scientific reports

OPEN

Hydro-chemical characterization and irrigation suitability assessment of a tropical decaying river in India

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Water pollution is a major concern for a decaying river. Polluted water reduces ecosystem services and human use of rivers. Therefore, the present study aims to assess the irrigation suitability of the Jalangi River water. A total of 34 pre-selected water samples were gathered from the source to the sink of the Jalangi River with an interval of 10 km and one secondary station's data from February 2012 to January 2022 were used for this purpose. The Piper diagram exhibits that the Jalangi River water is Na^+–HCO_3^- types, and the alkaline earth (Ca^{2+} + Mg^{2+}) outperforms alkalises (Na^+ + K^+) and weak acids (HCO_3^- + CO_3^{2-}) outperform strong acids (Cl^- + SO_4^{2-}). SAR values ranging from 0.35 to 0.64 show that water is suitable for irrigation and poses no sodicity risks. The %Na results show that 91.18% of water samples are good and acceptable for irrigation. RSC levels indicate a significant alkalinity hazard, with 94.12% of samples considered inappropriate for irrigation. PI findings show that 91.18% of water samples are suitable for irrigation. Apart from the spatial water samples, seasonal water samples exhibit a wide variations as per the nature of irrigation hazards. Gibbs plot demonstrates that the weathering of rocks determined the hydro-chemical evolution of Jalangi River water. This study identifies very little evaporation dominance for pre- and post-monsoon water. The analysis of variance (ANOVA) test illustrates that there are no spatial variations in water quality while seasonal variations are widely noted ($p < 0.05$). The results also revealed that river water for irrigation during monsoon is suitable compared to the pre-monsoon season. Anthropogenic interventions including riverbed agriculture, and the discharge of untreated sewage from urban areas are playing a crucial role in deteriorating the water quality of the river, which needs substantial attention from the various stakeholders in a participatory, and sustainable manner.

Keywords Irrigation hazards, River decay, Jalangi River, Monsoonal variation, Saturation index, Principal component analysis, Hierarchical cluster analysis

The availability of water resources is essential for the sustainability of social and economic development worldwide. The need for quality water in adequate quantity to fulfill the demands of people and ecosystems is one of the major issues facing mankind in the twenty-first century[1]. The increased demand for irrigation, drinking, and potable water has stressed the world's freshwater resources including rivers, and lakes[2]. Thus, evaluating water quality is crucial, particularly in highly populated areas that rely on river water supply. The ongoing population growth exerts enormous pressure on the agricultural field for a large quantity of agricultural production[3]. However, before the development of irrigation systems, people relied on rainfall for crop production[4]. Following the green revolution and the development of irrigation systems in agriculture, people depended either on

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groundwater or surface (river, lake, and pond) water for crop production[5]. Hence, river water is an important source of irrigation water nowadays. However, this river's water quality is degrading gradually due to multiple points and non-point sources of pollutants discharged into the rivers[6]. River water is a vital source of irrigation, and its quality influences crop health and crop production[7]. In Bangladesh escalating industrialization coupled with a lack of effective policy implementation increasing river water pollution threatens surface water irrigation[8]. Lu et al.[9] studied that intensive surface water pollution leads to the degradation of grain quality in China. Thus, it is essential to assess the irrigation water quality for the sustainable development of agriculture. A lot of studies have been done previously at the global scale as well as in India. Etteieb et al.[10] used hydrographical methods and the PHREEQC geochemical programme to assess the water quality of the Medjerda River, Tunisia and found that the salt concentration was high in some places and needed immediate attention. Similarly, Misaghi et al.[11] showed a higher variation regarding the irrigation water quality from upstream to downstream of Ghezel Ozan River, Iram. Mandal et al.[12] monitored Ganga River water from 2009 to 2014 to assess the irrigation water quality and found a high chloride concentration. Kumarasamy et al.[13] revealed excellent irrigation water quality apart from some estuarine locations of the Tamiraparani River in southern India. Sarkar and Islam[14] demonstrated that the lower Churni River received industrial effluents from the Darshana sugar mill situated in Bangladesh degrading the irrigation water quality.

The concentration of physicochemical parameters determines the irrigation water quality of a river. However, a higher concentration of these parameters, even a single parameter, can lead to various irrigation hazards in the agricultural field, impacting the sustainability of agricultural developments. In this regard, several hazards (sodicity, alkalinity, permeability, salinity, and magnesium) with several indices such as sodium percentage (%Na), sodium adsorption ratio (SAR), residual sodium carbonate (RSC), permeability index (PI), potential salinity (PS), magnesium hazard (MH), and irrigation water quality index (IWQI) are used globally for evaluating the quality of irrigation water for its suitability[7,15–18].

Jalangi, one of the 'Nadia Rivers' was navigable even in the nineteenth century and first quarter of the twentieth century, and it was in better condition than that of Bhagirathi and Mathabhanga in some years[19,20], and the steamer would go through the river[21]. However, the river has degraded significantly after being disconnected from the Padma. Along with the natural process of closure of off-take, ploughing on banks, improper fishing practices, encroaching river bed, soil cutting from banks by brick kilns, etc., have fastened the decaying process alarmingly[22]. As a result, stagnant water lost its quality to serve its aquatic ecosystem, provide quality water to the villagers on the banks for their domestic uses, and irrigate agricultural lands. Recently, the pollution of the river reached an elevated level. Every year, during a few weeks of monsoon months, filthy black stinking water comes to the river Jalangi through the Suti Nadi[23], a tributary of the Jalangi River.

Jalangi River has been studied by several scholars from different angles. Kumar et al.[24] evaluated spatio-temporal availability and dynamics of groundwater at the Bhagirathi–Jalangi interfluve and commented that groundwater seepage contributes to the baseflow of both rivers. Chatterjee et al.[25] investigated the current conditions and spatial changes and also focused on emerging issues related to riparian wetlands in Bhagirathi–Jalangi interfluve and concluded that accelerated anthropogenic intervention in wetlands requires special attention to ensure ecological sustainability. Sarkar and Das[26] assessed the Jalangi River water quality and ecosystem health and found that the water quality is poor due to its lentic nature. However, the spatio-temporal and seasonal assessment of the water quality of the Jalangi River for irrigation purposes has not been studied yet. Therefore, it would be novel to address the river water chemistry, the evolution of river water and irrigation hazards from an integrated perspective in the context of surface water–groundwater interactions for an anthropogeny-controlled river.

Hence, the present study proceeds to bridge this gap in the existing literature. Thus, the present research aims to address a few objectives–(1) to characterize the water quality in terms of hydro-chemical parameters and ionic chemistry, (2) to trace out the hydro-chemical processes controlling river water, and (3) to assess the water quality for irrigation purposes using irrigation hazards indices. These issues would be explored from a spatial approach (one-time data collected from different monitoring stations from source to mouth), and a temporal and seasonal approach (variations of water quality in a hydrological station). Hence, the present study will be the first scientific attempt to analyze the suitability of Jalangi River water for irrigation from spatial and temporal (seasonal) dimensions. As this region is agro-based, the irrigational water quality analysis would be helpful for the farmers and planners for the sustainable development of agricultural production in the concerned floodplain region. This will ensure the food security of the rural communities in the Jalangi River basin. Thus, sustainable development goals (SDG 8–decent work and economic growth) and SDG 11–sustainable cities and communities) are aimed through the study findings.

Database and methodology

Study area

The river Jalangi, a distributary of the Ganga River and a tributary of the Bhagirathi River in Eastern India (Fig. 1a) maintains a course of 233 km with a catchment area of 4300 km^2 [27]and comes from the extreme north of Nadia district to Swarupganj in West Bengal. However, only 182 km of the river i.e. downstream of the Jalangi–Bhairab confluence at Char Moktarpur village in Nadia district is maintained for only two–three weeks during the monsoon period of a year. The river exhibits a higher sinuosity of 2.67[22]. Several tributaries of the Jalangi River like Chota Bhairab, Sialmari, Suti, Anjana, Saraswati and Kalma collect excess rainwear during the monsoon period (Fig. 1b).

River Jalangi drains the moribund tract of Murshidabad and Nadia district of the deltaic West Bengal. The region is a gently south-sloping monotonous plain scattered with swamps, paleo-channels, oxbow lakes, and meander scars. The region consists of the alluvium of Jalangi formation belonging to the Paleocene to lower Paleocene[28]. The top of the surface is formed by recent alluvium. There is a veneer of highly fertile and productive

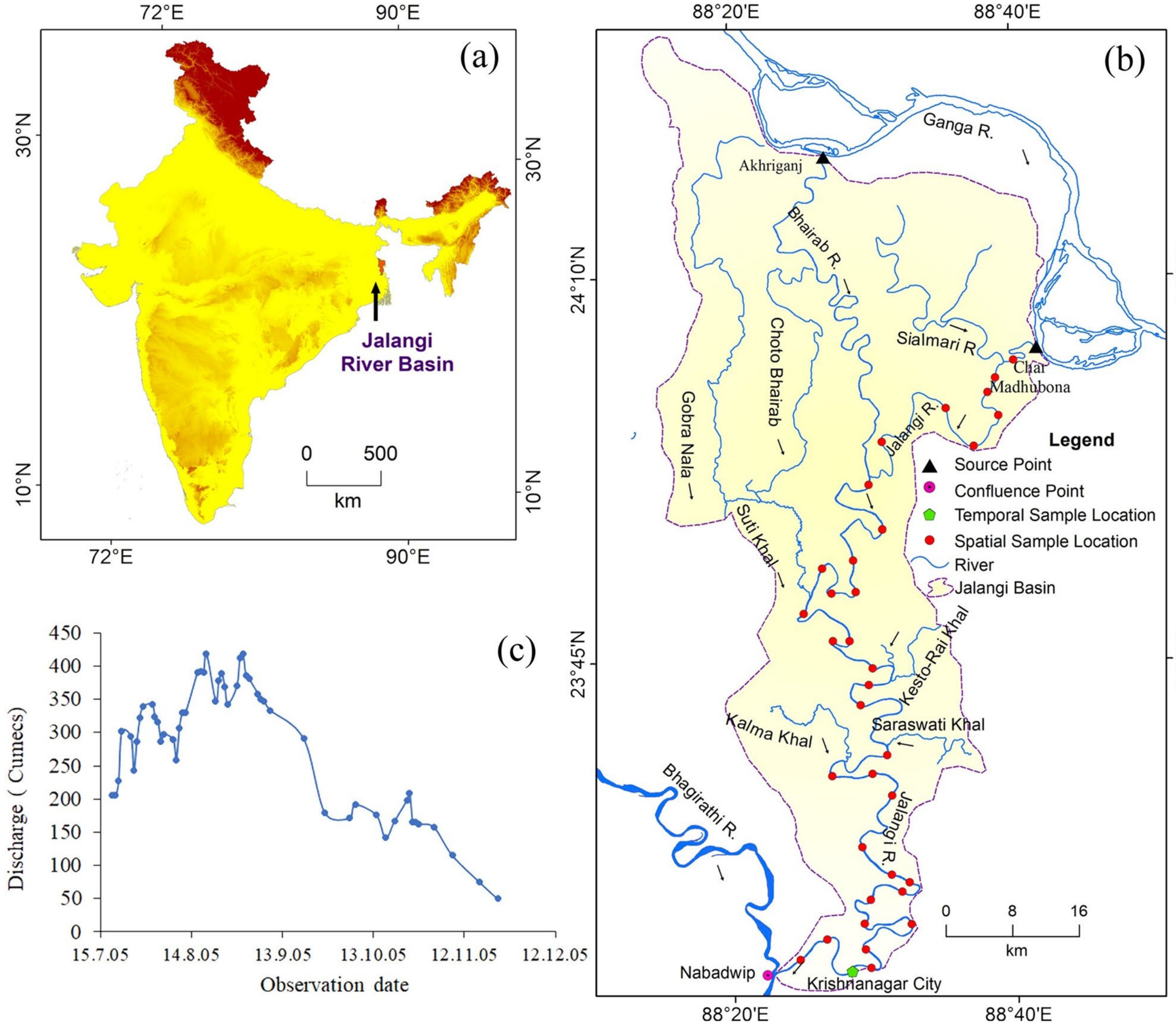

Fig. 1. Locational attributes of the Jalangi River, (**a**) Jalangi River basin in eastern India, (**b**) Jalangi River systems and location of the water samples, (**c**) discharge hydrograph of Jalangi River at Swarupganj (note: spatial sample locations are placed from source to mouth i.e. the uppermost location is S1 and the lowermost point near Nabadwip is S34) (source: prepared by the authors using ArcGIS (version 10.4), Microsoft Office Excel (version 2010) and Adobe Photoshop (version 7.0).

loose silt. The Janalgi–Bhagirathi interfluves are known as 'Kalantar', a low-lying tract of black clay soil with fine external deposits. The soil is azonal in nature and its textural pattern (i.e., sand, loam, clay, sandy loam, loamy sand) varies through the basin, triggering the bank erosion and causing a change in the river course[29]. The slope of the floodplain is from northeast to southwest, influencing the river to flow in the same direction. The slope is very gentle, and the area is interspersed with beels (relict channels of rivers or other waterlogged depressions), jhils (larger beel), marshes, and old beds of rivers and human interference, that the general slope is not easily traceable. The highest elevation of the study area is 20 m at Gopalpur Police Station of Karimpur-I near the abandoned off-take of the river Jalangi. At all other places up to Krishnanagar, height above sea level ranges from 11 to 13 m which decreases gradually to 9 m at Amghata and 6 m at Mayapur ghat (location of a river used for bathing or related activities), opposite Swarupganj near Nabdwip (Fig. 1b).

Typically, the Jalangi basin comes under the tropical monsoon (MON) climate. The average annual rainfall is 1473 mm, of which 68% comes during the MON months (June to September) with a swelling of the river discharge[22] (Fig. 1c). The flat terrain and fertile and productive land have attracted people long ago to settle in the Jalangi floodplain. Here a large ~ 75% of people are engaged in the agrarian economy[22].

Sample collection and analytical design

A systematic sampling design was adopted for the study. A total of 34 water samples were collected from 34 cross-sections (equally spaced at 5 km distance) of the Jalangi River during 10–15 February 2022 (Fig. 1b and Table S1). From the middle portion of each cross-section, one sample was taken. A 51 km upper reach of the river was excluded from sampling because this part is completely dried up and used for agriculture. Then, water samples were tested by the Ramkrishna Ashram Krishi Vigyan Kendra, Nimpith located in South 24 Parganas district, West Bengal. Water samples were taken in prewashed high-density polypropylene (HDPP) bottles as per the American Public Health Association[30]. Two duplicated samples collected from each site were filtered through a 0.45 m membrane filter (MF-Millipore™, USA). Water samples in HDPP containers were refrigerated at 4 °C using cooler box[31]. The cations (K^+, Na^+, Ca^{2+}, and Mg^{2+}) and anions (SO_4^{2-}, Cl^-, HCO_3^-, NO_3^-, and F^-) analysed with the help of ion chromatography dionex ICS-90. The calibration used mixed standard solutions with three concentrations (1, 5, and 20 mg/L). Analytical accuracy was measured with a recognized reference material (Fluka Analytical, Sigma–Aldrich, Germany). Moreover, temporal (February 2012 to January 2022) water quality data for the Jalangi River was taken from an available station immediately downstream of Krishnanagar as measured by the West Bengal Pollution Control Board following APHA standard methods (Table S1). Furthermore, the samples' charge balance error (CBE), ranging from 3.32 to 8.67 (average 8.22%) indicates the preciseness of the analysis as the CBE threshold lies within 10%[14]. The % CBE is computed based on Eq. (1) [32].

$$\%CBE = \frac{TC - TA}{TC + TA} \times 100 \quad (1)$$

where TA and TC depict respective total anion and cation concentrations (mg/L).

Methodology

Irrigation water quality indices

Agricultural practices of the lower Ganga delta are highly dependent on irrigation water during the non-monsoon season[33]. As irrigation water quality affects the soil's response to food production, it becomes imperative to assess the irrigation water quality. Sodium and salinity play an important role in determining water quality which is widely used in assessing river water suitability for irrigation[14]. The following indicators are considered while quantifying irrigation water quality.

Sodium adsorption ratio (SAR). Sodium absorption ratio (SAR) which helps quantify sodium concentration concerning calcium and magnesium, is computed using Eq. (2) [17].

$$SAR = \frac{Na^+}{\sqrt{\left(Ca^{2+} + Mg^{2+}\right)/2}} \quad (2)$$

where Ca^{2+}, and Mg^{2+}, Na^+ represent the concentrations of calcium, magnesium and sodium respectively in water samples.

Sodium percentage (%Na). Percentage sodium (%Na) is computed using Eq. (3) following Richards[34] and Wilcox[35]. Sodium's higher concentration in irrigation water can reduce soil permeability and distress the growth of plant communities[14].

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

where Na^+, K^+, Ca^{2+}, and Mg^{2+} exhibit the sodium, potassium, calcium and magnesium concentrations respectively in water samples.

Residual sodium carbonate (RSC). The sodium carbonate concentration in the river water is computed using Eq. (4).

$$RSC = \left(CO_3^{2-} + HCO_3^-\right) - \left(Ca^{2+} + Mg^{2+}\right) \quad (4)$$

where Ca^{2+}, Mg^{2+}, CO_3^{2-}, and HCO_3^- show the concentration of calcium, magnesium, carbonate, and bicarbonate respectively in water samples.

Permeability index (PI). The PI is computed after Doneen[15] and Raghunath[16] using Eq. (5). The underlying reason for selecting the PI method is that the permeability of soil is significantly affected by the relative ionic concentrations. High sodium levels relative to calcium and magnesium can lead to soil dispersion, reducing permeability and negatively impacting soil structure[14].

$$PI = \frac{\left(Na^+ + \sqrt{HCO_3{}^-}\right)}{\left(Ca^{2+} + Mg^{2+} + Na^+\right)} \times 100 \quad (5)$$

where Na^+, Ca^{2+}, Mg^{2+}, and HCO_3^- denote the concentrations of sodium, calcium, magnesium and bicarbonate in the water.

Salinity hazard. The salinity hazard is generally measured based on EC, TDS, chloride, and sulphate in water. The United States Salinity Laboratory (USSL) used EC and TDS for determining salinity hazard. In the present context, we have used 'chloride plus half of sulphate concentrations' as a measure of the potential salinity (PS)[7].

Magnesium hazard (MH). MH is another key water quality measure to assess the irrigation water suitability of the Jalangi River. The high magnesium content in irrigation water affects soil structure and reduces soil infiltration rate owing to excessive water absorption between magnesium and clay particles. Water contaminated with magnesium affects soil quality and reduces crop production changing soil pH to alkalinity[18]. The MH value, computed using Eq. (6), of less than 50 indicates the irrigation water is safe, but more than 50 indicates unsafe[36].

$$MH = \frac{\left(Mg^{2+}\right)}{\left(Ca^{2+} + Mg^{2+}\right)} \times 100 \quad (6)$$

where Ca^{2+} and Mg^{2+} are calcium and magnesium concentrations in water samples.

Hydro-chemical analysis

The Gibbs plot and the saturation index are valuable tools for studying surface water hydrochemical evolution because they provide a better understanding of the geochemical processes that govern water chemistry.

Gibbs plot. The Gibbs plot was designed specifically for surface water, making it more appropriate for assessing surface water chemistry[37]. However, the same is also applied to groundwater for distinguishing three basic processes: precipitation, rock interactions, and evaporation by graphing $Na^+/(Na^+ + Ca^{2+})$ vs total dissolved solids (TDS) and $Cl^-/(Cl^- + HCO_3^-)$ versus TDS[38]. This distinction is crucial for understanding the genesis and evolution of solutes in the Janangi river water. Water samples falling in the precipitation dominance field are influenced primarily by atmospheric inputs[37]. These waters generally have low TDS values because they have not yet undergone significant interaction with geological formations. In the rock dominance field, water samples exhibit higher TDS values due to interactions with minerals in geological formations. These interactions include processes such as the weathering of rocks, dissolution of minerals, and ion exchange between water and rock materials[39]. The evaporation dominance signifies a hydrochemical condition characterized by elevated TDS and is influenced significantly by evaporation processes[38,40].

Saturation index. Surface water and groundwater hydrochemistry are caused by various mechanisms one of which is rock-water interaction. In the present context, the evolution of Jalangi river water is examined in terms of saturation index (SI) as the Jalangi river water quality is affected by the base flow from groundwater and water coming from the Ganga River system[22]. Rock weathering can be estimated with the help of the SI[41] using Eq. (7).

$$\mathrm{SI} = \frac{KIAP}{KSP} \quad (7)$$

Where KSP denotes the solubility product of that mineral and KIAP denotes the ions activity product for a mineral reaction. For determining the SI of minerals in the water, the PHREEQC programme (version 3.3.7) is beneficial[42]. The SI value illustrates the nature of chemical equilibrium between water and minerals in relation to water–rock interaction. $SI > 0$ denotes the supersaturated condition at which the minerals begin to precipitate, whereas $SI < 0$ denotes the unsaturated states where the minerals are continually eroded by groundwater or surface water. Additionally, SI values near 0 represent mineral phase equilibrium states.

Statistical analysis

Hierarchical cluster analysis (HCA). HCA is applied to make clusters or groups according to the variables' similarity for classifying variables[6]. Here, it is used to classify the different irrigation suitability indices for clustering. HCA was executed by Ward linkage with the Euclidean distance method using the international business machines (IBM) statistical package for social sciences (SPSS) (v.26).

$$\|a - b\|\frac{2}{2} = \sum_i (a_i - b_i)^2 \quad (8)$$

Principal component analysis (PCA). The PCA is used to reduce the amount of multivariate data dimensions and help to alter these data into the principal components without missing information[6]. It is also a popular and operative statistical tool for analysing the irrigation suitability indices to perceive the leading, controlling factor of irrigation water quality. In this regard, PCA was performed by Quartimax with Kaiser normalization using IBM SPSS (v. 26).

$$\mathrm{Zj} = \mathrm{a_{j1}P_1 + a_{j2}P_2 \ldots + a_{jn}P_n \ldots \left(j = 1, 2, \ldots n\right)} \quad (9)$$

where i denotes 1,2, …, n (for "n" variable), j for 1,2…m (for "m" attribute), PCA_r captures factor loadings of a particular stage, λr reflects eigenvalue of a stage and each of the observed variables are considered as linear with regard to the uncorrelated components like P1, P2,…, Pn.

Analysis of variance (ANOVA). ANOVA is a statistical tool that is used to illustrate the variance between two or more variables by significance tests. This statistical analysis technique is also used in the present context to show the significant variation among the spatial and temporal (pre-monsoon as PRM, monsoon as MON, and post-monsoon as POM) irrigation suitability indices with the help of one-way ANOVA in Microsoft Office Excel (v. 2016).

$$F = \frac{MST}{MSE} \quad (10)$$

where F exhibits the coefficient of ANOVA, MST implies the mean sum of all the squares owing to the treatment, and MSE depicts the mean sum of squares owing to an error.

Results

Physicochemical parameters and water facies

Studied physicochemical parameters are compared based on their usual range in irrigation water, prescribed by the Food and Agriculture Organization (FAO)[43]. Results show that the concentration of CO_3^{2-} in the samples (100%) and of K^+ in almost all the samples (spatial = 94.12%, PRM = 97.44%, MON = 87.5% and POM = 100%) exceeded the usual range in the spatio-temporal framework. The higher concentration of carbonate results in soil sodicity and reduced permeability. Moreover, carbonate ions can alkalize the soil, impacting nutrient availability and microbial activity. Potassium is an essential nutrient for plant growth, but high concentrations in irrigation water can lead to soil salinity issues and affect crop yield. The elevated levels of K^+ in the Jalangi River may come from potential sources such as agricultural runoff, and industrial activities. High levels of K^+ in irrigation water can lead to soil salinity, which can negatively impact soil structure, reduce water infiltration, and affect nutrient availability to plants. Moreover, the concentration of HCO_3^- in 20.59%, 7.69%, and 5% of samples exceeded its usual range in spatial, PRM, and POM, respectively. High bicarbonate levels can elevate soil pH, resulting in alkalinity. This can reduce nutritional availability, particularly for micronutrients such as iron, manganese, zinc, and copper, which become less soluble under alkaline conditions. Elevated bicarbonate levels can cause calcium to precipitate as calcium carbonate, limiting soil permeability and altering soil structure[44]. This can cause poor aeration and drainage, making it difficult for roots to obtain water and nutrients[14]. The pH concentration in 2.94% spatial and 2.5% POM samples exceeded its threshold limit for irrigation water. High pH levels can cause nutritional imbalances by making some nutrients unavailable or precipitating them out of solution[45]. For example, iron deficiency is frequent in high-pH soils, causing plant chlorosis (yellowing of the leaves). A neutral pH is frequently best for soil microbial activity. High pH can inhibit microbial activity, influencing processes such as nitrogen fixation and organic matter decomposition, both of which are important for soil fertility[46]. However, the PO_4^{3-} concentration in 35.29% of spatial samples only exceeded its usual range in irrigation water (Table 1).

The spatial distribution of physicochemical parameters exhibits that chemical oxygen demand (COD) concentration is high and NO_3^- concentration is low. In contrast, the variability of K^+ concentration is higher than the other parameters (Fig. 2a). Seasonal distribution shows that the concentration of physicochemical parameters in PRM is high in comparison to the PRM and POM seasons. Concerning all seasons, EC is high and PO_4^{3-} is low among the other parameters (Fig. 2b). Turbidity exhibited higher variations in the MON season. Based on the mean values, the concentration of cationic parameters can be arranged as $Ca^{2+} > Mg^{2+} > Na^+ > K^+$ while the anionic parameters are arranged as $HCO_3^- > CO_3^{2-} > SO_4^{2-} > Cl^- > PO_4^{3-} > F^- > NO_3^-$. Piper trilinear diagram for spatial dynamics shows specific toxicity hazards degree and found that the dominant water facies are HCO_3^-–CO_3^{2-}–SO_4^{2-}–Cl^-–Ca^{2+}. Besides, HCO_3^- is dominant in the anionic triangle, while Ca^{2+} is in the cationic triangle. From the cationic triangle, it was also observed that 50%, 44.12%, and 5.88% of water samples were calcium, no dominant, and magnesium type, respectively. On the other hand, the anionic triangle shows 91.18%, 2.94%, and 5.88% of samples are bicarbonate, sulphate, and no dominated type, respectively. Moreover, the Piper trilinear diagram demonstrates that 91.18%, 2.94%, and 5.88% of samples fall in zones 8, 5, and 9, i.e., sodium-bicarbonate, carbonate hardness, and mixed type, respectively (Fig. 3a). These findings suggest that the

Parameters	FAO[43]	Percentage (%) of samples beyond the ranges			
			Temporal		
		Spatial	Pre-monsoon	Monsoon	Post-monsoon
pH	6.0–8.5	2.94 (1)	0	0	2.5 (1)
EC ($\mu S \cdot cm^{-1}$)	0–3000	0	0	0	0
TDS (mg/L)	0–2000	0	0	0	0
Na^+ (meq/L)	0–40	0	0	0	0
K^+ (mg/L)	0–2	94.12 (32)	97.44 (38)	87.5 (35)	100 (40)
Ca^{2+} (meq/L)	0–20	0	0	0	0
Mg^{2+} (meq/L)	0–5	0	0	0	0
HCO_3^- (meq/L)	0–10	20.59 (7)	7.69 (3)	0	5 (2)
CO_3^{2-} (meq/L)	0–0.1	100 (34)	100 (39)	100 (40)	100 (40)
SO_4^{2-} (meq/L)	0–20	0	0	0	0
Cl^- (meq/L)	0–30	0	0	0	0
NO_3^- (mg/L)	0–10	0	0	0	0
PO_4^{3-} (mg/L)	0–2	35.29 (12)	0	0	0

Table 1. Evaluation of water quality for irrigation use. Note: Figures within parentheses indicate the number of samples (N). *FAO* Food and Agriculture Organization.

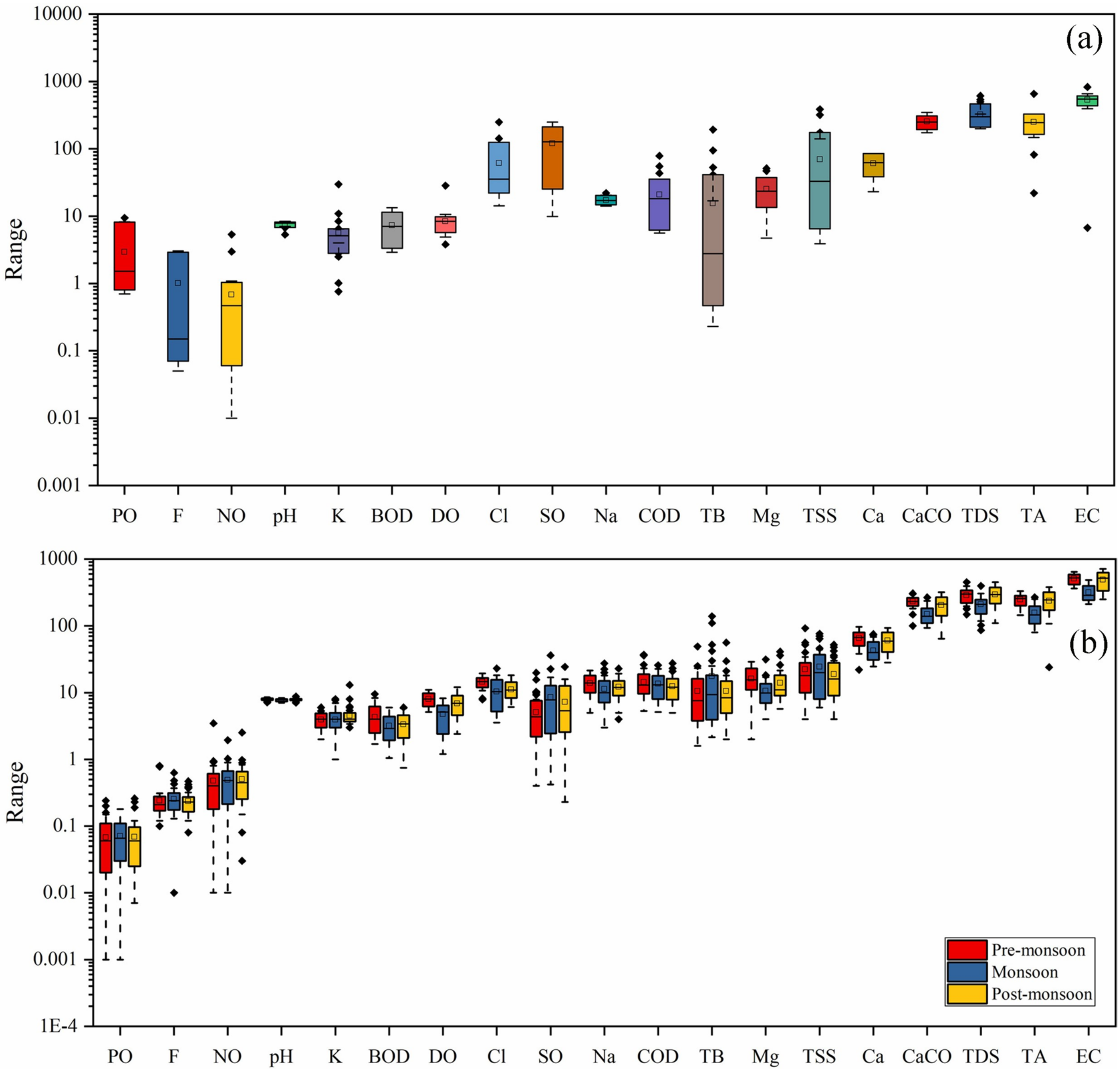

Fig. 2. Distributional nature of the major ionic chemistry, (**a**) spatial variations (N = 34) and (**b**) seasonal variations (N = 39 for pre-monsoon, 40 each for monsoon and post-monsoon) (note: the variables are explained in Sect "Methodology". *PO* for PO_4^{3-}, *F* for F^-, *NO* for NO_3^-, *pH* for potential of hydrogen, *K* for K^+, *BOD* for biological oxygen demand, *DO* for dissolved oxygen, *Cl* for Cl^-, *SO* for SO_4^{2-}, *Na* for Na^+, *COD* for chemical oxygen demand, *TB* for turbidity, *Mg* for Mg^{2+}, *TSS* for total suspended solids, *Ca* for Ca^{2+}, *CaCO* for $CaCO_3$, *TDS* for total dissolved solids, *TA* for total alkalinity, *EC* for electrical conductivity.

alkaline earth ($Ca^{2+} + Mg^{2+}$) outperforms alkalises ($Na^+ + K^+$) and weak acids ($HCO_3^- + CO_3^{2-}$) exceeds strong acids ($Cl^- + SO_4^{2-}$). Furthermore, seasonal dynamics show that all the seasons' water is Na^+–HCO_3^- types as Ca^{2+} dominates in the cationic triangle while HCO_3^- dominates in the anionic triangle (Fig. 3b). Besides, it also observed that a little water is a mixed type, found in the cationic triangle.

Hydrochemical processes controlling river water

Gibbs plot for anion and cation

The Gibbs plot of spatial dynamics shows that 82% and 79% of the waters from the Jalangi River fall into the dominant rock zone for cation and anion, respectively (Fig. 4a, b). For seasonal dynamics, Gibbs plot also shows that almost all water from all the seasons falls into the dominant rock zone for both cation and anion (Fig. 4c, d). This indicates that rock weathering is dominant in controlling hydro-chemical evolution and water quality compared to other factors (evaporation and precipitation). Furthermore, MON water quality is fully controlled by rock weathering while for PRM and POM, very little evaporation dominance is also found for controlling

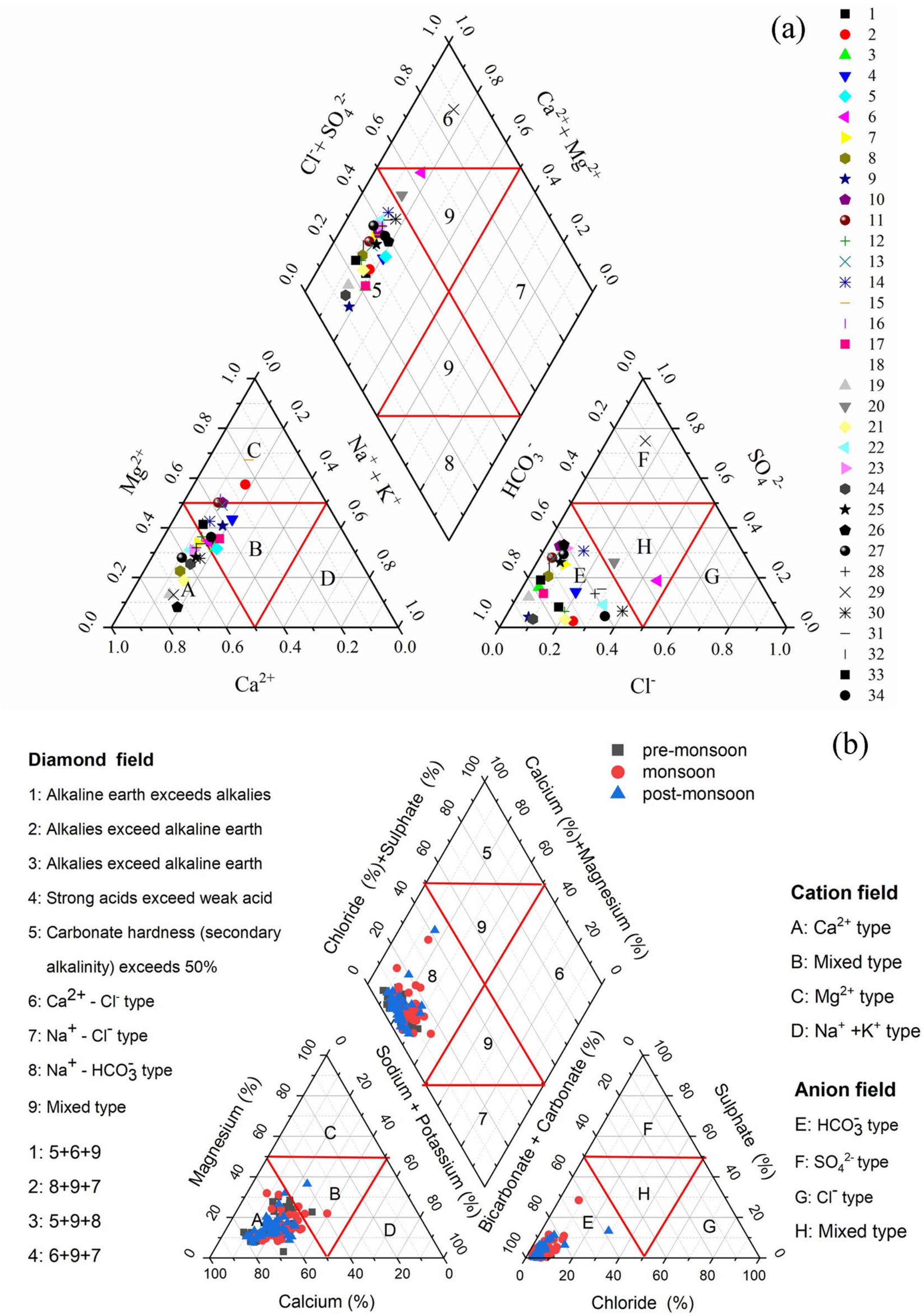

Fig. 3. Hydro-chemical classifications of water sample as per the Piper trilinear diagram, (**a**) spatial dynamics, (**b**) seasonal dynamics.

river water quality. During the PRM and POM seasons even though there is less rainfall, the river experiences high chloride levels. Less rainfall lowers the dilution capacity of the river, which highlights the presence of existing chloride concentrations from natural and anthropogenic sources. Anthropogenic activities like industrial discharge and agricultural runoff introduce significant levels of chlorine into the river[39]. Groundwater interactions are especially important since the baseflow of chloride-rich groundwater in this area raises the levels of chloride in the river[47].

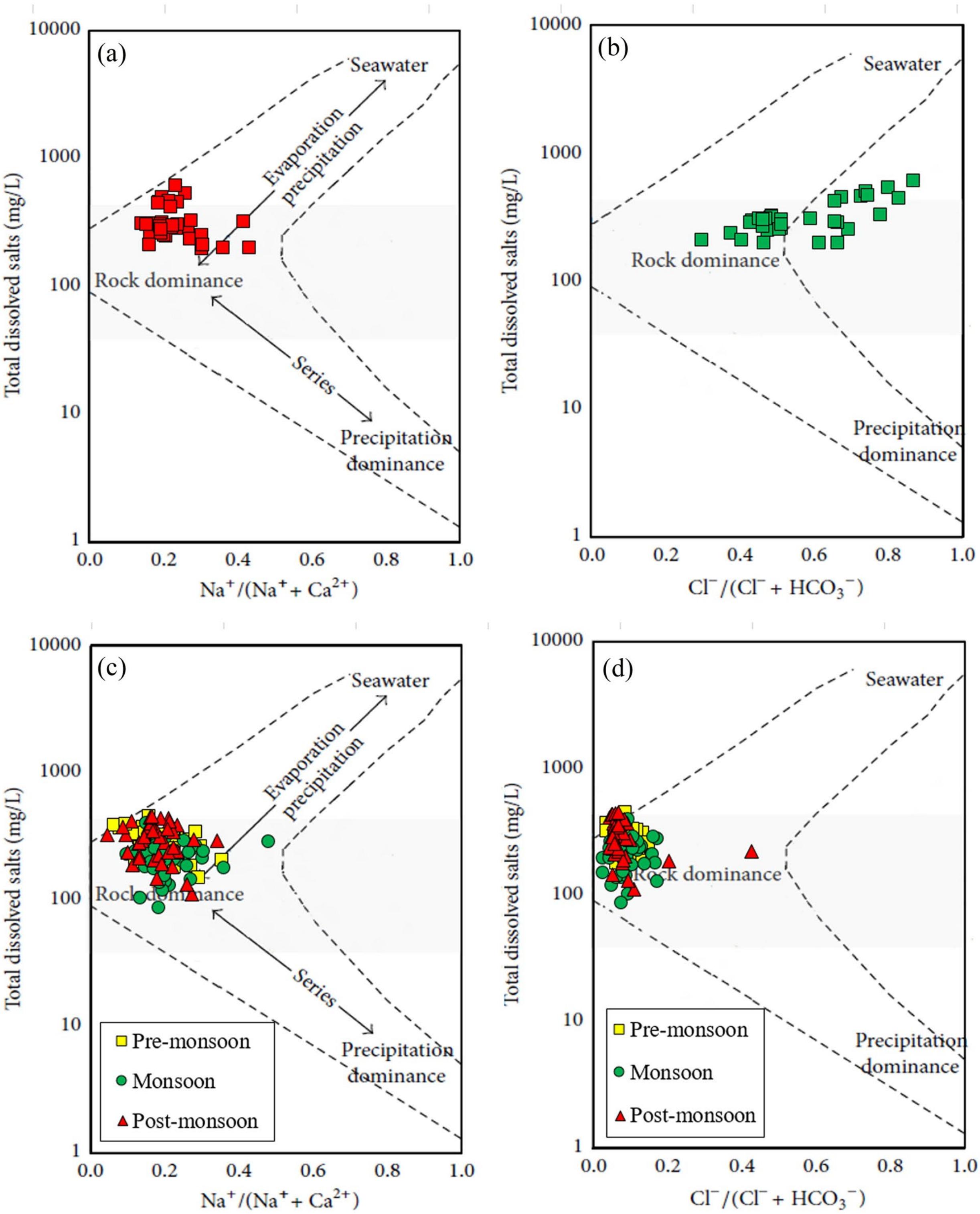

Fig. 4. Gibbs plot for anion and cation (**a**) cations (spatial dynamics), (**b**) anions (spatial dynamics), (**c**) cations (seasonal dynamics), (**d**) anion (seasonal dynamics) (note: 34 samples for spatial variations and seasonal variations (N = 39 for pre-monsoon, 40 each for monsoon and post-monsoon; the variables are explained in Sect "Methodology").

Saturation index and mineral dissolution

This index of every mineral represents the natural process of rock-water interaction, which affects surface water hydrochemistry. All SI_{Halite} recorded negative indicates Na^{+} and Cl^{-} continuously dissolve in the surface water. Similarly, regarding $SI_{Silvite,}$ all values negatively represent sylvite minerals' weathering. $SI_{Calcite}$ and $SI_{Dolomite}$ (except one sample) > 0 indicate the super-saturated status of the carbonate minerals. The $SI_{Calcite}$ and $SI_{Dolomite}$ ranged from 0.06 to 3.41 and − 0.14 to 6.62, with mean values of 2.71 and 5.18, respectively. About 10% of samples record $SI_{Gypsum} < 0$, indicating gypsum dissolution into the water. About 90% of samples record the precipitation status of the gypsum. Gypsum dissolution into groundwater results from the reaction of $CaSO_4{\cdot}2H_2O = Ca^{2+} + SO_4^{2-} + 2H_2O$, which incorporates calcium and sulfate into water[41]. Regarding argonite and anhydrite, about 97% of samples record the $SI_{Argonite} > 0$, and about 80% of samples record $SI_{Anhydrite} > 0$, representing the precipitation status of the minerals in the river water. However, 35% of river water samples represent the dissolution status of fluorite (SI < 0). The concentrations of Ca^{2+}, HCO_3^-, Mg^{2+}, and HCO_3^- were not strongly correlated with $SI_{Calcite}$ and $SI_{Dolomite}$ indicating that the calcite and dolomite weathering did not continue; the mineral will precipitate and may be a negligible part of dolomite will be dissolving. SI_{Halite} is less than 0 and positively associated with TDS (Table 2), while only 12% $SI_{Gypsum} < 0$, and there is no such correlation observed with TDS. The scatter plots of Na^+, Cl^- versus SI_{Halite} and Ca^{2+}, SO_4^{2-} versus SI_{Gypsum}, and the correlation coefficients (R^2) are 0.83, 0.20, 0.33, and 0.59, respectively (Table 2). Exponential intensifications of Na^+, Cl^- and Ca^{2+}, SO_4^{2-} are determined by the dissolution of halite and gypsum, suggesting the dominancy of halite and gypsum minerals along the flow direction.

It has been observed that seasonally the degree of precipitation and dissolution varies from region to region. From PRM to MON, the dissolution intensity decreased for the salt anhydrite and gypsum while it increased for halite and sylvite. Moreover, the precipitation rate also decreased for aragonite, calcite, dolomite, and sylvite. Similarly, regarding MON to POM, the degree of dissolution is decreased for sylvite, halite, and gypsum, while the precipitation rate increased for aragonite, calcite, dolomite and fluorite. The relationship between different ion concentrations and salts also seasonally differs. There is a strong relationship between chloride and dolomite during PRM and MON, while the relationship becomes weak during POM. A similar observation has been found for aragonite salt (Table 3). Some salts (i.e., anhydrite, aragonite, calcite, and dolomite) have a strong relationship with TDS during MON and POM, and no seasonal variation has been found in the relation with fluorite. Throughout all the seasons, the relationship remains strong for sodium and halite, chloride and sylvite, sulphate and anhydrite, and chloride and halite. Some ions and salts have a stronger relationship during MON than in other seasons (calcium and anhydrite, calcium and calcite, sodium and sylvite, aragonite and calcium) (Table 3). Gypsum and calcium have a positive relationship during PRM and POM, while a strong negative relationship is found during MON. During MON, sulphate has a comparatively strong negative relationship with aragonite, calcite and dolomite, while a strong positive relationship has been found with gypsum and anhydrite. Moreover, magnesium and anhydrite, sulphate and fluorite, and magnesium and gypsum have weak relationships throughout the season (Table 3).

Irrigation water quality assessment

River water is an important source of irrigation water. Thus, its assessment is crucial for crop production and cropping health with sustainable irrigation development[7]. In the present study, sodicity (a. SAR b. %Na), alkalinity (RSC), permeability (PI), salinity (PS), and magnesium hazard (MH) are employed to analyse the river's water suitability for irrigation.

Sodicity hazard

(a) SAR indicates the soil's sodium hazard and the irrigation water's suitability. It is also a significant water quality parameter for sodium-affected soil management[48]. Its high concentration in irrigation water distresses soil permeability and salinity. These two jointly affect crop health which reduces crop production. The spatial and seasonal dynamics of SAR are mentioned in Fig. 7a–d and Table 4. The SAR values range from 0.35 to 0.64 ($\overline{x} = 0.47$) with a higher coefficient of variation (CV) (Table 5). Furthermore, the SAR values are classified

Saturation index (SI) of minerals	Range (minimum to maximum)				Average				Standard deviation (SD)			
	Spatial	Pre-monsoon	Monsoon	Post-monsoon	Spatial	Pre-monsoon	Monsoon	Post-monsoon	Spatial	Pre-monsoon	Monsoon	Post-monsoon
$SI_{Anhydrite}$	− 0.9 to 0.81	− 1.88 to − 0.15	− 1.79 to 0.2	− 2.07 to − 0.1	0.24	− 0.90	− 0.73	− 0.84	0.34	0.38	0.44	0.48
$SI_{Aragonite}$	− 0.09 to 3.27	2.51 to 3.5	1.74 to3.47	2 to 3.45	2.57	3.08	2.66	2.95	0.64	0.28	0.43	0.34
$SI_{Calcite}$	0.06 to 3.41	2.65 to 3.64	1.88 to 3.6	2.14 to 3.6	2.71	3.22	2.79	3.10	0.64	0.28	0.43	0.34
$SI_{Dolomite}$	− 0.14 to 6.62	4.62 to 6.86	3.53 to 6.65	3.72 to 6.88	5.18	6.00	5.19	5.70	1.33	0.59	0.84	0.69
$SI_{Fluorite}$	− 0.72 to 2.95	− 0.03 to 2.04	− 2.04 to 1.66	− 0.08 to 1.52	0.81	0.77	0.67	0.81	1.30	0.46	0.56	0.37
SI_{Gypsum}	− 0.65 to 1.05	− 1.63 to 0.11	− 1.58 to 0.43	− 1.73 to 0.15	0.50	− 0.64	− 0.49	− 0.54	0.34	0.39	0.45	0.47
SI_{Halite}	− 5.55 to − 4.27	− 6 to − 5.33	− 6.48 to − 5.07	− 6.23 to − 5.39	− 5.04	− 5.61	− 5.87	− 5.78	0.33	0.19	0.39	0.22
$SI_{Sylvite}$	− 5.66 to − 4.01	− 5.86 to − 5.17	− 6.17 to − 5.17	− 5.85 to − 4.94	− 4.98	− 5.48	− 5.67	− 5.54	0.38	0.16	0.24	0.19

Table 2. Descriptive statistics for saturation indices.

Space/time	Ions	Anhydrite	Aragonite	Calcite	Dolomite	Fluorite	Gypsum	Halite	Sylvite
Spatial	TDS	0.05	−0.45**	−0.45**	−0.46**	−0.18	0.10	0.70**	0.70**
	Sodium	−0.10	−0.04	−0.04	−0.05	−0.49**	−0.09	0.45**	0.56**
	Magnesium	−0.09	0.09	0.10	0.29	0.19	−0.11	−0.13	0.04
	Calcium	0.56**	0.06	0.06	−0.13	0.15	0.58**	0.00	0.15
	Chloride	−0.25	−0.52**	−0.52**	−0.50**	−0.44*	−0.21	0.91**	0.68**
	Sulphate	0.80**	0.08	0.08	0.04	0.55**	0.77**	−0.55**	−0.32
Pre-monsoon	TDS	−0.12	−0.03	−0.03	−0.08	0.25	−0.11	−0.32*	−0.27
	Sodium	0.36*	0.17	0.17	0.21	−0.02	0.36*	0.82**	0.06
	Magnesium	0.03	0.06	0.07	0.45**	−0.31	0.05	0.21	0.29
	Calcium	0.20	0.24	0.24	−0.06	0.41*	0.22	−0.14	−0.31
	Chloride	−0.16	0.38*	0.38*	0.42**	−0.39*	−0.18	0.55**	0.71**
	Sulphate	0.87**	0.04	0.04	0.03	−0.15	0.87**	0.17	0.09
Monsoon	TDS	−0.26	0.35*	0.35*	0.37*	−0.25	−0.27	0.47**	0.27
	Sodium	−0.18	0.45**	0.45**	0.50**	0.14	−0.19	0.86**	0.56**
	Magnesium	0.09	0.28	0.28	0.46**	−0.02	0.08	0.49**	0.21
	Calcium	−0.37*	0.67**	0.68**	0.56**	0.22	−0.37*	0.43**	0.17
	Chloride	−0.24	0.38*	0.38*	0.48**	−0.10	−0.26	0.92**	0.61**
	Sulphate	0.87**	−0.30	−0.30	−0.27	−0.06	0.87**	−0.08	−0.06
Post-monsoon	TDS	−0.22	0.40*	0.40*	0.36*	0.20	−0.17	0.41**	0.20
	Sodium	0.01	0.32*	0.32*	0.41**	−0.03	0.05	0.85**	0.00
	Magnesium	0.07	0.19	0.19	0.35*	0.13	0.12	0.58**	0.04
	Calcium	0.23	0.48**	0.49**	0.35*	0.34*	0.29	0.38*	0.36*
	Chloride	−0.06	0.19	0.19	0.17	0.20	−0.01	0.64**	0.70**
	Sulphate	0.84**	−0.03	−0.04	−0.01	−0.05	0.83**	−0.04	0.03

Table 3. Correlation among the ion concentration and saturation indices. *TDS* total dissolved solids. *Significant at 95% level. **Significant at 99% level.

into four categories, i.e., excellent (SAR < 10), good (10 < SAR < 18), doubtful (18 < SAR < 26), and unsuitable (SAR > 26) for agriculture (Table 5). Analysing the samples, it is found that all the samples (100%) are categorised under the excellent category (Table 5). Furthermore, these findings suggest that 100% water samples are appropriate for irrigation and do not pose any sodicity risks. Besides the spatial variation of SAR, this study has also detected temporal variation from 2012 to 2022. The SAR values were found to be 0.11 to 0.99 ($\overline{x} = 0.39$) with CV 33.07% from 2012 to 2022. While for seasonal variation, they range from 0.14 to 0.66 ($\overline{x} = 0.402$) with CV 30.8 in the PRM, 0.11 to 0.99 ($\overline{x} = 0.400$) with CV 39.38 in the MON and 0.11 to 0.59 ($\overline{x} = 0.37$) with CV 28.31 in the POM season (Table 6). Based on the SAR values, it was observed that the sodicity hazard in the PRM was highly flowed by MON and POM seasons. Moreover, through categorical classification of SAR values, it was also observed that water (100%) is excellent for agricultural use and free from sodicity hazards in all seasons. Furthermore, the United States Salinity Laboratory (USSL) diagram has been used to represent the river water suitability for irrigation. Fig demonstrates that all the water for spatial and seasonal dynamics lay under S1, i.e., low sodium (alkali) hazard (Fig. 5a, b).

(b) %Na is a significant water quality parameter indicating sodicity hazard and irrigation water suitability. This study found that the %Na ranged from 10.16 to 20.81 ($\overline{x} = 15.09$), and the CV is 19.06 (Table 5). Based on the irrigation suitability (Table 5), %Na is classified into five categories, i.e., excellent (< 20), good (20–40), permissible (40–60), doubtful (60–80), and unsuitable (> 80). According to the %Na classification, it was observed that 91.18% of water samples come under the excellent and 8.82% are under the good category (Table 5). Hence, all samples are suitable for irrigation in terms of irrigation suitability. Besides the spatial variation, temporal variation of %Na has also been measured from 2012 to 2022 in this study. The %Na values range from 5.56 to 30.30 ($\overline{x} = 14.75$) with CV 29.82% from 2012 to 2022. Although they range from 5.83 to 25.26 ($\overline{x} = 13.55$) with CV 30.14 in the PRM, 5.56 to 30.30 ($\overline{x} = 16.57$) with CV 27.59 in the MON and 7.68 to 23.29 ($\overline{x} = 14.11$) with CV 28.49 in the POM season (Table 6). According to the %Na means values, it was found that the sodicity hazard was high in the MON while low in PRM seasons. Moreover, in the categorical classification of %Na values for irrigation suitability, it was also found that 92.31, 80 and 90% of water are excellent, while 7.69, 20 and 10% of water are good in PRM, MON, and POM, respectively. These results also indicate that water is free from seasonal sodicity hazards. Further, the Wilcox diagram is used to classify the suitability of Jalangi River water and found that all river water is within the excellent category throughout the spatial and temporal (seasonal) dimensions (Fig. 5c, d).

Alkalinity hazard

RSC is a crucial water quality parameter used to measure alkalinity hazards which affects crop growth by hampering water supply to its root. The RSC of the samples ranges from – 3.54 to 36.39 meq/l ($\overline{x} = 11.47 meq/l$) with

Variables	Spatial		Pre-monsoon		Monsoon		Post-monsoon	
	Equation	R^2 with significance	Equation	R^2 with significance	Equation	R^2 with significance	Equation	R^2 with significance
SAR	$y = 57.878x^{-0.08}$	0.2301**	$y = 18.411e^{0.0916x}$	0.3785	$y = 9.7869\ln(x) + 25.242$	0.5159*	$y = 1.7x + 28.05$	0.527*
%Na	$y = 19.207x^{-0.099}$	0.2143**	$y = 0.1872\ln(x) + 14.276$	0.001	$y = 12.584x^{0.1704}$	0.3512	$y = 1.7427\ln(x) + 11.476$	0.2968
MH	$y = 50.164e^{-0.016x}$	0.1579*	$y = 26.378x^{-0.045}$	0.0491	$y = 31.318x^{-0.079}$	0.065	$y = 20.103e^{0.0581x}$	0.6696**
RSC	$y = -0.425\ln(x) + 12.58$	0.0034	$y = -2.4935x + 35.74$	0.1059	$y = 0.6199\ln(x) + 5.9431$	0.1736	$y = 0.6199\ln(x) + 5.9431$	0.1736
PI	$y = -4.996\ln(x) + 75.139$	0.1285	$y = 6.1345e^{0.246x}$	0.1246	$y = 83.623x^{-0.036}$	0.1905	$y = -0.3451x + 70.88$	0.0447
PS	$y = 2.1938e^{0.0127x}$	0.1276	$y = 0.4169e^{0.0176x}$	0.1007	$y = 0.4169e^{0.0176x}$	0.1007	$y = 0.3421e^{0.0196x}$	0.0828

Table 4. Best-fit regression line with significance level. Note: the variables are explained in Sect "Methodology". *0.05 Significance level. **0.01 Significance level.

Variables	Range	Water class	Number of samples (%)	Descriptive statistics		
				Range	Mean	CV
%Na	< 20	Excellent	31 (91.18)	10.16–20.81	15.09	19.06
	20–40	Good	3 (8.82)			
	40–60	Permissible	–			
	60–80	Doubtful	–			
	> 80	Unsuitable				
SAR	< 10	Excellent	34 (100)	0.35–0.64	0.47	15.24
	10–18	Good	–			
	19–26	Doubtful	–			
	> 26	Unsuitable	–			
RSC (Meq/l)	< 1.25	Good	1 (2.94)	− 3.54–36.39	11.47	54.40
	1.25–2.50	Doubtful	1 (2.94)			
	> 2.50	Unsuitable	32 (94.12)			
PI (%)	<80 (>75% of maximum soil permeability)	Good	31 (91.18)	27.81–88.51	62.12	19.31
	80–100 (25 – 75% of maximum soil permeability)	Moderate	3 (8.82)			
	>100 (<25% of maximum soil permeability)	Unsuitable	–			
PS (Meq/l)	< 3	Excellent to good	20 (58.82%)	1–7.58	2.97	42.07
	3–5	Good to injurious	13 (38.24%)			
	> 5	Injurious to unsatisfactory	1 (2.94%)			
MH (%)	< 50	Acceptable	26 (76.47%)	10.16–78.66	40.98	36.29
	> 50	Non-acceptable	8 (23.53%)			

Table 5. Spatial classification of water for irrigation use. Source: computed by authors, 2022; note: the variables are explained in Sect "Methodology"; thresholds of water class are based on previous works[49,50].

a higher CV (54.40%). A high CV and outlier of RSC values indicate that the spatial variability of RSC is high among the other indices (Fig. 6a). Based on irrigation water suitability (Table 5), the RSC values can be classified as good (RSC < 1.25), doubtful (1.25 < RSC < 2.5), and unsuitable (RSC > 2.5). Based on this classification, 94.12% of water samples were found unsuitable for irrigation use, while 2.94% of water samples were found as good and doubtful (Table 5). Besides the spatial variation of RSC, in this study, temporal variation has also been measured from 2012 to 2022. The RSC values vary from 1.45 to 14.82 meq/l ($\overline{x} = 9.01$meq/l) with CV 32.07 from 2012 to 2022. While for seasonal variation, they vary from 4.62 to 14.11 meq/l ($\overline{x} = 10.77$meq/l), 4.22 to 12.32 meq/l ($\overline{x} = 6.88$meq/l) and 1.45 to 14.82 meq/l ($\overline{x} = 9.43$meq/l) with CV 17.75, 28.87, and 33.26% in the PRM, MON, and POM seasons, respectively (Table 6). It was observed that the Alkalinity hazard was high in the PRM. In contrast, low in MON seasons (Fig. 6b). Moreover, according to the categorical classification of RSC values for irrigation suitability, it was also observed that the water is not suitable for irrigation use in all seasons. However, only 2.5% of water is doubtful in POM. These results also indicate that water is not free from Alkalinity hazards in all seasons.

Permeability hazard
PI is a significant water quality parameter to evaluate irrigation water suitability. In the present study, the PI values are calculated to measure the suitability of the Jalangi River for irrigation. Results show that PI values ranged from 27.81 to 88.51% (62.12% mean) with a lower CV value. PI is classified into three classes- PI <80% (class 1) as good (>75% of maximum soil permeability); PI 80-100% (class 2) as moderate (25 – 75% of maximum soil permeability); PI>100% (class 3) as poor (<25% of maximum soil permeability) (Table 5). Based on these classifications, it was found that 91.18% of water samples were good, and 8.82% of water samples were moderate for irrigation use (Table 5). In the temporal scale, the PI values are found to be 55.19 to 104.46 ($\overline{x} = 71.46$) with CV 15.54 from 2012 to 2022. Although they range from 55.19 to 104.46 ($\overline{x} = 65.95$) with CV 13.73 in the PRM, 59.22 to 97.67 ($\overline{x} = 79.30$) with CV 11.67 in the MON and 55.22 to 91.23 ($\overline{x} = 68.98$) with CV 15.05 in the POM season (Table 6). Based on PI mean values and box plots, it was found that the permeability hazard was high in the MON. In contrast, low in PRM seasons (Fig. 6b). Moreover, in the categorical classification of PI values for irrigation suitability, it was also found that 94.87, 47.5, and 82.5% of water was good in PRM, MON, and POM, respectively (Table 6). In comparison, only 2.5% of water is unsuitable in PRM season. These results indicate that water is free from permeability hazards in PRM and POM seasons (Fig. 7a–d; Table 4).

Salinity hazard
PS is used as a water quality parameter to indicate irrigation water's suitability. The result shows that the PS values were 1 to 7.58, with a mean value of 2.97 (Table 5). The calculated CV value of PS (42.07) was very high, indicating more variability of the PS values. From the observed PS value, it was found that 58.82%, 38.24%,

						Descriptive statistics								
			Number of samples (%)			Range			Mean			CV		
Variables	Range	Water class	Pre-monsoon	Monsoon	Post-monsoon	Pre-monsoon	Monsoon	Post-monsoon	Pre-monsoon	Monsoon	Post-monsoon	Pre-monsoon	Monsoon	Post-monsoon
%Na	< 20	Excellent	36 (92.31)	32 (80)	36 (90)	5.83–25.26	5.56–30.30	7.68–23.29	13.55	16.57	14.11	30.14	27.59	28.49
	20–40	Good	3 (7.69)	8 (20)	4 (10)									
	40–60	Permissible	–	–	–									
	60–80	Doubtful	–	–	–									
	> 80	Unsuitable	–	–	–									
SAR	< 10	Excellent	39 (100)	40 (100)	40 (100)	0.14–0.66	0.11–0.99	0.11–0.59	0.4	0.4	0.37	30.8	39.38	28.31
	10–18	Good	–	–	–									
	19–26	Doubtful	–	–	–									
	> 26	Unsuitable	–	–	–									
RSC (Meq/l)	< 1.25	Good	–	–	–	4.62–14.11	4.22–12.32	1.45–14.82	10.77	6.88	9.43	17.75	28.87	33.26
	1.25–2.50	Doubtful	–	–	1 (2.5)									
	> 2.50	Unsuitable	39 (100)	40 (100)	39 (97.5)									
PI (%)	<80 (> 75% of maximum soil permeability)	Good	37 (94.87)	19 (47.5)	33 (82.5)	55.19–104.46	59.22–97.67	55.22–91.23	65.95	79.3	68.98	13.73	11.67	15.05
	80-100 (25–75% of maximum soil permeability)	Moderate	1 (2.56)	21 (52.5)	7 (17.5)									
	>100 (< 25% of maximum soil permeability)	Unsuitable	1 (2.56)	–	–									
PS (Meq/l)	< 3	Excellent to good	39 (100)	40 (100)	40 (100)	0.25–0.61	0.15–0.73	0.22–0.60	0.46	0.38	0.39	18.09	41.1	26.74
	3–5	Good to injurious	–	–	–									
	> 5	Injurious to unsatisfactory	–	–	–									
MH (%)	< 50	Acceptable	39 (100)	40 (100)	38 (95)	6.90–47.95	16.39–48.70	14.15–60.39	29.45	29.57	27.54	39.12	32.41	32.61
	> 50	Non-acceptable	–	–	2 (5)									

Table 6. Temporal classification of water for irrigation use. Source: computed by authors, 2022; note: the variables are explained in Sect "Methodology"; thresholds of water class are based on previous works[49,50].

and 2.94% of studied water samples came under the excellent to good, good to injurious, and injurious to unsatisfactory categories, respectively (Table 5). Besides the spatial variation of PS, temporal variation has also been analysed from 2012 to 2022 in this study (Fig. 7a–d; Table 4). The PS values range from 0.15 to 0.73 meq/l ($\overline{x} = 0.41 meq/l$) with CV 30.12 from 2012 to 2022. While for seasonal variation, they range from 0.25 to 0.61 meq/l ($\overline{x} = 0.46$meq/l) with CV 18.09 in the PRM, 0.15 to 0.73 ($\overline{x} = 0.38$meq/l) with CV 41.10 in the MON and 0.22 to 0.60 ($\overline{x} = 0.39$meq/l) with CV 26.74 in the POM season (Table 6). According to the PS mean values, it was observed that the salinity hazard in the PRM was highly flowed by POM and MON seasons (Fig. 6b). Moreover, through categorical classification of PS values, it was also observed that water (100%) is excellent to good for agricultural use and free from salinity hazard in all seasons. Furthermore, the USSL diagram is utilized to estimate the suitability of river water for agriculture. According to this diagram, it was found that almost all water samples throughout the river are in C2, i.e., medium salinity hazard (Fig. 6a). However, seasonally, maximum water samples of PRM and POMs lay in C2. However, the water of MON comes within C1 to C2, i.e., low to medium salinity hazard (Fig. 6b). The seasonal dynamics results indicate that the MON season has a lower salinity hazard compared to the other seasons. These findings show that Jalangi River water has a medium salinity hazard in terms of irrigation suitability.

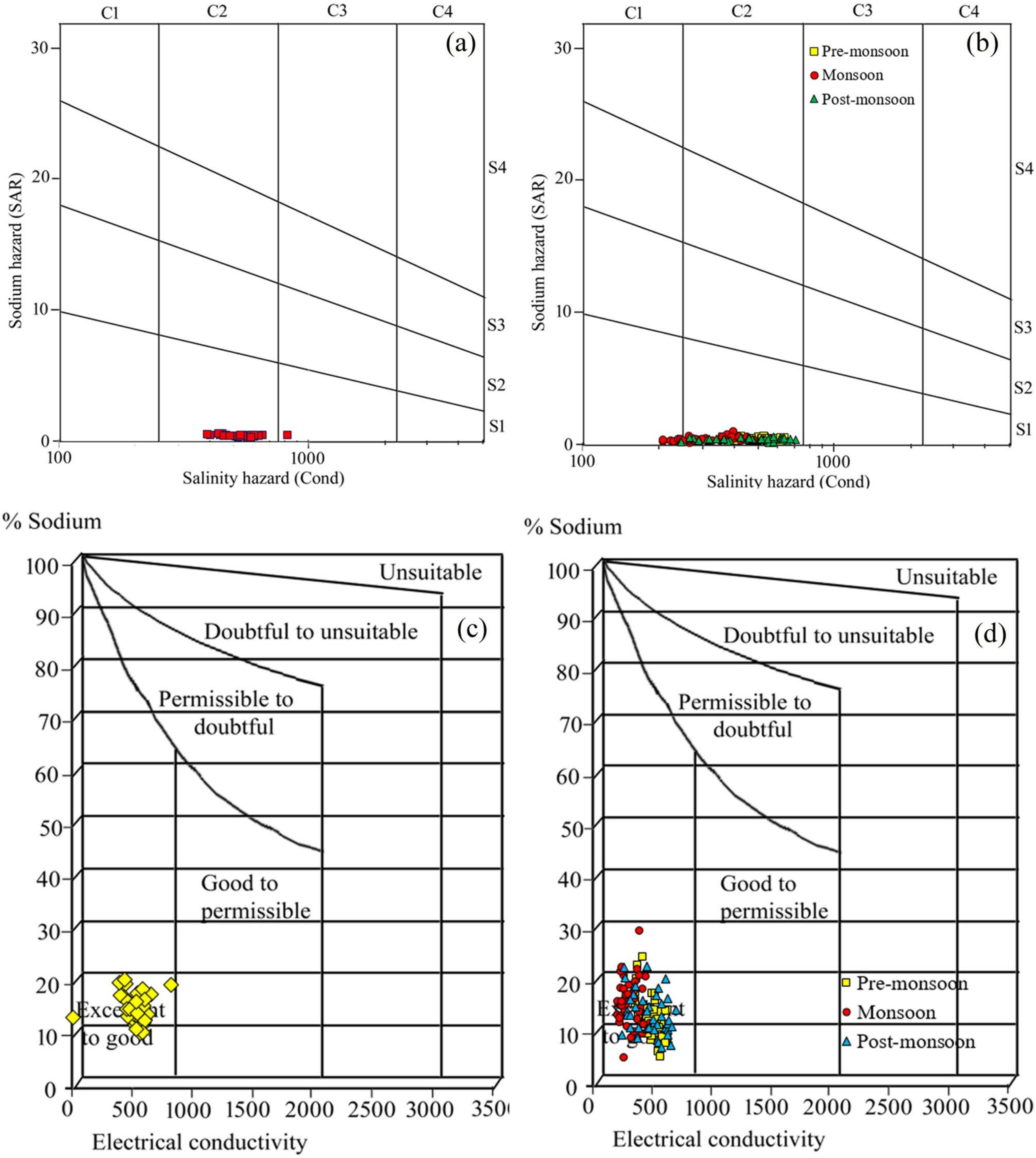

Fig. 5. Water suitability for irrigation, (**a**) United States (U.S) Salinity Laboratory diagram (spatial dynamics), (**b**) U.S Salinity Laboratory diagram (seasonal dynamics), (**c**) Wilcox diagram (spatial dynamics), (**d**) Wilcox diagram (seasonal dynamics) (note: total samples (N = 34) for spatial variations and seasonal variations (N = 39 for pre-monsoon, 40 each for monsoon and post-monsoon).

Magnesium hazard

The result shows that the MH values of samples ranged from 10.16 to 78.66 ($\overline{x} = 40.98$) with a lower CV value (36.29%) (Table 5). Moreover, 76.47% of samples lay within safe limits, while 23.53% of water samples lay unsafe for irrigation use in the study area. Besides the spatial variation of MH in this study, temporal variation has also been measured from 2012 to 2022. The MH values vary from 6.90 to 60.39 ($\overline{x} = 28.85$) with CV 34.77 from 2012 to 2022. Although they vary from 6.90 to 47.95 ($\overline{x} = 29.45$), 16.39 to 48.70 ($\overline{x} = 29.57$) and 14.15 to 60.39 ($\overline{x} = 27.54$) with CV 39.12, 32.41, and 32.61% in the PRM, MON, and POM seasons respectively (Table 6). It

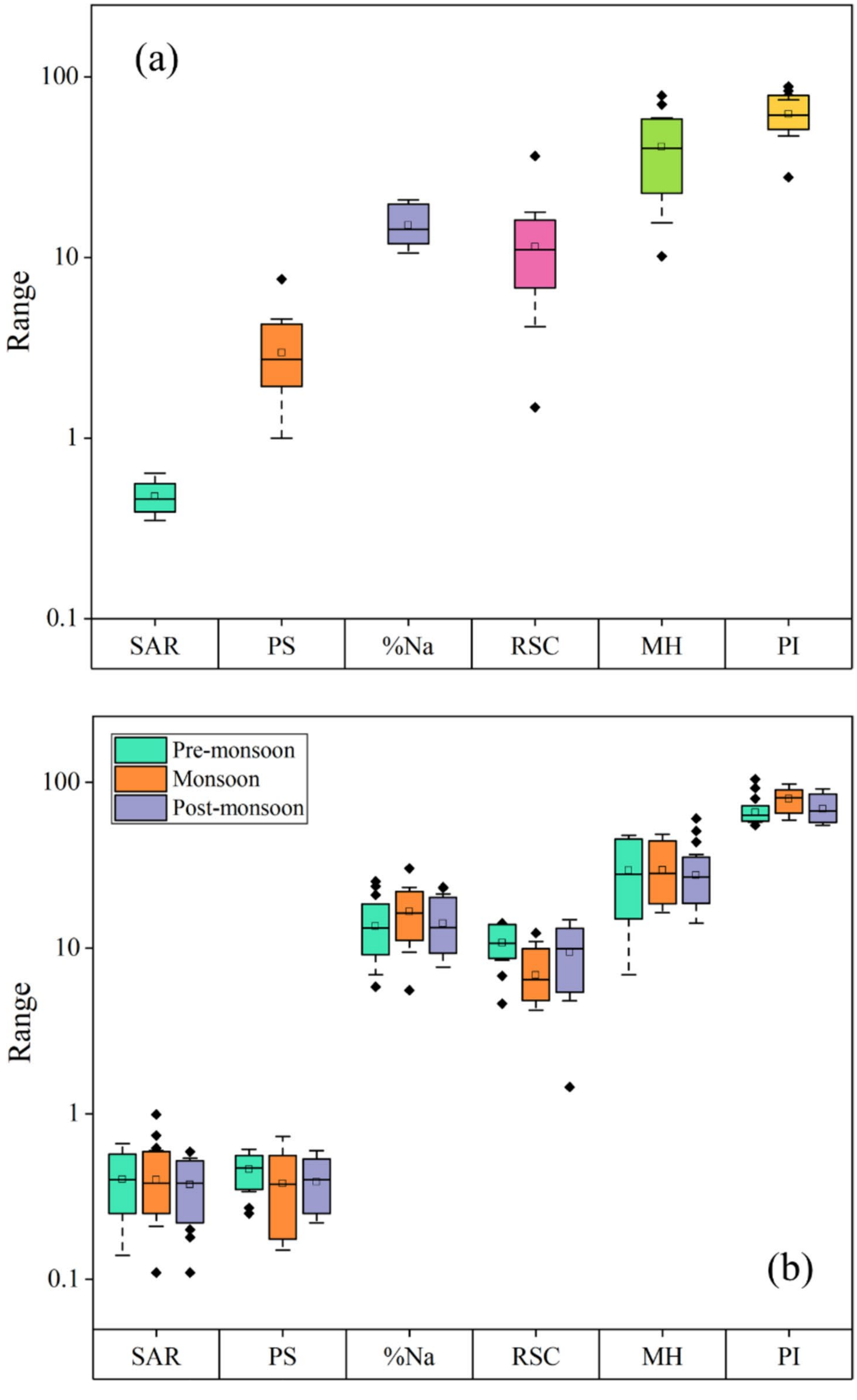

Fig. 6. Box plots showing the (**a**) spatial (**b**) seasonal variations in water quality indices (note: the variables such as SAR, PS, %Na, RSC, MH, and PI are explained in Sect "Methodology".

was noticed that the magnesium hazard was high in the MON followed by PRM and POM seasons (Fig. 6b; Fig. 7 b-d). Moreover, according to the categorical classification of MH values for irrigation suitability, it was also observed that water is suitable for irrigation use in all seasons. However, only 5% of water is unsuitable in POM. These results indicate that water is free from magnesium hazards in all seasons.

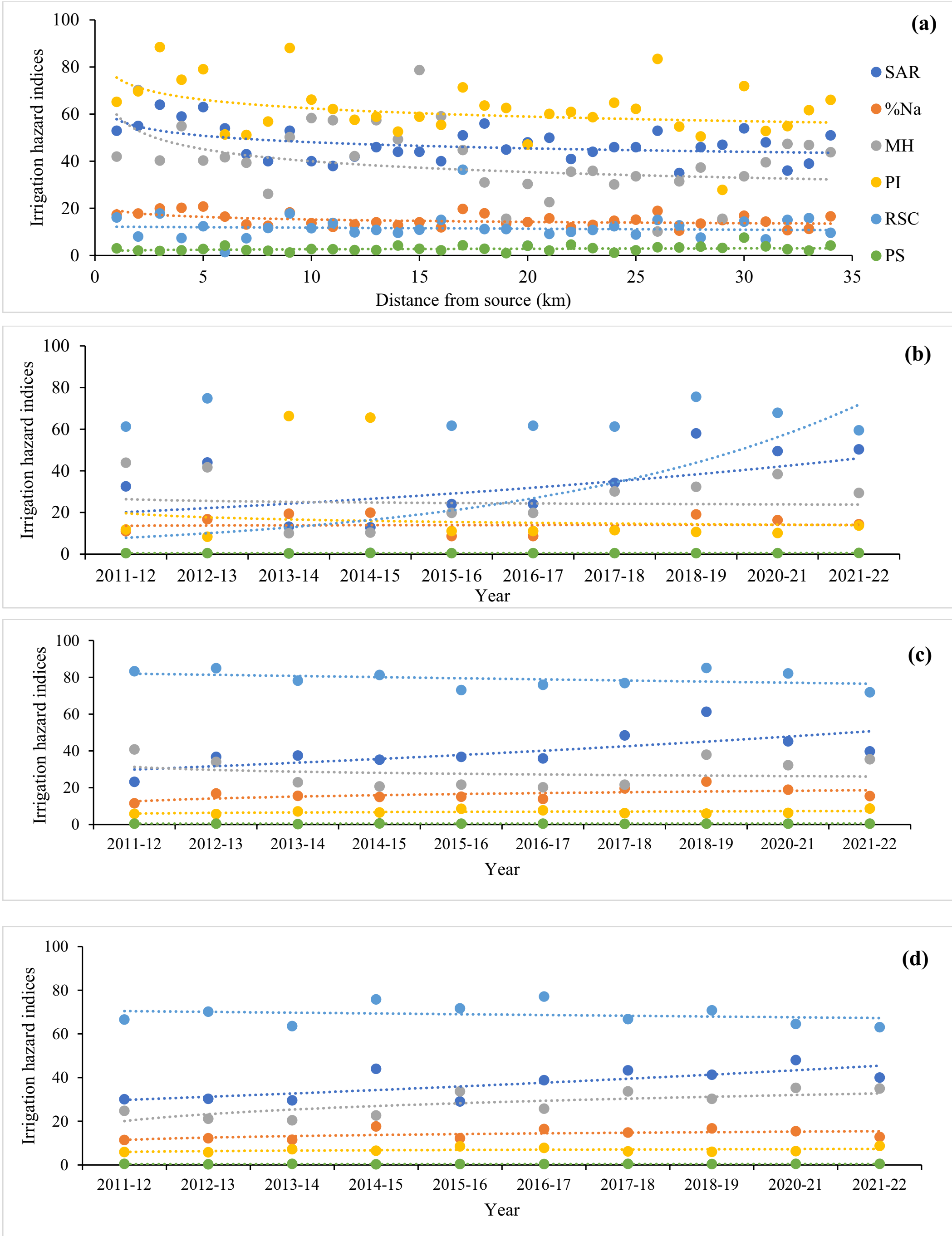

Fig. 7. Spatio-temporal variation of the irrigation hazards, (**a**) variation from the source to the mouth of the Jalangi River, (**b**) pre-monsoon variation, (**c**) monsoon variation, (**d**) post-monsoon variation (notes: 7b–d share the same legend as 7a; the trendlines are the best-fit lines; the irrigation hazard indices are explained in Sect "Methodology").

HCA on irrigation indices

In the present work, HCA was performed on spatiotemporal irrigation suitability indices and found that the spatial indices were clustered into two groups and seven subgroups. Similarly, the temporal indices were clustered into two broad clusters and a few sub-clusters. Regarding the spatial water samples, the first broad clusters were formed with two sub-clusters and the sample Ids. 28, 31,7, 20, 6, 8, 27, 24, 25, 22, 23 and 12 formed the first sub-cluster while 19, 21, 26 and 29 formed another sub-cluster. Similarly, the second broad cluster also formed with two sub-clusters i.e. first sub-cluster with the sample Ids. 1, 34, 18, 30, 3, 5, 9 and 17 while the second sub-cluster with Ids. 10, 11, 13, 16, 32, 33, 14, 2, 4 and 15 (Fig. 8a). It is interesting to note that all the spatial samples except for sample Id. 29 located at Paschim Panditpur characterized by higher human interventions ay ghat (public bathing place) are fused at a short distance (2–5 at rescaled distance of Ward linkage). This implies a greater homogeneity in the clustering of the spatial samples. Moreover, according to the temporal study, the HCA of PRM, MON and POM shows that few samples make small clusters and the number of small clusters is high in the temporal HCA i.e. during PRM four discrete clusters formed with only one sample (Ids. 6,1,12 and 32). Similarly, six discrete clusters are formed only with two samples (Ids. 21, 22; 7, 4; 5, 37; 28, 38; 30, 31; 8, 36) (Fig. 8b). Except for sample Id. 32 of the PRM period of May 2019 with elevated pollution level, all samples

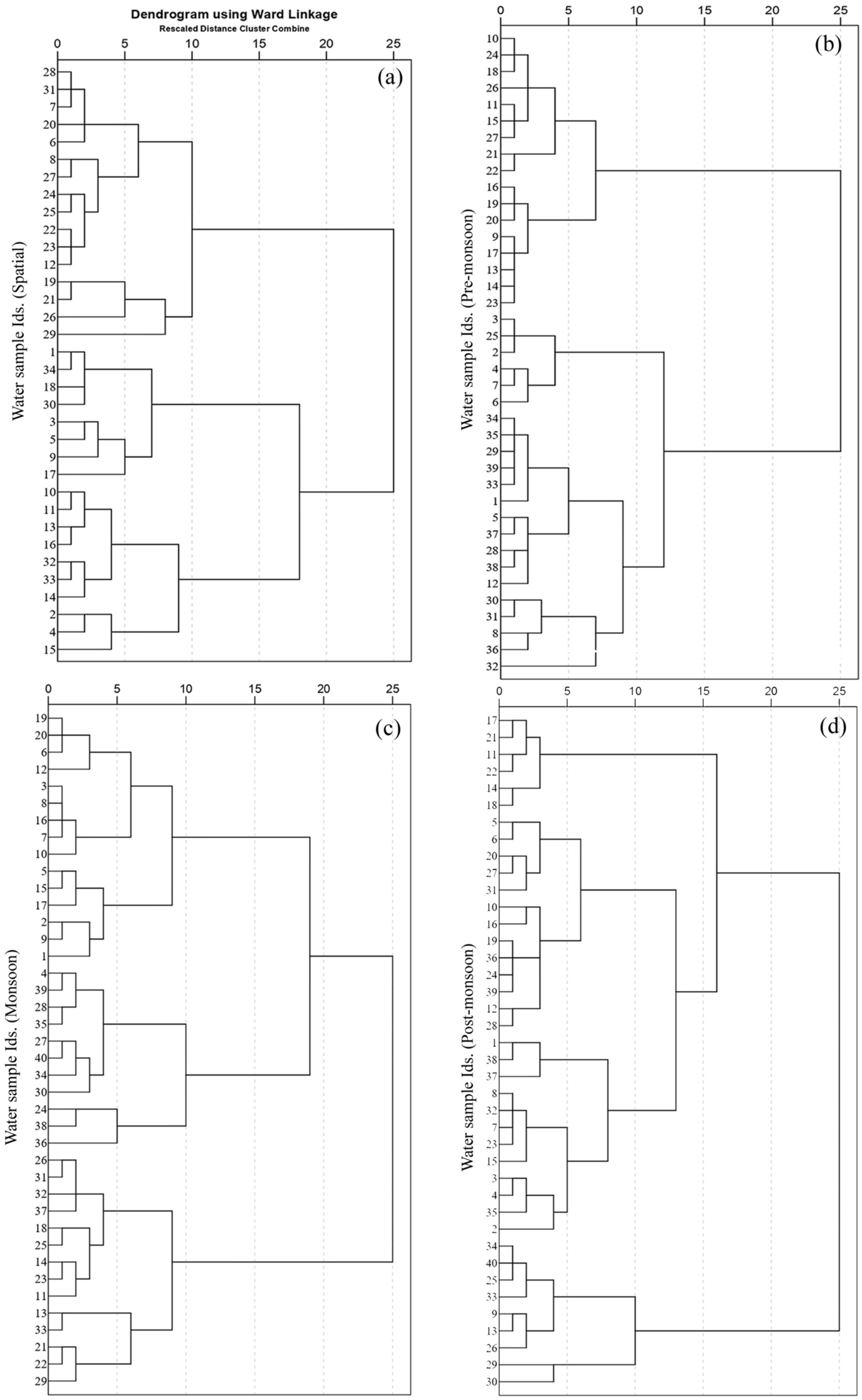

Fig. 8. Dendrogram using hierarchical cluster analysis of Jalangi River water quality parameters (**a**) spatial, (**b**) pre-monsoon variation, (**c**) monsoon variation, (**d**) post-monsoon variation.

are fused at a short distance (< 5) of ward linkage scale indicating intra-group homogeneity (Fig. 8b). Similar intra-group homogeneous pattern has been observed for MON and POM seasons (Fig. 8c, d). However, the inter-group pattern differs from PRM to MON and POM i.e. the smaller sub-cluster is located on the upper part of the dendrogram for PRM while the reverse is observed for the MON and POM. This is due to the elevated pollution during the PRM compared to the MON and POM.

PCA for the relationship among the irrigation hazard indices

Liu et al.[51] classified PCA factor loadings as strong (> 0.75), moderate (0.5–0.75), and weak (0.3–0.5). Based on this classification, the spatial data indicates that %Na, SAR, and PI are the primary contributors to the first principal component (PC1), with strong loadings of 0.967, 0.935, and 0.774, respectively. This implies that the primary determinants of the water quality are these variables, which most likely correspond to salinity and salt concentration. RSC and MH contribute significantly to the second principal component (PC2), with moderate loadings of 0.705 and 0.647, respectively, suggesting their influence on several facets of water quality. PS has a negative loading on PC2, indicating a slight but substantial impact. Besides, the seasonality-related PCA findings show that %Na, SAR, and PI are the main variables affecting water quality in the PRM, MON, and POM periods. These factors play a critical role in determining the salinity and sodium properties of water because they considerably contribute to the PC1 in all seasons. Even though RSC and MH are significant factors; their impact varies seasonally in response to shifts in the dynamics of water quality. The first two components account for a range of 65.238% to 75.9% of the total variance, which indicates a strong representation of the dataset. The post-monsoon period has the maximum cumulative variance, indicating a more stable and consistent pattern of water quality throughout this time (Table 7).

ANOVA for spatio-temporal variation in irrigation suitability

The ANOVA results show no significant difference in irrigation water quality among the spatial variation. However, some indices like SAR, %Na, MH, and PI tend to have little difference among the spatial variation of irrigation water quality. Moreover, for temporal or seasonal variation, the irrigation water quality suitability indices like PS, %Na, RSC, and PI significantly differ among the seasons (Table 8). Hence, these results indicate that there are no spatial variations in irrigation water quality due to homogenous floodplains[22] with standstill water and no significant point source pollution effects[27] during the pre-monsoon season when spatial water samples were collected; however seasonal variations have been found in the study area due significant differences in

Variables	Component							
			Temporal					
	Spatial		Pre-monsoon		Monsoon		Post-monsoon	
	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2
%Na	0.967	−0.062	0.946	0.253	−0.315	0.937	0.76	0.58
SAR	0.935	−0.206	0.745	0.504	0.21	0.951	0.238	0.877
PI	0.774	0.497	0.918	−0.153	−0.959	0.082	0.911	0.106
RSC	0.332	0.705	−0.674	0.465	0.958	−0.009	−0.906	0.054
MH	−0.085	0.647	0.037	0.103	−0.122	0.02	−0.205	0.738
PS	0.09	−0.451	0.048	0.772	0.498	0.343	−0.749	0.05
Total variance	2.535	1.413	2.751	1.163	2.243	1.906	2.887	1.667
Variance (%)	42.249	23.543	45.847	19.391	37.378	31.771	48.116	27.784
Cumulative variance (%)	42.249	65.792	45.847	65.238	37.378	69.149	48.116	75.9

Table 7. Principal component analysis for detecting the multi-variate response of irrigation water quality indices. Note: the variables are explained in the Sect "Methodology".

Variables	Spatial				Temporal			
	F	P-value	F-critical	Remarks	F	P-value	F-critical	Remarks
SAR	2.187	0.129	3.305	Null	0.575	0.564	3.074	Null
PS	1.691	0.201		Null	5.905	0.004		Alternative
%Na	2.468	0.101		Null	5.720	0.004		Alternative
RSC	0.311	0.735		Null	26.513	0.000		Alternative
MH	2.715	0.082		Null	0.509	0.603		Null
PI	2.482	0.100		Null	21.173	0.000		Alternative

Table 8. One-way ANOVA for showing the spatio-temporal variation in irrigation water quality or suitability. Degree of freedom: 2, significance level: 0.05; note: the variables are explained in Sect "Methodology".

monsoon regime especially concentration of rainfall within three months (July to September) that influences the pollution concentrations[14].

Discussion

The physicochemical examination showed that all the water quality parameters, except for K^+ and CO_3^{2-} in the water, are within the acceptable range for irrigation use. Specifically, the Jalangi River is free from sodicity and permeability hazards, while the region has a relatively higher alkalinity hazard. A similar phenomenon is also observed for the neighbour rivers, i.e., the Bhagirathi and Churni Rivers[14]. Moreover, this study also found that the seasonal variability in Jalangi River water quality and during the PRM water quality is the worst among all the other seasons. Hence, this result indicates that the Indian MON regime is one of the main controlling aspects of Jalangi River water quality. On the other hand, Raymond et al.[52] found that extensive agricultural practices (mainly due to extensive use of fertiliser and irrigation) tend to increase the ion concentration responsible for irrigation hazards. Thus, extensive agricultural practices should intensify the study area's bicarbonate concentration. Giday Adhanom[53] found that Shwarobit River water was affected by salinity hazards, and emphasis was given to crop selection and removal of excess soil leaching besides the uses of fertiliser and irrigation. In the study, area salinity hazard is relatively higher in some specific reaches where these strategies may be helpful along with the periodical monitoring of river water.

The hydrochemistry of the Jalangi River is influenced by several factors, including its link to the Ganga River, regional geological variations, and baseflow-controlled river water[22]. Similar results were reported by the works of Nsabimana et al.[54]. As the Jalangi River is connected to the Ganga River and receives a significant discharge in the MON season, the hydro-chemical properties of the Jalangi River are impacted by the rock-water interaction processes that take place in the Ganga River basin[55,56]. Furthermore, during the dry season, when surface water flow is decreased, the Jalangi River relies more on groundwater base flow, strengthening its link to regional geological fluctuations[22]. These regional geological changes might affect the mineral concentration and overall chemistry of the groundwater that feeds the Jalangi River, altering its hydrochemistry[57]. Understanding these complex dynamics is critical for controlling and protecting water quality in the Jalangi River and its basin. Furthermore, human activities such as agriculture, industrial effluents, and household waste disposal may release pollutants into the river, affecting its hydrochemistry[58]. The works of Zhao et al.[59] and He and Li[60] also reported similar observations from China.

The river exhibited gradual decay with time[61]. One of the primary factors contributing to the River Jalangi's course deteriorating is the closure of its off-take from the river Padma, which feeds into the studied river. Moreover, Bhairab feeding the Jalangi River is also suffering low influx from the Ganga River[27]. This is primarily driven by the eastward titling of the Bengal basin that triggered the longitudinal disconnection of the rivers of south Bengal from the Ganga-Padma delta system[39,62–64]. The off-take of the river Jalangi has split apart and sludge-blocked due to this movement (Fig. 9a–k). Thus, the river discharge during the PRM season is very low (Fig. 1c) which is primarily controlled by base flow[61]. Therefore, low river flows are also a factor in natural changes in water quality during the PRM season. For instance, sustained base flows throughout the PRM season raise the water's temperature and reduce dissolved oxygen levels[65]. If there is a significant amount of habitat variability, native species can endure such circumstances. Besides, the increasing anthropogenic activities such as channel narrowing, free flow blockage, and urban effluent mixing have also exacerbated the existing problems[66].

The man-made river decay, especially in water quality, is well demonstrated worldwide (e.g., Chin et al.[67]) and in the Bengal delta (e.g. Das et al.[58]). Therefore, the policy practice, including the structural (e.g. river offtake dredging, sewage treatment plants, etc.) and non-structural measures (e.g. lowering in the untreated discharge of effluents from urban, industrial and agricultural sectors), must be executed sustainably to restore the river's necessary environmental flow and ecological stability. These initiatives should be participatory, involving local communities, government, and other stakeholders to revive the river and river basin. This study analyses the spatio-temporal variation of Jalangi River water quality for evaluating irrigation suitability. Thus, the findings of this study would be helpful to the stakeholders of the Jalani River, agri-irrigation engineers and regional planners.

In 2020, the Nodal Agency Municipal Engineering Directorate (NAMED) of the Department of Urban Development & Municipal Affairs, Government of West Bengal, submitted a proposal titled "Action Plan for Rejuvenation of River Jalangi, Krishnagar" to the Central Pollution Control Board (CPCB) in Delhi. This proposal was subsequently approved by the River Rejuvenation Committee (RRC) of West Bengal, established in compliance with the directives of the Hon'ble National Green Tribunal. The action plan aims to address various aspects of rejuvenating the River Jalangi and its catchment areas. This includes managing discharges from industrial sources, municipal outfalls, sewage-carrying drains, solid waste, biomedical waste, and e-waste, as well as implementing groundwater management, rainwater harvesting, environmental flow maintenance, floodplain zone protection, improved irrigation practices, riverbank plantation, and the establishment of a biodiversity park. The RRC forwarded the action plan to CPCB on February 12, 2020[68].

Subsequently, the Task Team suggested revisions during its 10th Meeting on February 26, 2020, which were approved by the RRC in its 7th meeting on June 9, 2020. This revised plan was sent to CPCB on June 9, 2020, reviewed once again by CPCB in its 12th Task Team meeting on June 11, 2020, and further modified based on their recommendations. The finalized action plan, incorporating CPCB's suggestions, was approved by the RRC in its 8th meeting on July 2, 2020. The report highlighted a 5.0 km stretch of the river identified as "Polluted," which remains so year-round, particularly around Krishnagar town. The principal pollutants in this stretch are primarily biological. Despite being perennial, water in this stretch is predominantly used for agricultural and fishing purposes. The proposed plan's estimated cost is Indian National Rupees (INR) 47.98 crore, with an additional Operation and Maintenance Expenditure of INR 25.16 crore per year[68]. The scheduled completion date for the work was set for June 30, 2021. However, apart from setting some iron nets in large sewers to prevent

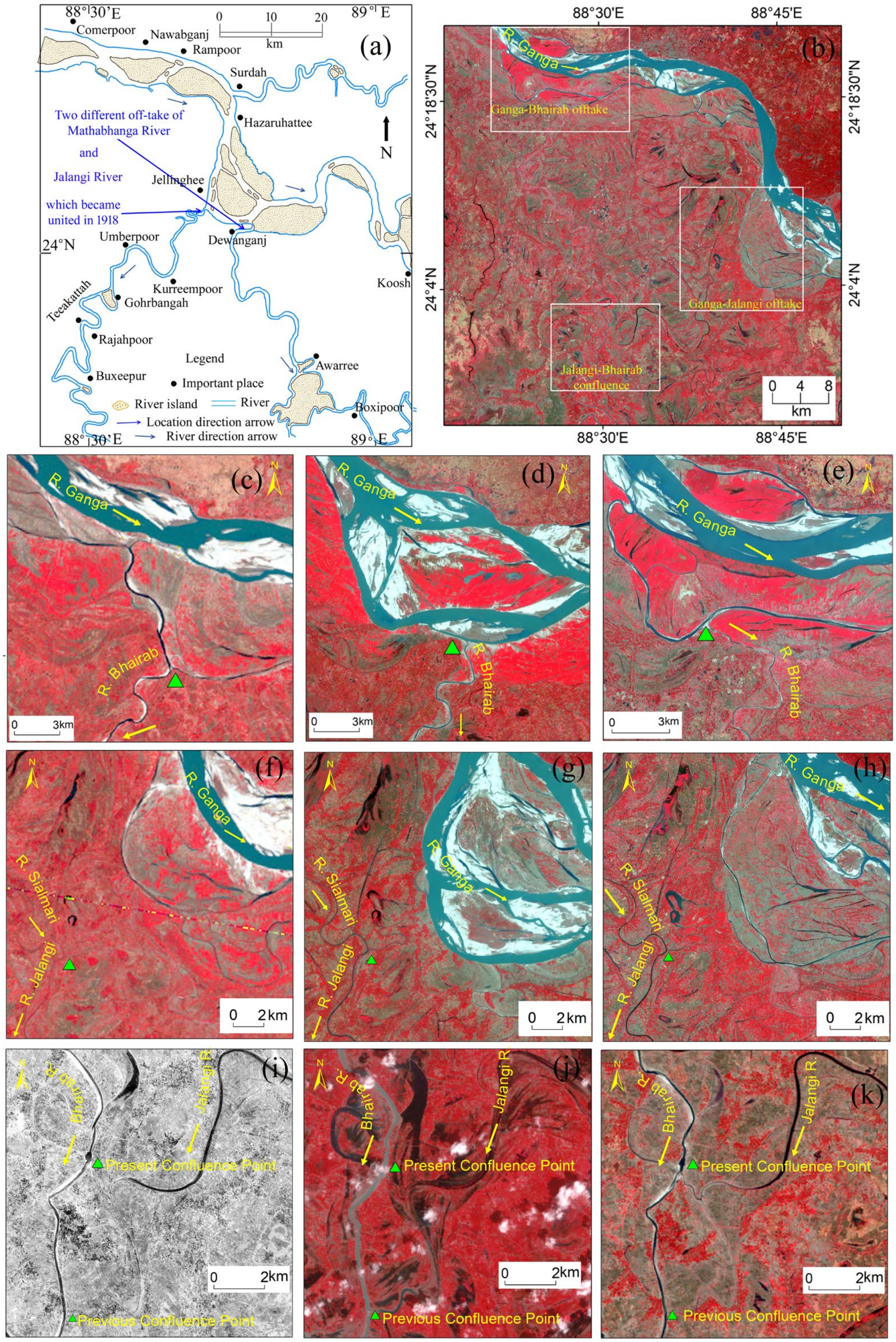

Fig. 9. Decay of Jalangi River through historical time (**a**) Jalangi River in 1840's scenario in Tassin's map (based on Das[22]) (**b**) index map of the Ganga–Bhairab offtake, Ganga–Jalangi offtake, and Jalangi–Bhairab confluence (Sentinel 2A tiles number T45QXG dated 15 Nov 2020), (**c**–**e**) represent the evolution of Ganga–Bhaibrab offtake in 1973 (Landsat 1 multi-spectral scanner (MSS), path 149, row 43 dated 17 Jan 1973), 2000 (Landsat 7 enhanced thematic mapper plus (ETM +), path 138, row 43 dated 17 Nov 2000) and 2020 (same as 9b), (**f**–**h**) show evolution of the Ganga–Jalangi offtake in 1973 (same as 9c), 2000 (same as 9d) and 2020 (same as 9b); (**i**–**k**) depict Jalangi–Bhairab confluence in 1968 (Corona Satellite KH-4A 45, Entity ID DS1045-2196DF120 dated 06 Feb 1968), 2000 (Landsat 5 thematic mapper (TM), path 138, row 43 dated 08 Oct 2000) and 2020 (same as 9b) (source: prepared by the authors based on using ArcGIS (version 10.4), and Adobe Photoshop (version 7.0).

large solid wastes (plastics) from entering the river, nothing significant was done. Additionally, a small treatment plant at Krishnagar bus stand was left incomplete and never became operational. The main limitations of this current research work are–(1) the unavailability of secondary water quality data in spatial extensions and (2) the lack of extensive monitoring sites for testing the seasonal water quality for spatial variations. These deserve further investigation.

Though river water is free from sodicity and permeability hazards, alkalinity hazards tend to affect irrigation water quality. This is due to the intensive agricultural activities and urban sewage discharge into the river before proper treatment. The study basin is almost ungauged in terms of hydrological and chemical measurements. There is no secondary data, except for one station on water quality. Thus, the study missed the temporal dimension of hydro-chemical assessment for all the river stretches. However, future attempts are required to portray the seasonal variations in water quality. Besides, eco-restoration practices are to be ushered in following a diagnostic river survey. The channel decay, and environmental flow in the context of the neotectonics movement, climate change and the 'Anthropocene' may be other perspectives of future endeavours. Finally, apart from irrigation water quality assessment, geochemical modelling may be extended in the future.

Conclusions

The present study focuses on the first systematic attempt to assess the Jalangi River's water quality for irrigation purposes. The study reported that river water quality is suitable for irrigation purposes. All the water quality parameters lie within acceptable limits except K^+ and CO_3^{2-} for irrigation in spatio-temporal dynamics. Jalangi River water samples are Na^+–HCO_3^- types and the alkaline earth ($Ca^{2+} + Mg^{2+}$) exceeds alkalises ($Na^+ + K^+$) and weak acids ($HCO_3^- + CO_3^{2-}$) exceeds strong acids ($Cl^- + SO_4^{2-}$). Gibbs plot shows that rock weathering has a leading role in controlling the hydro-chemical evolution of Jalangi River water. Although, very little evaporation dominance is also noticed in PRM and POM seasons. The Jalangi River water is free from all other hazards except for alkalinity in the spatio-temporal dimension. There are no spatial variations in irrigation water quality due to homogenous floodplains with an absence of point source pollution during the PRM. This study also found that MON water is more suitable for irrigation compared to PRM water.

The limited connectedness with the Ganga–Padma delta system, discharge of urban waste water and widespread agricultural practices are closely related to the deterioration of the river. While an action plan was put into place to revitalize the river, significant progress has not been made, which emphasizes the need for more focused and efficient efforts. To maintain the ecological health of the river and ensure its sustainable usage for irrigation and other functions, future research should devote the greatest attention to eco-restoration techniques, thorough spatial and temporal monitoring, and strict management of human effects. To repair and sustain the Jalangi River's environmental flow and water quality, this research emphasizes the need for an all-encompassing and cooperative strategy including local people, government organizations, and stakeholders.

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Received: 14 November 2023; Accepted: 21 August 2024
Published online: 29 August 2024

References

1. Mahammad, S. & Islam, A. Surface water quality assessment for drinking and irrigation using DEMATEL, entropy-based models and irrigation hazard indices. *Environ. Earth Sci.* **83**(10), 332. https://doi.org/10.1007/s12665-024-11633-y (2024).
2. Hoque, M. M. & Islam, A. Spatio-temporal dynamics of ecological, bacteriological, and overall water quality of the Damodar River, India. *Environ. Sci. Pollut. Res.* **31**, 18465–18484. https://doi.org/10.1007/s11356-024-32185-5 (2024).
3. Putri, R. F. *et al.* The impact of population pressure on agricultural land towards food sufficiency (Case in West Kalimantan Province, Indonesia). In *IOP Conference Series: Earth and Environmental Science* 012050 (IOP Publishing, 2019).
4. Angelakıs, A. N. *et al.* Irrigation of world agricultural lands: Evolution through the millennia. *Water* **12**(5), 1285. https://doi.org/10.3390/w12051285 (2020).
5. Singh N, Singh OP. Green revolution in India and its impact on water resources. Millennium water story. https://millenniumwaterstory.org/Pages/Photostories/Water-and-Livelihood/Green-Revolution-in-India-and-its-Impact-on-Water-Resources.html. Accessed on 15 May 2024. (2021).
6. Hoque, M. M., Islam, A. & Mahammad, S. Assessing the surface and bottom river water quality for drinking purpose and human health risk analysis: A study of Damodar River, India. *Arab. J. Geosci.* **15**(23), 1–23. https://doi.org/10.1007/s12517-022-10987-6 (2022).
7. Hoque, M. M., Islam, A., Sarkar, B. & Saha, U. Assessing the surface and bottom river water quality for irrigation: A study of Damodar River, India. *Int. J. Energy Water Resour.* https://doi.org/10.1007/s42108-022-00206-z (2022).
8. Roy, K. *et al.* Irrigation water quality assessment and identification of river pollution sources in Bangladesh: Implications in policy and management. *J. Water Resour. Hydraul. Eng.* **4**(4), 303–317 (2015).
9. Lu, Y. *et al.* Impacts of soil and water pollution on food safety and health risks in China. *Environ. Int.* **77**, 5–15 (2015).
10. Etteieb, S., Cherif, S. & Tarhouni, J. Hydrochemical assessment of water quality for irrigation: A case study of the Medjerda River in Tunisia. *Appl. Water Sci.* **7**, 469–480 (2017).
11. Misaghi, F., Delgosha, F., Razzaghmanesh, M. & Myers, B. Introducing a water quality index for assessing water for irrigation purposes: A case study of the Ghezel Ozan River. *S. Total Environ.* **589**, 107–116 (2017).
12. Mandal, S. K., Dutta, S. K., Pramanik, S. & Kole, R. K. Assessment of river water quality for agricultural irrigation. *Int. J. Environ. Sci. Technol.* **16**, 451–462 (2018).
13. Kumarasamy, P., Dahms, H. U., Jeon, H. J., Rajendran, A. & Arthur James, R. Irrigation water quality assessment—An example from the Tamiraparani river, Southern India. *Arab. J. Geosci.* **7**, 5209–5220 (2014).
14. Sarkar, B. & Islam, A. Assessing the suitability of water for irrigation using major physical parameters and ion chemistry: A study of the Churni River, India. *Arab. J. Geosci.* **12**(20), 1–16. https://doi.org/10.1007/s12517-019-4827-9 (2019).
15. Doneen, L. D. *Water Quality for Agriculture. Department of irrigation* (University of California, 1964).

16. Raghunath, H. M. *Groundwater: Hydrogeology, Groundwater Survey and Pumping Tests, Rural Water Supply, and Irrigation Systems* (New Age International, 1987).
17. Todd, D. K. & Mays, L. W. *Groundwater Hydrology* (John Wiley & Sons, 2004).
18. Gowd, S. S. Assessment of groundwater quality for drinking and irrigation purposes: A case study of Peddavanka watershed, Anantapur District, Andhra Pradesh, India. *Environ. Geol.* **48**(6), 702–712. https://doi.org/10.1007/s00254-005-0009-z (2005).
19. Garrett JHE. Bengal District Gazetteer. Bengal Secretariat Book Depot, Nadia. 1–21. https://archive.org/details/in.ernet.dli.2015.55776/page/n5/mode/1up (1910).
20. Fergusson J. *On Recent Changes in The Delta of the Ganges*. Quarterly Journal of the Geological Society of London. Vol. XIX, PP. 321–354. https://doi.org/10.1144/GSL.JGS.1863.019.01-02.35. (1863).
21. Reaks HG. Report on the physical and hydraulic characteristics of the rivers of the delta. In Moore et al. (1919). *Report on the Hooghly River and Its Head-Waters*. Vol-I, The Bengal Secretariat Book Depot, Calcutta. Reprinted by Biswas (2001), *Rivers of Bengal*, Vol-II, Government of West Bengal, pp. 87, 107 (1919).
22. Das, B. C. *Changes and Deterioration of the Course of River Jalangi and its Impact on the People Living on its Banks Nadia West Bengal* (University of Calcutta, 2013).
23. Anandabazar Patrika. Jalangi River: Black water in Jalangi River threatening mass extictions. https://www.anandabazar.com/west-bengal/nadia-murshidabad/water-of-the-jalangi-river-turned-black/cid/1356119. Accessed on 13 Jul 2022. (2022).
24. Kumar, S., Halder, S. & Singhal, D. C. Groundwater resources management through flow modeling in lower part of Bhagirathi—Jalangi interfluve, Nadia, West Bengal. *J. Geol. Soc. India* **78**(6), 587–598 (2011).
25. Chatterjee, S., Chakraborty, K. & Mura, S. N. S. Investigating the present status, spatial change, and emerging issues related to riparian wetlands of Bhagirathi–Jalangi Floodplain (BJF) in lower deltaic West Bengal, India. *Environ. Dev. Sustain.* **24**(5), 7388–7434 (2022).
26. Sarkar, B. & Das, B. C. A cross-sectional study on the water quality and ecosystem health of the Jalangi and Bhagirathi river and their selected Oxbow-lakes. In *Fluvial Systems in the Anthropocene* (eds Islam, A. *et al.*) (Springer, 2022).
27. Das, B. C. & Bhattacharya, S. The Jalangi: A story of killing of a dying river. In *Anthropogeomorphology of Bhagirathi–Hooghly River System in India* 381–431 (CRC Press, 2020).
28. Dasgupta, A. B. Geology of the Bengal Basin. *Indian J. Geol.* **69**(2), 161–176 (1997).
29. Guchhait, S. K., Islam, A., Ghosh, S., Das, B. C. & Maji, N. K. Role of hydrological regime and floodplain sediments in channel instability of the Bhagirathi River, Ganga–Brahmaputra Delta, India. *Phys. Geogr.* **37**(6), 476–510. https://doi.org/10.1080/02723646.2016.1230986 (2016).
30. APHA. In: Baird RB, Eaton AD, Rice EW (Eds), Standard Methods for the Examination of Water and Wastewater, 23rd ed. American Public Health Association, American Water Works Association, Water Environment Federation, Washington, DC, USA. (2017).
31. Jannat, J. N. *et al.* Hydro-chemical assessment of fluoride and nitrate in groundwater from east and west coasts of Bangladesh and India. *J. Clean. Prod.* **372**, 133675 (2022).
32. Li, P., He, S., He, X. & Tian, R. Seasonal hydrochemical characterization and groundwater quality delineation based on matter element extension analysis in a paper wastewater irrigation area, northwest China. *Expo. Health* **10**, 241–258. https://doi.org/10.1007/s12403-017-0258-6 (2018).
33. Das L, Joshi D. Agricultural Water Demand in West Bengal-Supplementary Information: Working group reports from grassroots field exposure Session-December 2018. https://nora.nerc.ac.uk/id/eprint/528940/1/N528940CR.pdf, Accessed on 10 Nov 2022. (2019).
34. Richards, L. A. Diagnosis and improvement of saline and alkali soils. *Soil Sci.* **78**, 154 (1954).
35. Wilcox, L. *Classification and Use of Irrigation Waters (Circular No. 969),* US Department of Agriculture, Washington DC. Accessed 15 March 2024. https://ia803201.us.archive.org/10/items/classificationus969wilc/classificationus969wilc.pdf (1955).
36. Hossain, M. S. *et al.* Hydro-chemical characteristics and groundwater quality evaluation in south-western region of Bangladesh: A GIS-based approach and multivariate analyses. *Heliyon* https://doi.org/10.1016/j.heliyon.2024.e24011 (2024).
37. Gibbs, R. J. Mechanisms controlling world water chemistry. *Science* **170**(3962), 1088–1090. https://doi.org/10.1126/science.170.3962.1088 (1970).
38. Marandi, A. & Shand, P. Groundwater chemistry and the Gibbs diagram. *Appl. Geochem.* **97**, 209–212. https://doi.org/10.1016/j.apgeochem.2018.07.009 (2018).
39. Sarkar, B., Islam, A. & Das, B. C. Role of declining discharge and water pollution on habitat suitability of fish community in the Mathabhanga–Churni River, India. *J. Clean. Prod.* **326**, 129426 (2021).
40. Nazzal, Y. *et al.* A pragmatic approach to study the groundwater quality suitability for domestic and agricultural usage, Saq aquifer, northwest of Saudi Arabia. *Environ. Monit. Assess.* **186**(8), 4655–4667. https://doi.org/10.1007/s10661-014-3728-3 (2014).
41. Zhang, B. *et al.* Hydrochemical characteristics of groundwater and dominant water–rock interactions in the Delingha Area, Qaidam Basin, Northwest China. *Water* **12**(3), 836. https://doi.org/10.3390/w12030836 (2020).
42. Parkhurst DL, Appelo CAJ. User's Guide to PHREEQC (Version 2) a Computer Program for Speciation, Batch-Reaction, One-Dimensional Transport, and Inverse Geochemical Calculations: U.S Geological Survey Water-Resources Investigations Report 99–4259. https://pubs.usgs.gov/wri/1999/4259/report.pdf. Accessed on 21 Sept 2022. (1999).
43. Food and Agriculture Organization (FAO). Soil Survey Investigation for Irrigation. Soil Bulletin 42. Food and Agriculture Organization of the United Nations, Rome, Italy. (1985).
44. Shahabi, A., Malakouti, M. J. & Fallahi, E. Effects of bicarbonate content of irrigation water on nutritional disorders of some apple varieties. *J. Plant Nutr.* **28**(9), 1663–1678 (2005).
45. Alexopoulos, A. A. *et al.* Effect of nutrient solution pH on the growth, yield and quality of *Taraxacum officinale* and *Reichardia picroides* in a floating hydroponic system. *Agronomy* **11**(6), 1118. https://doi.org/10.3390/agronomy11061118 (2021).
46. Wei, X. *et al.* Enhancing soil health and plant growth through microbial fertilizers: Mechanisms, benefits, and sustainable agricultural practices. *Agronomy* **14**(3), 609. https://doi.org/10.3390/agronomy14030609 (2024).
47. Sarkar, B. & Islam, A. Assessing the suitability of groundwater for irrigation in the light of natural forcing and anthropogenic influx: A study in the Gangetic West Bengal, India. *Environ. Earth Sci.* **80**(24), 807. https://doi.org/10.1007/s12665-021-10087-w (2021).
48. Singh, P., Sharma, K.K., Legese, B., Godana, G. Effect of Irrigation Salinity Water on Soil Properties of Nagaur Region, Rajasthan, India. Annals of the Romanian Society for Cell Biology, **25** (5), 470–476. (2021).
49. Tiri, A., Belkhiri, L., Asma, M. & Mouni, L. Suitability and assessment of surface water for irrigation purpose. *Water Chem.* https://doi.org/10.5772/intechopen.86651 (2020).
50. El-Amier, Y. A. *et al.* Hydrochemical assessment of the irrigation water quality of the El-Salam canal, Egypt. *Water* **13**(17), 2428. https://doi.org/10.3390/w13172428 (2021).
51. Liu, C. W., Lin, K. H. & Kuo, Y. M. Application of factor analysis inthe assessment of groundwater quality in a blackfoot diseasearea in Taiwan. *Sci. Total Environ.* **313**(1–3), 77–89. https://doi.org/10.1016/S0048-9697(02)00683-6 (2003).
52. Raymond, P. A., Oh, N. H., Turner, R. E. & Broussard, W. Anthropogenically enhanced fluxes of water and carbon from the Mississippi River. *Nature* **451**(7177), 449–452 (2008).
53. Giday Adhanom, O. Salinity and sodicity hazard characterization in major irrigated areas and irrigation water sources, Northern Ethiopia. *Cogent Food Agric.* **5**(1), 1673110 (2019).

54. Nsabimana, A., Li, P., Alam, S. K. & Fida, M. Surface water quality for irrigation and industrial purposes: A comparison between the south and north sides of the Wei River Plain (northwest China). *Environ. Monit. Assess.* **195**(6), 696. https://doi.org/10.1007/s10661-023-11263-0 (2023).
55. Singh, M., Singh, I. B. & Müller, G. Sediment characteristics and transportation dynamics of the Ganga River. *Geomorphology* **86**(1–2), 144–175 (2007).
56. NMCG. Assessment of Water Quality and Sediment to understand the Special Properties of River Ganga. https://nmcg.nic.in/writereaddata/fileupload/NMCGNEERI%20Ganga%20Report.pdf . Accessed on 20 Apr 2024. (2024).
57. CGWB. Ground Water Quality of West Bengal. Technical Report: Series 'D', No. 294. Central Ground Water Board Eastern Region, Kolkata Ministry of Jal Shakti Department of Water Resources, River Development and Ganga Rejuvenation Government Of India. https://www.cgwb.gov.in/cgwbpnm/public/uploads/documents/1707999879220951 86file.pdf. Accessed on 15 Mar 2024. (2023).
58. Das, B. C., Ghosh, S., Islam, A. & Roy, S. An appraisal to anthropogeomorphology of the Bhagirathi–Hooghly river system: Concepts, ideas and issues. In *Anthropogeomorphology of Bhagirathi–Hooghly River System in India* 1–40 (CRC Press, 2020).
59. Zhao, H., Li, P., He, X. & Ning, J. Microplastics pollution and risk assessment in selected surface waters of the Wei River Plain, China. *Expo. Health* **15**(4), 745–755. https://doi.org/10.1007/s12403-022-00522-z (2023).
60. He, X. & Li, P. Surface water pollution in the middle Chinese Loess Plateau with special focus on hexavalent chromium (Cr6+): Occurrence, sources and health risks. *Expo. Health* **12**(3), 385–401. https://doi.org/10.1007/s12403-020-00344-x (2020).
61. Das, B. C. Socio–economic impact of a decaying river on fishermen: A case study of Taranipur village, West Bengal. *Int. J. Res. Manag. Sci. Technol.* **3**(4), 141–149 (2015).
62. Allison, M. A. *et al.* Stratigraphic evolution of the late holocene Ganges–Brahmaputra lower delta plain. *Sediment. Geol.* **155**, 317–342 (2003).
63. Goodbred, S. L. Jr. & Kuhel, S. A. The significance of large sediment supply, active tectonism, eustasy on the margin sequence development: Late quaternary stratigraphy and evolution of the Ganges–Brahmaputra Delta. *Sediment. Geol.* **133**(3–4), 227–248 (2000).
64. Islam, A. & Guchhait, S. K. Characterizing cross-sectional morphology and channel inefficiency of lower Bhagirathi River, India, in post-Farakka barrage condition. *Nat. Hazards* **103**(3), 3803–3836 (2020).
65. Nilsson, C. & Renöfält, B. M. Linking flow regime and water quality in rivers: A challenge to adaptive catchment management. *Ecol. Soc.* **13**(2), 18 (2008).
66. Islam, A. *et al.* Assessing river water quality for ecological risk in the context of a decaying river in India. *Environ. Sci. Pollut. Res.* https://doi.org/10.1007/s11356-024-33684-1 (2024).
67. Chin, A., Fu, R., Harbor, J., Taylor, M. P. & Vanacker, V. Anthropocene: Human interactions with earth systems. *Anthropocene* **1**, 1–2 (2013).
68. NAMED. Action Plan for Rejuvenation of River Jalangi, Krishnagar, West Bengal, Priority—IV, Nodal Agency, Municipal Engineering Directorate, Department of Urban Development & Municipal Affairs, Government of West Bengal, Approved by River Rejuvenation Committee, West Bengal. Submitted to Central Pollution Control Board, Delhi, 1–20. (2020).

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Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-024-70851-3.

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