Hydrogeochemical assessment of streamwater quality for its suitability for irrigation: the case of Manthong village, Kanglung (Bhutan)

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ABSTRACT

Mountain streams/springs are the primary irrigation water resource in Bhutan Himalaya, besides supporting drinking and other domestic needs. Successful crop production implies an adequate supply of high-quality irrigation water, among other factors. Thus, this study was conducted to assess the suitability of spring-fed streamwater for irrigation use and evaluate hydrogeochemical processes that regulate streamwater chemistry at the Manthong village in Kanglung, Bhutan. The water samples were analyzed for temperature, pH, electrical conductivity (EC), turbidity, total dissolved solute (TDS) and major ions. Piper and Durov diagrams indicated that most samples are of the intermediate type and simple dissolution or linear mixing is the primary hydrochemical process regulating streamwater chemistry. All the measured physicochemical parameters were within the acceptable thresholds of the FAO guidelines recommended for agricultural use. Analytical results of the streamwater water quality indices, including EC, %Na, residual sodium bicarbonate (RSBC), sodium adsorption ratio (SAR), Kelley's ratio (KR) and permeability index (PI), revealed its suitability for irrigation use except for magnesium hazard (MH). The Irrigation Water Quality Index (IWQI) results confirmed that the WS-1 has no restriction as irrigation water; however, WS-2 falls under the high-restriction category. The findings of this study will serve as the baseline data and guide irrigation water management and sustainable irrigation development in the region.

Key words: Bhutan Himalaya, hydrogeochemistry, irrigation water quality indices, streamwater

HIGHLIGHTS

- A simple dissolution or linear mixing is the primary hydrochemical process regulating the streamwater chemistry resulting in mixed water type used for irrigation in Manthong village.
- The spring-fed streamwater in the study area is generally fit for irrigational use as per the various irrigation water quality indices except magnesium hazard.
- The IWQI provides easy and usable water quality information.
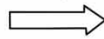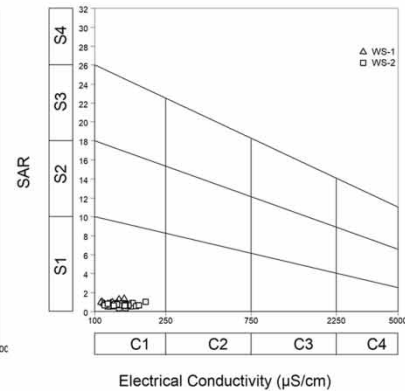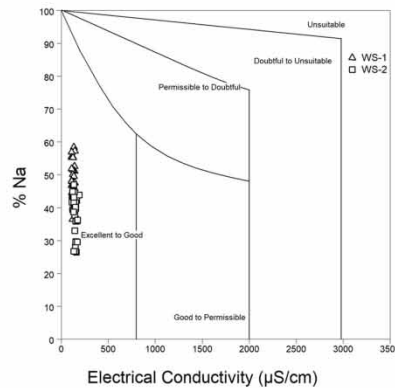
GRAPHICAL ABSTRACT

Stream: Irrigation water

Sample collection and laboratory analysis

Irrigation water Quality Indices & IWQI

Paddy field

1. INTRODUCTION

The Himalayan region is often referred to as the 'Water Tower of Asia' as it is the headwaters for some of the world's largest rivers, such as Brahmaputra and Ganges, draining glacierized basins (Wood *et al.* 2020). However, most of these rivers and streams in headwater catchments are not accessible to farmers because they generally flow at the bottom of gorges and ravines, while settlements and farmlands are on upper slopes and hilltops (ADB 2016). Thereby, mountain springs and streams are traditionally primary source water for millions of people in rural communities of the Himalayas for their drinking, domestic and agricultural needs (Kulkarni *et al.* 2021). As such, mountain springs and streams play a pivotal role in socio-economic development and ensuring food security in the region.

Agriculture and hydropower are two main economic activities in Bhutan. About 58% of Bhutan's population is directly supported by subsistence agriculture, contributing approximately 15% of the nation's GDP (ADB 2016). Bhutanese farmers grow almost all kinds of crops ranging from subtropical to temperate crops. However, the main food crops include rice, maize, wheat and barley. Among the main food crops, terraced rice cultivation constitutes 27.86% of the country's cultivable land, mostly irrigated (Chhogyel & Kumar 2018). Irrigation of paddy is primarily dependent on monsoon recharged spring waters and streams fed by small springs or sourced by snow or glacier meltwaters (Chhogyel & Kumar 2018). In recent years, the Himalayan springs and streams are either becoming seasonal or drying up at an unprecedented rate (Tambe *et al.* 2012; Ansari *et al.* 2015). Besides climate change, anthropogenic activities resulting from population increase and economic development are attributable to a decline in river and stream discharges in the high Himalayas. The water quality of these available freshwaters is also deteriorating due to an alteration in the land use pattern and human activities.

Infiltration of wastewater and septic systems into groundwater aquifers, including agricultural and industrial runoff, is considered the primary source of pollution impacting the water quality of springs and streams, making them unfit for consumption and agricultural use and other purposes (Ansari *et al.* 2015). Climate change and related extreme events exacerbate the water quality trend negatively (Barbieri *et al.* 2021). For instance, increased glacier melting in the Himalayas influences the water chemistry and, in turn, the water quality of glacier-fed rivers and streams (Zhang *et al.* 2015). The accelerated glacier melting due to increasing global temperature may release toxic chemicals as glacier ice may contain a substantial amount of such pollutants that have been stored in the deeper layers of the ice (Kang *et al.* 2019; Tshering *et al.* 2022).

The productivity of irrigated crops depends on a continuous supply of high-quality irrigation water. The utilization of poor-quality waters in irrigation can impact plant growth directly through toxicity or deficiency or indirectly by limiting the availability of nutrients in the soil (Kadyampakeni *et al.* 2018). Thereby, to ensure high-quality crop production, it is imperative to monitor irrigation water quality. The suitability of irrigation water is assessed based on the relative concentration of certain chemical constituents or dissolved ions generally associated with particular irrigation problems or some specific hazard due to their presence (Simsek & Gunduz 2007). The water accrues dissolved ions while routing through geological formations or from anthropogenic sources determining water quality (Aksever 2019; Barbieri *et al.* 2019; Ricolfi *et al.* 2020). The most commonly employed irrigation water quality indices include salinity hazard (SH), sodium percentage (%Na), sodium adsorption ratio (SAR), residual sodium bicarbonate (RSBC), soluble sodium percentage (SSP), magnesium ratio (MR), permeability index (PI) and Kelley's ratio (KR) (Aksever *et al.* 2016; Kadyampakeni *et al.* 2018; Aksever 2019). Moreover, there are guidelines for assessing the suitability of water quality for irrigation developed by the Food and Agriculture Organization (FAO) (Ayers & Westcot 1985).

Despite the heavy dependency on the streams and springs for agricultural purposes and possible anthropogenic pressure, there is no information on the quality of water used for irrigation purposes in Bhutan. Therefore, this study evaluates spring-fed streamwater quality to determine its suitability for irrigation use and investigates hydrochemical processes controlling the streamwater chemistry to determine the possible sources of pollution. Our findings will be helpful for evidence-based decision making and implementing a water resource management plan for sustainable use of spring water for irrigation purposes.
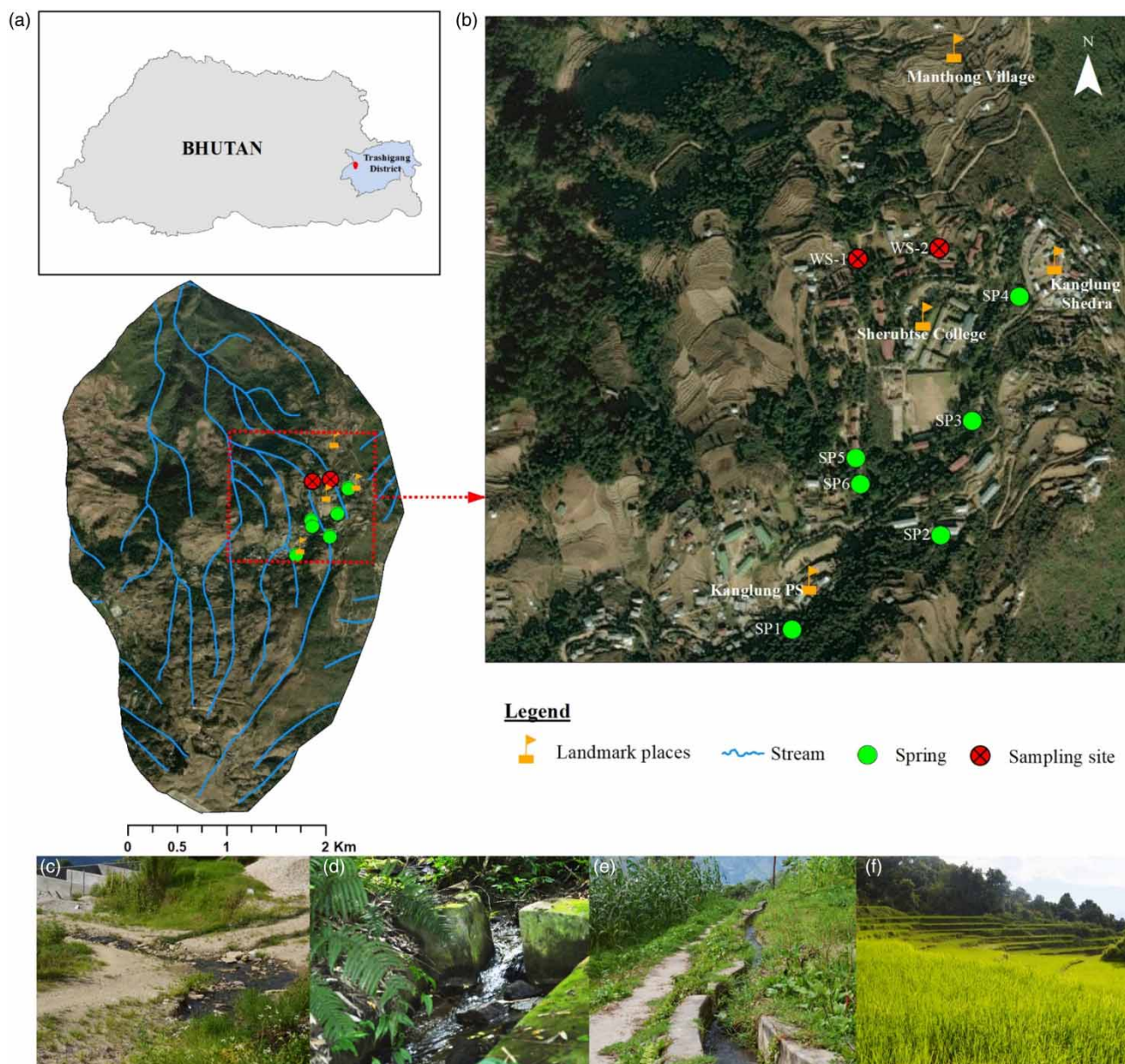
2. MATERIALS AND METHODS

2.1. Study area

The Manthong is one of the nine villages in Kanglung Gewog (the smallest administrative unit consisting of several villages), Trashigang district, Eastern Bhutan, adjoining Sherubtse College on its north side (Figure 1). Kanglung is situated at 1,930 metres above sea level. The area experiences a hydroclimate influenced mainly by the Indian summer monsoon typical of the eastern Himalayas. The monsoon season begins in June, peaks in July–August and ends in September, resulting in peak discharge. Annual rainfall measured at Kanglung climate station during 1996 to 2021 ranges from 885.6 mm to 1,487.3 mm. In 2020 and 2021, the maximum rainfall occurred in May and October, measuring 103.0 mm and 71.8 mm, respectively. The average annual temperature maximum and minimum recorded at the station during 1996–2021 were 21.81 °C and 10.59 °C, respectively. In 2021, the daily temperature ranged between 0.5 °C (December) and 29.0 °C (May) (Figure 2).

The livelihood of farmers in the Manthong mainly depends on subsistence agriculture. Paddy and potatoes are major food crops grown by farmers. The farmers depend on streams fed by small spring waters from the Sherubtse College campus and peripheral areas to irrigate their paddy fields and water their vegetable gardens. Five perennial springs (SP1 to SP6) combine into two small streams at the lower boundary of the College (Figure 1). These streams are then taken to paddy fields in the Manthong village through small concrete canals. The springs SP1, SP2, SP5 and SP6 flow through a natural wetland before the stream outflow is diverted for irrigation. It is noteworthy that domestic wastewater from student dormitories, staff quarters, mess, canteen, and academic buildings, including science laboratories, drains into these streams. Despite this, the wastewater's impact on these streams' quality has remained largely unexplored.

2.2. Water sampling and analysis

Seventy grab streamwater samples were collected weekly from October 2020 through May 2021 at two points (WS-1 and WS-2) upstream of Manthong village (Figure 1). WS-1 was sampled at the stream outflow of the natural wetland fed by springs SP1, SP2, SP5 and SP6, while WS-2 was sampled at the stream fed by spring SP3 and SP4 before the confluence (Figure 1).

Figure 1 | The study site in Kanglung community: (a) regional locator; (b) sampling points and location of Sherubtse College, Kanglung Shedra (monastry), and Manthong village, and location of spring water sources; (c) sampling site WS-2; (d) sampling site WS-1; (e) irrigation channel in the Manthong village; and (f) terraced paddy field in the Manthong village.

One-litre high-density polyethylene bottles (HDPE) were used for collecting the water samples. The sampling bottles were washed with deionized (DI) water and dried before the sample collection. The sampling bottle was also rinsed at least five times with water samples onsite during the sample collection. The HDPE bottle was filled up with a water sample maintaining a positive meniscus and carefully capped, leaving no headspace. Samples were immediately transported to the Center for Science and Environmental Research (CSER) Water Chemistry Laboratory, Sherubtse College, and stored at 4 °C until the analyses.

The water samples collected were analyzed for physicochemical properties such as temperature, pH, electrical conductivity (EC), turbidity, total dissolved solute (TDS), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), acid neutralizing capacity (ANC), chloride (Cl^-), sulphate (SO_4^{2-}), nitrate nitrogen (NO_3^--N), and phosphate (PO_4^{3-})
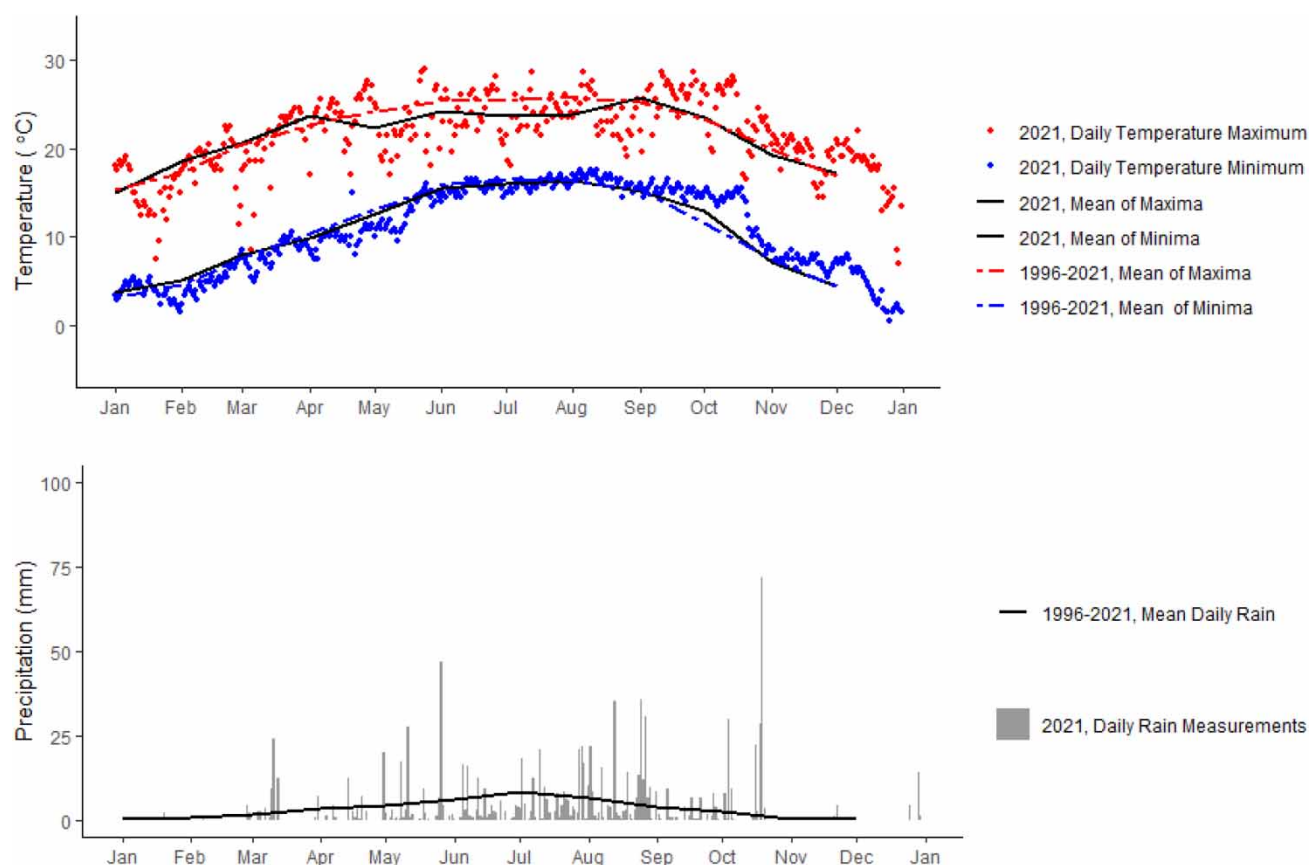
Figure 2 | Hydroclimate data from 1996 to 2021 including 2021 water year indicating annual fluctuations for (top) temperature, and (bottom) precipitation for the study area.

following the standard methods for the analyses of water and wastewater by the American Public Health Association (Baird *et al.* 2017).

The temperature was measured on-site using an Accro-tech AT-272 thermometer. The pH and EC were measured using a Fisher Accumet AB150 pH meter, and a Mettler Toledo-SevenCompact Conductivity meter on the unfiltered samples. Ca^{2+} and Mg^{2+} were estimated by the ethylene diamine tetraacetic acid (EDTA, 0.01M) titrimetric method using Eriochrome Black T and Murexide indicators, respectively. The Na^+ and K^+ were measured with the Flame Photometer 128 (Systronics, India), calibrated according to the manufacturer's specifications, and also blank samples (DI) were measured after every three measurements of samples (Banerjee & Prasad 2020). The Cl^- concentration was analyzed by the argentometric method by titrating against silver nitrate solution (0.014 N), while the gravimetric method was employed to determine the SO_4^{2-} concentration by precipitating $BaSO_4$ using $BaCl_2$ (Belle-Oudry 2008). The ANC (considered to equal bicarbonate alkalinity, HCO_3^-) was measured by the Gran titration technique on a filtered water sample using a Fisher Accumet AB150 pH meter and a micrometer burette-style dispenser (Gilmont GS-1200-A; Cole-Parmer GmbH, Wertheim, Germany), as per the standard operating procedure developed by Arikaree Environmental Laboratory, Institute of Arctic and Alpine Research, University of Colorado, USA. A digital turbidity meter was used to measure the turbidity of the water samples. The gravimetric method was used to determine the TDS of the water samples; samples were filtered through a 0.45 μm cellulose acetate membrane filter before use (Gilmore & Luong 2016). The NO_3^--N and PO_4^{3-} were measured using a UV-Vis spectrophotometer (HACH model: DR6000). The NO_3^--N analysis was performed using the cadmium reduction method (HACH method 8039) using NitraVer 5 nitrate reagent pillows using stored programme 355 N and Nitrate HR PP at a measurement wavelength of 500 nm and a range of 0.3–30.0 mg/L NO_3^--N (Hach Company 2007). The PO_4^{3-} analysis was performed using phosphate reagent powder pillows using stored programme 485 P React. Amino (HACH method 8178) which measures dissolved orthophosphates in a range from 0.23 to 30.00 mg/L (Pritchett & Yuan 2017). The analytical precision of the dissolved

ions dataset was checked by charge balance error (CBE) given by the equation:

$$CBE\% = \frac{mEq \text{ (cations)} - mEq \text{ (anions)}}{mEq \text{ (cations)} + mEq \text{ (anions)}} \times 100 \qquad (1)$$

The CBE values of most of the samples were within the acceptable range of $\pm 10\%$.

2.3. Hydrochemical methods

The streamwater samples were plotted in a Piper trilinear diagram using AqQA software (Figure 3) to understand the stream-water's hydrogeochemical facies and hydrochemical evolution (Piper 1944). The hydrochemical data have been plotted on a Durov diagram (Durov 1948) using AqQA software to verify further the geochemical processes occurring in the streamwater of the study area (Figure 4).

2.4. Streamwater suitability assessment for irrigation

The irrigation water quality was assessed using standard water quality indices available, including EC, percent sodium (%Na), Kelley's ratio (KR), residual sodium bicarbonate (RSBC), sodium absorption ratio (SAR), magnesium hazard (MH) and permeability index (PI). Wilcox and USSL diagrams were also generated using Diagrammes software to evaluate this spring-fed streamwater quality concerning irrigational use (Figure 5).

2.4.1. Salinity hazard

The EC and TDS are important parameters of irrigation water for assessing its salinity hazard as high salt content in water leads to the formation of saline soil where drainage is poor (Tiwari *et al.* 2017). The excessive dissolved salts in irrigation water will negatively affect the growth of the plants directly or indirectly by altering the soil's structure, permeability, and aeration. Based on the classification by the United States' salinity laboratory, irrigation water is classified as excellent or
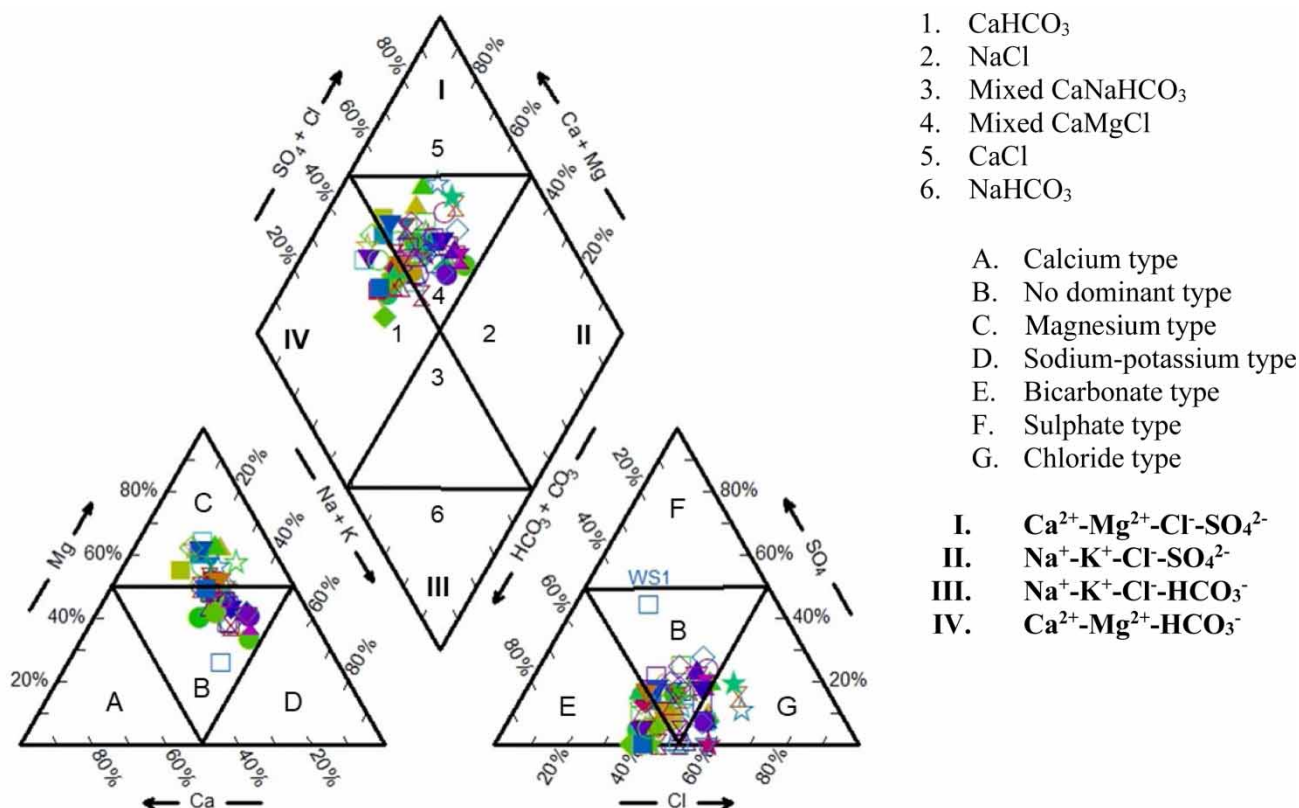

Figure 3 | Piper diagram depicting hydrogeochemical facies of streamwater.
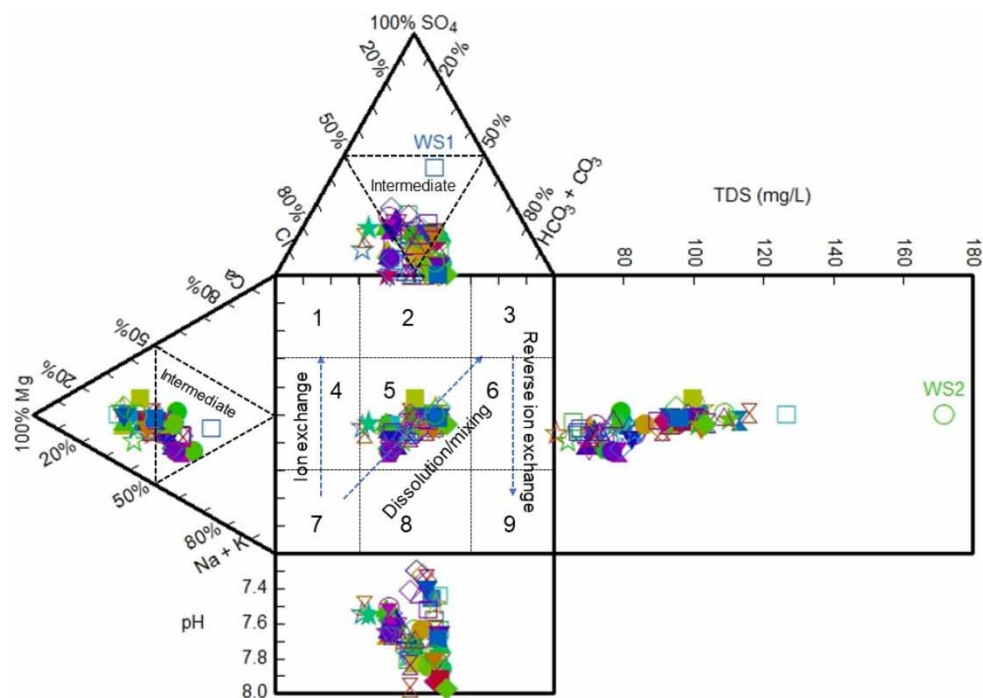
Figure 4 | Durov diagram depicting hydrochemical facies and processes in streamwater.
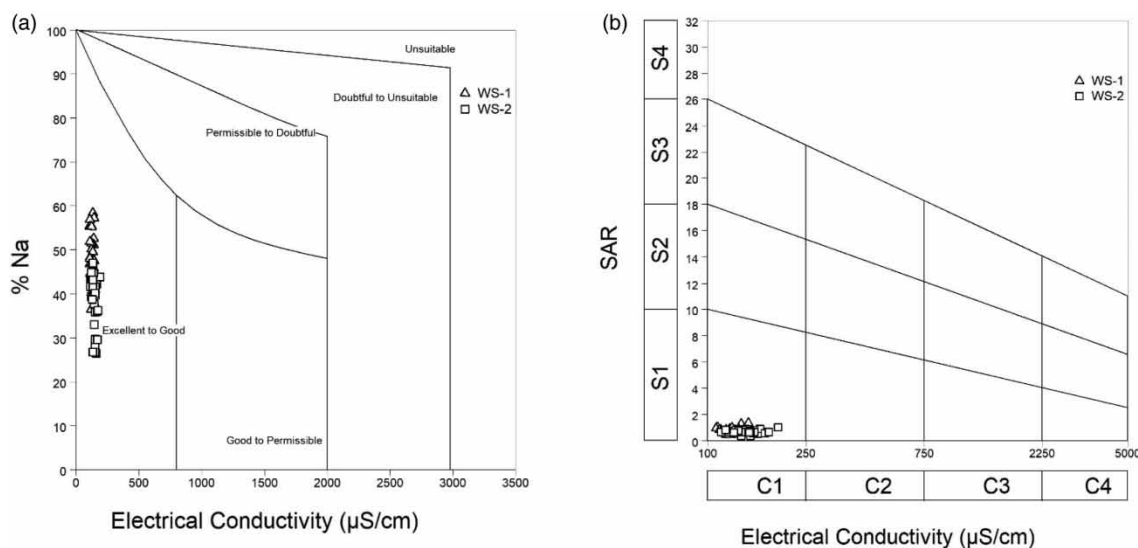

Figure 5 | (a) Classification of streamwaters based on %Na versus EC values (Wilcox plot); (b) classification of streamwater samples in relation to salinity hazard and sodium hazard (USSL).

low salinity class (EC = <250 μS/cm), good or medium salinity class (EC = 250–750 μS/cm), permissible or high salinity (EC = 750–2,250 μS/cm), and unsuitable or very high salinity class (EC = 2,250–5,000 μS/cm) (Richards 1954).

2.4.2. Sodium hazards

High Na concentration in irrigation water makes soil alkaline where it can impair growth affecting crop yields. The Na or alkali hazard of irrigation water is determined by the absolute and relative concentration of cations and is expressed in terms of the sodium absorption ratio (SAR) (Tiwari *et al.* 2017). The SAR index was applied to estimate the rate of Na

adsorption and exchange ratio by water to assess its suitability for irrigation (Richards 1954). The SAR is calculated by Equation (2) where it measures the amount of Na relative to Ca and Mg in water where concentrations are expressed in milli-equivalents per litre (mEq/L). If the water used for irrigation is high in Na and low in Ca and Mg, the cation exchange complex may become saturated with Na, which can destroy the soil structure and plant roots (Kadyampakeni et al. 2018; Mahato et al. 2018). Based on SAR values, irrigation water is categorized into four different alkali waters: excellent (SAR = 0–10) with low Na rate where water poses no risk of exchangeable Na; good (SAR = 10–18) with medium Na rate where long-term irrigation by this water is not advisable; doubtful (SAR = 18–26) where Na rate is intensive and where water is not suitable for irrigation; and poor (SAR > 26) where Na rate is very intensive, indicating water is not at all ideal for irrigation as it can lead to harmful levels of exchangeable Na in soils.

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

Another widely used parameter to characterize sodium hazards of irrigation water is percentage sodium (%Na), also referred to as the soluble sodium percentage (Wilcox 1955). A higher sodium content in irrigation water destroys soil structure and reduces its permeability, impeding water absorption by crops. %Na expresses the percentage of Na out of total cations as shown in Equation (3), where all values are expressed in mEq/L (Shil et al. 2019):

$$\%Na = \left[\frac{(Na^+ + K^+)}{(Ca^{2+} + Mg^{2+} + K^+ + Na^+)}\right] \times 100 \tag{3}$$

2.4.3. United States Salinity Laboratory (USSL) and Wilcox diagrams

To get deeper insights about the suitability of streamwater for irrigational use in the study area, the Wilcox diagram (Wilcox 1955) and the USSL diagram (Richards 1954) were used. These diagrams evaluate the salinity and sodium hazards of irrigation water on soil property better as they are based on multi-parameter criteria. The SAR values were plotted against their corresponding EC values on the USSL diagrams (Richards 1954). The USSL diagram classifies water into 16 classes, i.e., low, medium, high and very high, respectively, on each axis. C is the sign of salinity, and S is the Na content. The Wilcox diagram is based on salinity hazard (EC) and sodium hazard (%Na), which is also used for the determination of irrigation water suitability.

2.4.4. Residual sodium bicarbonate (RSBC)

Irrigation waters with high concentrations of CO_3^- and HCO_3^- have high pH values and make soil infertile due to sodium carbonate deposition (Ehya & Marbouti 2018). As the concentrations of CO_3^- and HCO_3^- increase, so does the potential sodium hazard because of the tendency of Ca and Mg ions to precipitate as carbonates increase which in turn will increase Na in solution. Moreover, higher sodium bicarbonates also affect the uptake of nutrients by plants. However, most of the natural waters do not contain carbonate ions in appreciable quantity, and HCO_3^- ions do not precipitate Mg ions. So, the RSBC has been calculated by Equation (4) where all values are expressed in mEq/L, to determine the hazardous effect of alkalinity or HCO_3^- on irrigation water quality (Gupta & Gupta 1987; Shil et al. 2019). If the RSBC is lower than 5 mEq/L, the irrigation water is classified as satisfactory; if the RSBC is in the range of 5–10 mEq/L, the irrigation water falls under the marginal class; and if the RSBC is above 10 mEq/L, the irrigation water is classified as unsatisfactory (Ghalib 2017).

$$RSBC = (HCO_3^- - Ca^{2+}) \tag{4}$$

2.4.5. Magnesium hazard (MH)

For the growth of plants, Mg is also one of the essential nutrients. A deficiency of Mg causes yellowing and a reduction in the growth and yield of crops (Waraich et al. 2011). Generally, Ca and Mg ions in most waters maintain a state of equilibrium. However, excess Mg relative to Ca in irrigation water causes the soil's physical properties to deteriorate due to the increased Na concentration, resulting in crop failure (Kumar et al. 2007). The relative concentration of Mg to Ca in water decides water

quality and suitability for use in irrigation purposes. MH is an index that measures the effect of Mg in water and assesses its suitability in agriculture. It is calculated using Equation (5), where all values are expressed in mEq/L (Szabolcs & Darab 1964). An MH value greater than 50% is considered harmful and unsuitable for irrigation.

$$MH = \left[\frac{(Mg^{2+})}{Ca^{2+} + Mg^{2+}} \right] \times 100 \tag{5}$$

The streamwater samples were also classified as suitable or unsuitable for irrigation based on the Mg/Ca ratio: safe (<1.5), moderate (1.5–3.0), and unsafe (>3) (Ravikumar *et al.* 2011).

2.4.6. Kelley's ratio (KR)

The KR is used to estimate the harmful effect of Na on irrigation water quality. If KR is more than 1 it indicates an excess of Na; on the other hand, KR less than 1 signifies a deficit of Na in water (Kelley 1963). The KR is computed by Equation (6), where all values are expressed in mEq/L. Based on KR, water can be categorized as suitable (KR < 1), marginal (1 < KR < 2) and unsuitable (KR > 2) (Madhav *et al.* 2018).

$$Kelley's\ ratio = \left[\frac{(Na^+)}{(Ca^{2+} + Mg^{2+})} \right] \tag{6}$$

2.4.7. Permeability index (PI)

The soil permeability can be influenced by the Na^+, Ca^{2+}, Mg^{2+}, and HCO_3^- contents of irrigation water on long-term use (Kumar *et al.* 2007). Doneen (1964) developed a criterion for assessing the suitability of water for irrigation based on PI values. The PI is computed from Equation (7) shown below, and all values are expressed in mEq/L. The irrigation water can be categorized as classes I, II, and III based on PI values. Classes I and II water with 25%–75% or more of maximum permeability are classified as excellent to good for irrigation, while class III water is unsuitable with 25% of maximum permeability.

$$Permeability\ Index\ (PI) = \left[\frac{(Na^+ + \sqrt{HCO_3^-}) \times 100}{(Ca^{2+} + Mg^{2+} + Na^+ + K^+)} \right] \tag{7}$$

2.4.8. Irrigation Water Quality Index (IWQI)

Water quality index has been regarded as an effective tool for monitoring water quality as it provides an overview of the water quality as a summarized composite effect of each parameter to evaluate fitness for various uses (Elemile *et al.* 2022). It defines water quality by a single value, thereby avoiding water quality evaluations involving multiple parameters (Yıldız & Karakuş 2020). In this study, the Irrigation Water Quality Index (IWQI) was calculated based on the five water quality parameters of EC, SAR, Na^+, Cl^-, and HCO_3^- developed by Meireles *et al.* (2010). The value of each parameter estimated on the basis of irrigation water quality parameters recommended by University of California Committee of Consultants (UCCC) and the criteria determined by Ayers & Westcot (1985) was used to evaluate the relative value which provides the basis for this method. Higher values of this water quality parameter (q_i) represented by a dimensionless number are indicative of higher water qualities. Values of q_i were calculated using Equation (8), based on the tolerance limits shown in Table 1 and water quality results determined in the laboratory:

$$q_i = q_{i\,max} - \left[\frac{(X_{ij} - X_{inf}) \times q_{iamp}}{X_{amp}} \right] \tag{8}$$

where q_{max} is the maximum value of q_i for each class (Table 1); X_{ij} is the measured value of each parameter; X_{inf} denotes the lower limit value of the class to which the parameter belongs; q_{iamp} is class amplitude; X_{amp} is the class amplitude to which the parameter belongs. In order to evaluate X_{amp} of the last class of each parameter, the highest measured value is taken into consideration as the highest limit.

Table 1 | Parameter limiting values for quality measurement (q_i) (Meireles et al. 2010)

q_i	EC (μS/cm)	SAR (mEq/L)$^{1/2}$	Na$^+$ (mEq/L)	Cl$^-$ (mEq/L)	HCO$_3^-$ (mEq/L)
85–100	200–750	<3	2–3	<4	1–1.5
60–85	750–1500	3–6	3–6	4–7	1.5–4.5
35–60	1500–3000	6–12	6–9	7–10	4.5–8.5
0–35	<200 or >3000	>12	<2 or >9	>10	<1 or >8.5

The weight of each parameter (w_i) was assigned based on its relative importance in the overall quality of irrigation water as suggested by Meireles et al. (2010), as shown in Table 2. Then, the IWQI value was determined according to Equation (9) taking into account the above-mentioned values of q_i and w_i:

$$IWQI = \sum_{j=1}^{k} q_i \times w_i \tag{9}$$

Based on the calculated IWQI values, the characteristics of irrigation water can be classified into five categories with respect to soil characteristics and plant tolerance: 85–100 (no restriction); 70–85 (low restriction); 55–70 (moderate restriction); 40–55 (high restriction); and 0–40 (severe restriction). These categories are proposed considering the soil salinity risks, problems of decreasing soil water infiltration rate, the problems of toxicity in plants and other various effects on sensitive crops (Meireles et al. 2010).

2.5. Statistical data analysis

One-way analysis of variance (ANOVA) was used to test the significant variations ($p < 0.05$) in mean concentrations of physicochemical parameters measured and irrigation water quality indices determined in water from the two sampling points. All the data analyses were performed using Statistical Package for Social Sciences (SPSS) version 21.

3. RESULTS & DISCUSSION

3.1. Streamwater chemistry

Physicochemical properties and agriculture suitability assessments of irrigation water samples in the study area are illustrated in Table 3. The temperature of the water samples varied from 9 to 17 °C, and the average turbidity values were 9.0 ± 7.7 NTU and 12.9 ± 12.5 NTU for WS-1 and WS-2, respectively. The overall pH of the water samples was found to be neutral (7.30–7.98). The irrigation water samples of the study area had low EC and TDS values in the range 99.7–269.4 μS/cm and 61.3–172.4 mg/L, respectively. The Cl$^-$ was the dominant anion contributing 66.87% of the total anions, followed by SO$_4^{2-}$, PO$_4^{3-}$, NO$_3^-$ and HCO$_3^-$ accounting for 25.1%, 4.4%, 2.3% and 2.0%, respectively. In cation chemistry, Na$^+$ was dominant, accounting for 33.8% of total cations, followed by Mg^{2+} (33.5%), Ca^{2+} (24.4%), and K$^+$ (8.3%). The measured concentration of major ions including pH and EC of the streamwater were within the acceptable thresholds of the FAO and therefore pose no threat to crops (Ayers & Westcot 1985).

Table 2 | Weights for the parameters that are considered in the IWQI model (Meireles et al. 2010)

Parameters	W_i
EC (μS/cm)	0.211
SAR (mEq/L)$^{1/2}$	0.204
Na$^+$ (mEq/L)	0.202
Cl$^-$ (mEq/L)	0.194
HCO$_3^-$ (mEq/L)	0.189
Total	1

Table 3 | Physicochemical properties and agricultural suitability of irrigation samples in the study area

	WS-1				WS-2			
	Avg ($n = 35$)	Max	Min	STDV	Avg ($n = 35$)	Max	Min	STDV
Temp	10.72	14.00	9.00	1.37	13.26	17.00	11.00	1.87
Turb	9.03	31.00	2.00	7.69	12.94	51.00	1.00	12.51
pH	7.65	7.81	7.50	0.09	7.66	7.98	7.30	0.20
EC	117.20	130.80	99.70	8.33	157.97	269.40	121.30	24.10
TDS	75.76	113.79	61.25	8.73	101.10	172.42	77.63	15.42
Ca^{2+}	6.00	10.00	4.00	1.46	8.51	12.00	6.00	1.56
Mg^{2+}	4.83	9.60	2.40	1.41	7.23	13.20	4.80	2.32
Na^+	11.60	18.48	6.19	1.99	11.46	18.51	6.22	2.00
K^+	4.83	5.24	4.13	0.29	4.75	5.24	4.16	0.31
HCO_3^-	714.10	928.84	573.81	118.32	1,270.41	1,438.94	1,022.05	111.80
Cl^-	18.49	26.59	8.86	3.31	19.50	26.59	17.73	3.59
SO_4^{2+}	12.27	34.98	4.12	6.70	11.48	20.58	4.12	5.54
NO_3^-	1.60	2.40	0.74	0.49	0.96	1.30	0.44	0.16
PO_4^{3-}	1.13	6.59	0.41	1.19	1.32	8.94	0.41	1.98
%Na	47.68	58.38	36.39	5.93	38.38	47.05	26.39	5.96
SAR	0.87	1.36	0.46	0.17	0.71	1.04	0.37	0.13
RSBC	0.41	0.60	0.18	0.12	0.85	1.04	0.63	0.11
MH	56.71	74.80	33.10	7.93	57.67	68.52	49.74	5.07
MR	1.39	2.97	0.49	0.50	1.40	2.18	0.99	0.31
KR	0.75	1.19	0.39	0.19	0.51	0.71	0.25	0.13
PI	102.51	117.79	84.28	9.76	100.86	119.11	71.54	12.56

Units: temperature in °C; turbidity in NTU; EC in µS/cm; cations and anions and TDS are in mg/L except for HCO_3^- (µEq/L); %Na, SAR, RSC, MH, MR, KR and PI in mEq/L.

One-way ANOVA revealed that the concentrations of Ca^{2+}, Mg^{2+}, HCO_3^-, NO_3^--N including temperature, EC, turbidity, and TDS measured in WS-1 and WS-2 streamwater samples vary significantly ($p < 0.01$), whereas pH, Na^+, K^+, Cl^-, SO_4^{2-}, and PO_4^{3-} measured did not have significant variation between the two streamwater samples.

3.1.1. Hydrochemical facies

The streamwater samples were plotted in a Piper trilinear diagram using AqQA software (Figure 3) to understand the streamwater's hydrogeochemical facies and hydrochemical evolution (Piper 1944). Two hydrogeochemical facies were identified with a majority of the plotted samples falling on mixed Ca–Mg–Cl type followed by the Ca–HCO$_3$ type. In the cationic field of the Piper diagram, streamwater samples fall into zones A and B, almost equally, showing Mg^{2+} and no dominant cation water types, respectively. Similarly, most of the plotted streamwater samples fall into no dominant zone in the anionic field, followed by zones E and G indicating HCO_3^- and Cl^- anion water types, respectively. As most of the plotted samples occupy zone B, the mixed zone, the streamwater can be identified as neither anion-nor cation-dominant (Ravikumar & Somashekar 2017). However, those water samples falling in Ca–HCO$_3$ type demonstrate the dominance of Ca^{2+} and HCO_3^- ions, indicating sufficient recharge from shallow freshwaters (Kumar *et al.* 2007). Recharging waters are formed when water percolates through the subsurface; it carries dissolved carbonate in the form of HCO_3^- and the geochemically mobile Ca^{2+} accrued mostly from the dissolution of carbonate rocks such as limestone and dolomite (Ravikumar & Somashekar 2017). In general, the Piper diagram also illustrates the dominance of alkaline earths ($Ca^{2+} + Mg^{2+}$) over alkali ($Na^+ + K^+$), and strong acidic anions ($SO_4^{2-} + Cl^-$) exceed weak acidic anions (HCO_3^-). The occurrence of Cl^- and SO_4^{2-} in streamwater could result from anthropogenic input such as domestic sewage, urban and household waste besides weathering of minerals

(Li *et al.* 2015). SO_4^{2-} in streamwater could also result from the interaction of rainwater with soil as recently reported in Chamkhar river basin in Bhutan (Tshering *et al.* 2020; Zakaria *et al.* 2021).

The hydrochemical data have been plotted on a Durov diagram (Durov 1948) using AqQA software to verify further the geochemical processes occurring in the streamwater of the study area (Figure 4). The hydrochemical facies demonstrated by the Durov diagram corroborated the Piper plot, whereby the cation field shows both Mg^{2+} and intermediate types. In contrast, in the anion field, the majority of the plotted samples fall into the intermediate type followed by HCO_3^- and Cl^- types (Figure 4). Almost all the plotted samples are in field 5 in the central rectangle of the Durov diagram (Lloyd & Heathcote 1985), suggesting simple dissolution or linear mixing to be the main hydrochemical processes regulating the streamwater chemistry in the study area (Ghalib 2017; Chegbeleh *et al.* 2020). This streamwater is likely recharged by the rainwater and undergoes rock–water interaction, and mixing with pre-existing groundwater may have influenced the geochemical evolution of the streamwater (Ghalib 2017).

3.2. Suitability for irrigation

The salinity of streamwaters was classified based on the measured EC values (Table 3). The average EC values in water samples for WS-1 and WS-2 were $117.2 \pm 8.33\,\mu S/cm$ and $157.97 \pm 24.10\,\mu S/cm$, respectively, demonstrating that irrigation water is excellent with low salinity hazards. Generally, EC above $750\,\mu S/cm$ hampers crop productivity due to an inability of the plants to compete with ions in the soil solution for water (Abegunrin *et al.* 2016). The SAR classification also showed that the streamwater is in the excellent category, indicating that streamwater in the study area is fit for irrigation purposes with low Na or alkalinity hazard. The average SAR values of the WS-1 and WS-2 were 0.87 ± 0.17 and 0.71 ± 0.13, respectively. The analysis of variance showed that there was significant difference ($p < 0.01$) in SAR values in the WS-1 and WS-2 streamwater samples. The low SAR values are attributed to relatively higher concentrations of the alkaline earth metals than the alkali metals in the study area, demonstrating that the tendency of the irrigation water to enter into a cation - exchange reaction in the soil is minimal (Kadyampakeni *et al.* 2018). This implies that there is little hazard of Na^+ replacing adsorbed Ca^{2+} and Mg^{2+}, and thereby no damage to the soil structure and plant roots. Additionally, the USSL diagram (Figure 5(b)) revealed that 100% of streamwater samples for both WS-1 and WS-2 fall into the C1–S1 class, substantiating that streamwater in the study area is fit for irrigating most soils without causing any infiltration or permeability hazards (Mahato *et al.* 2018). Although the salinities are generally low in the study area, soil characteristics and poor drainage can lead to the retention of salts in the soil zone, thus leading to the accumulation of salts in these soils over the long term. As per the %Na, streamwater in the study area is safe for agricultural use as %Na values are lower than the maximum limit of 60% recommended for irrigation water (Singh *et al.* 2015). Additionally, the Wilcox plot of EC and %Na data also shows that the water samples are excellent to good (Wilcox 1955), substantiating that the streamwater is suitable for irrigation purposes (Figure 5(a)). As there is no imbalance of Na^+ content in the irrigation water, there will be no restriction on air and water circulation in the soil during the wet condition. The ANOVA result showed a significant difference ($p < 0.01$) in the %Na between WS-1 and WS-2 streamwater samples.

The calculated average RSBC values in WS-1 and WS-2 ranged from 0.18 to 0.60 and 0.63 to 1.04, respectively, which were significantly different ($p < 0.01$) (Table 3). The RSBC values are lower than 5 mEq/L, which implies that the risk of sodium carbonate salt accumulation in the soil is low, indicating little hazardous effect of alkalinity on irrigation water quality. Thereby, the streamwater in the study area is safe for irrigational usage (Durov 1948; Ehya & Marbouti 2018). Based on the PI values, 99% of the streamwater samples from WS-1 and WS-2 fall in the excellent category while only 1% fall in the good category, showing the suitability of the streamwater for irrigational usage (Table 3). As expected, the calculated KR values in both WS-1 and WS-2 are also less than 1 (Table 3) demonstrating a low level of Na^+, therefore the streamwater is good for irrigation purposes. The ANOVA result showed a significant difference ($p < 0.01$) in the PI and KR values between WS-1 and WS-2.

In the present study, the MH values of WS-1 and WS-2 varied from 33.10 to 74.80 and 49.74 to 68.52, respectively, however, there was no significant difference ($p = 0.40$) noted (Table 3). In WS-1, about 71% had MH values greater than 50, while 29% had MH values lower than 50, whereas for WS-2, MH values greater than 50 were 89% and MH values lower than 50 were only 11%. A majority of water samples had their MH values greater than 50, indicating that the water is unsuitable for irrigation, and applying such water will adversely influence the yield of the crops. Higher MH values in the present study could be due to the inflow of greywater from mess and dormitories into the streams. A recent study by Radingoana *et al.* (2020) found that 50% of the greywater samples had MH values higher than 50%, demonstrating a need for caution when

greywater is used for prolonged irrigation. Thereby, priority should be more on salt-tolerant crops for the use of these streams as irrigation water. However, based on the Mg to Ca molar ratio classification of irrigation water, 75.7% of water samples belong to the safe (Mg/Ca ratio ranged from 0.49 to 1.48) and 24.29% moderate (Mg/Ca ratio ranged from 1.6 to 2.97) categories. Adsorption of Na by soil and clay minerals is more at a higher Mg/Ca ratio because the bonding energy of Mg^{2+} is less than that of Ca^{2+}, which allows more Na^+ adsorption and happens when the ratio exceeds 4 (Tanvir Rahman *et al.* 2017). Thereby, the study areas have lower Mg/Ca ratios than 4, indicating no threat of infiltration problems for soil from the streamwater.

The IWQI is one of the most effective approaches for evaluating irrigation water quality for policymakers as it provides a clear classification for the irrigation water quality based on its impact on irrigated soil and toxicity to plants (Batarseh *et al.* 2021). In the present study, the IWQI values of WS-1 and WS-2 samples were 87.4 and 53.33, respectively. The IWQI results demonstrated that WS-1 has no restriction as irrigation water, and can be used for almost all soil types with no risks of salinity/sodicity problems (Kelley 1963). However, WS-2 falls under the high-restriction category, indicating that the water can be used in soils with high permeability without compact layers, and a high-frequency irrigation schedule is recommended (Meireles *et al.* 2010). As per the IWQI result, WS-2 water is suitable for irrigation of plants with moderate to high tolerance to salts with special salinity-control practices, except for water with low Na^+, Cl^- and HCO_3^- values. The contribution of the greywater or domestic wastewater from the student mess, dormitories and science laboratories into the WS-2 streamwater sampling site, including construction activities in the vicinity, could have altered the chemical properties of the stream. Relatively better-quality WS-1 streamwater demonstrates that the natural wetland helps improve the water quality by trapping or sinking ions onto wetland soils and accumulating them in the roots and leaves of wetland vegetation (Kinyua 2014). The findings corroborate the previous study in the same area, where the wetland was reasonably efficient in removing hardness, Cl^-, and PO_4^{3-} especially in the dry season (Batarseh *et al.* 2021).

4. CONCLUSIONS

Poor-quality irrigation water affects crop production and degrades soil properties. Periodic monitoring of irrigation water is required to ensure sustainable farmland use. The physicochemical characterization of streamwater is essential to determine the effects of natural processes and human activities to evaluate the suitability of streamwater for irrigation purposes.

All the graphical methods (USSL and Wilcox diagrams) and estimated indices (KR, PI, RSBC, SAR, MR, and %Na) used in irrigation suitability assessment, except MH, suggest that streams are of acceptable quality for irrigation purposes. The IWQI results demonstrated that WS-1 has no restriction as irrigation water, however, WS-2 falls under the high-restriction category, indicating that the water is suitable for irrigation of plants with moderate to high tolerance to salts with special salinity-control practices. Nevertheless, the physicochemical parameters measured in water samples are well within the FAO threshold levels recommended for irrigational use. Piper and Durov diagrams suggested that simple dissolution or linear mixing is the primary hydrochemical process regulating the streamwater chemistry resulting in mixed water type in the study area. Finally, it is concluded that a regular water quality analysis is required to check the suitability of streamwater for irrigation purposes. Our findings also demonstrate the requirement of domestic greywater to be treated before it is finally discharged into the environment to control the potential health risk for humans and ecology.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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