness campaigns on the safety, potential hazards and possible treatments of contaminated water resources. Further research is required to identify the sources of faecal contamination and to ensure safe drinking water for the community. The majority of the water samples assessed for irrigation use were found to meet national and international guidelines. However, results revealed potential problems with excess of Na^+ and Mg^{2+}. Analyses of water quality for irrigation need to be complemented by additional specific assessments, such as soil type, structure and composition, crop type and pattern, meteorological variables, etc. Such a holistic approach will facilitate the selection of optimal crops and the identification of appropriate remediation methods.

This study is the first of its kind to assess water quality for human consumption and irrigation on the southern slopes of Mt. Kilimanjaro. We acknowledge the limitations of this study due to the one-time snapshot measurement conducted during the dry season. Conducting regular water sampling campaigns throughout the year would be beneficial to gain additional insight into the temporal variation of water quality. This study also shows that the use of a water quality index is a valuable and flexible tool to summarise the analyses. However, a critical approach to the results and a good understanding of the system are essential to ensure correct interpretation.

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Author contributions All authors (F.C., F.S., L.B., S.M., S.J.) contributed to the study's conception and design. F.C. and F.S. carried out data collection in the field. F.C. analysed the data, wrote the first manuscript draft and prepared all the figures and graphs. All authors (F.C., F.S., L.B., S.M., S.J.) contributed to revising and finalizing the manuscript.

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Data availability All data generated and analysed in this study are included in the "Supplementary Material".

Declarations

Ethics approval and consent to participate Not applicable.

Competing interests The authors declare no competing interests.

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