ORIGINAL ARTICLE

Introducing an irrigation water quality index (IWQI) based on the case study of the Dwarka River basin, Birbhum, West Bengal, India

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Abstract

The assessment of groundwater for irrigation was a crucial step towards sustainable water resource management. Traditionally, irrigation water suitability was carried out by assessing several irrigation parameters individually. In this research, an attempt was made to develop a new irrigation water quality (IWQI) index by integrating various irrigation water suitability parameters i.e., sodium adsorption ratio (SAR), Magnesium Adsorption Ratio (MAR), residual sodium carbonate (RSC), Exchangeable sodium ratio or Kelly ratio (KR), Soluble Sodium Percentage (SSP), total hardness (TH), Electrical Conductivity (EC), Permeability index (PI) and fluoride (F^-). A stretch of the Dwarka River basin was selected as a type area for this research. Water sample collection, analysis followed by classification of water parameters into five different classes, and assigning weights and ranks were the principal methodologies adopted for the building up of the Irrigation water quality index (IWQI). The order of abundance of anions in the study area was $HCO_3^- > Cl^- > CO_3^{-2} > SO_4^{2-} > F^-$ and cation are $Ca^{+2} > Na^+ > Mg^{+2} > K^+$. A total of 607 water samples were collected and the computed IWQI with respect to the present study reveals that 95.38% (579 samples) of the total water sample were suitable for irrigation whereas the remaining 4.61% (28 samples) of the total sample show unsuitability for irrigation. Nawapara, Junidpur, Chakpara, Bhelian were among the most polluted village. Outcomes of the present study can be a first-hand tool to the policymakers, planners, and government officials for sustainable water resource management in the study area.

Keywords Groundwater quality · Irrigation suitability · Irrigation Water Quality Index (IWQI) · Dwarka River Basin · India

Introduction

The demand for portable and irrigation water is ever increasing due to continuous population expansion and industrialization and limited availability of groundwater and surface water resource makes the scenario worse exponentially (Keesari et al. 2016). Intensive irrigation using groundwater increases the risk of both quantity and quality degradation

of groundwater resources (Foster 1995). The demand for production is increasing by compelling farmers to use poor quality of water for irrigation (Raychaudhuri et al. 2014; Thapa et al. 2018a).

Groundwater quality is determined by several natural factors such as geology and its interaction with groundwater, groundwater flow speed and residence time in the aquifer, chemical and physical characteristics of aquifer material, rainfall distribution, and anthropogenic activities such as landfills, use of chemicals in agriculture (Appelo and Postma 1996; Zulu et al. 1996; Radstake et al. 1988; Jalali 2008; Thapa et al. 2017a, 2018b). Several researchers have carried out the assessment of groundwater suitability for irrigation purposes (Jalali 2008; Sarath-Prasanth et al. 2012; Zouahri et al. 2015; Nag and Suchetana 2016; Sharma et al. 2016).

Dwarka River basin depends heavily on groundwater for irrigation attributing to its semiarid region and limited availability of surface water throughout the year (Thapa et al. 2017b). Groundwater is the lifeline in the study area as a

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major portion of the study area is dominated by irrigation and agriculture is the main occupation of the majority population (Mondal et al. 2014; Thapa et al. 2017c, 2018b). The knowledge of the water quality of the study area can play an important role in the management of this natural resource.

Groundwater suitability for irrigation has been carried out by several researchers around the globe. To understand the irrigation suitability of water in the study area, parameters such as sodium adsorption ratio (SAR) magnesium adsorption ratio (MAR), residual sodium carbonate (RSC), exchangeable sodium ratio or Kelly ratio (KR), soluble sodium percentage (SSP), total hardness (TH), electrical conductivity (EC), permeability index (PI) and Fluoride (F^-) have been considered. In the study area, the occurrence of high fluoride in groundwater has been reported by several researchers (Mondal et al. 2014; Thapa et al. , 2017b,2018d; c). The use of high fluoride-containing groundwater for irrigation results in a higher concentration of fluoride accumulation in crops and vegetables grown (Mondal et al. 2014) in the study area. In this backdrop, F^- was also considered as one of the parameters to evaluate IWQI.

To understand the irrigation suitability several parameters such as SAR, MAR, RSC, KR, SSP etc. are considered but an approach integrating all these parameters into one system to differentiate areas with unsuitable groundwater for irrigation from areas with suitable water quality for irrigation. A geospatial approach to assess the irrigation water quality in the study area has been carried out (Thapa et al 2017d) but in this research, an attempt has been made to develop a simple indexing technique for assessing the quality of groundwater for irrigation. In this technique, the traditional techniques for assessing of irrigation water are revised from individual assessment of several parameters to an indexing method that considered all the parameters in one parenthesis and depicts the irrigation water quality status of an area. Unlike the traditional method of assessing irrigation water quality parameters individually, in this research work emphasis was given on developing a technique that provides a simple, effective and precise water quality classification with the imprints of all the essential parameters. Detail water sampling and their analysis were carried out in the study area to execute the above objectives.

Materials and methods

Study area

Located in the westernmost part of West Bengal, Dwarka River is an east–west elongated basin originating from the Chotanagpur plateau. The basin lying within 23° 58′ 12.115″ N to 24° 14′ 14.99″ N latitude and 87° 28′ 39.46″ E to 87° 56′ 24.98″ E longitude encompasses an area of approximately 858 km^2 (Fig. 1). Our study area experiences a sub-humid type of climatic condition where the major share of groundwater recharge is accomplished by rainfall.

Regarding the geology of the basin the Chottanagpur Gneissic Complex comprising of pink granite, granite gneiss with veins of pegmatite and quartz, and epidote granite marks the basement rocks. The Rajmahal Formation occurring in the western part of the study area comprises of inter-trappean sedimentaries and a succession of basaltic flow with the presence of megacrysts flow at the bottom. In the eastern part of the basin hard clay with impregnated caliche nodule (Rampurhat formation) occurs whereas the central part is mainly covered by laterites extending from north to south (Sen et al. 1987; Sen and Vijaya 2005).

The groundwater flow diagram within the study area is represented in Fig. 2. This map was created with the data obtained from the Public Health and Engineering Department, West Bengal (WBPhed 2017) which contains information of a total of 164 wells (which includes tube well, monitoring wells, and boreholes). The predominant regional groundwater flow direction is from west to east.

Areas with gentle slope and elevation allow more percolation of water from the surface facilitating higher water–rock interaction (Edmunds and Smedley 2005; Magesh et al. 2011a, b; Waikar and Nilawar 2014; Thapa et al. 2017a). The details of the elevation and slope of the study area are represented in Figs. 3 and 4, respectively. The Western parts of the study area generally consist of higher elevation (62–118 masl) and it gradually decreases from west to east. The eastern part of the study area consists of low elevation (below 42 masl) areas.

Sampling details

In the present study, very extensive water samplings were made within DRB in post-monsoon seasons (October, 2015–March, 2016) by collecting samples covering the majority of the villages along the Dwarka River. To carry out the irrigation water suitability index, altogether 607 groundwater samples were collected from 211 villages covering an area of 345 km^2 (Fig. 1). The south-western part of the basin is dominated by dug wells, depth ranging from 4.1 to 16.8 m. and tube wells, ranging ~ 35–90 m. Dug wells are almost absent in the northern, southern, and eastern part of the basin.

Physicochemical analysis of groundwater sample

The bottle was first rinsed with distilled water and then with respective groundwater before the collection of water samples in a plastic bottle. A water sample from the tube well was collected after pumping the tube well for 5–10 min. Various parameters such as geographical coordinate, pH, total
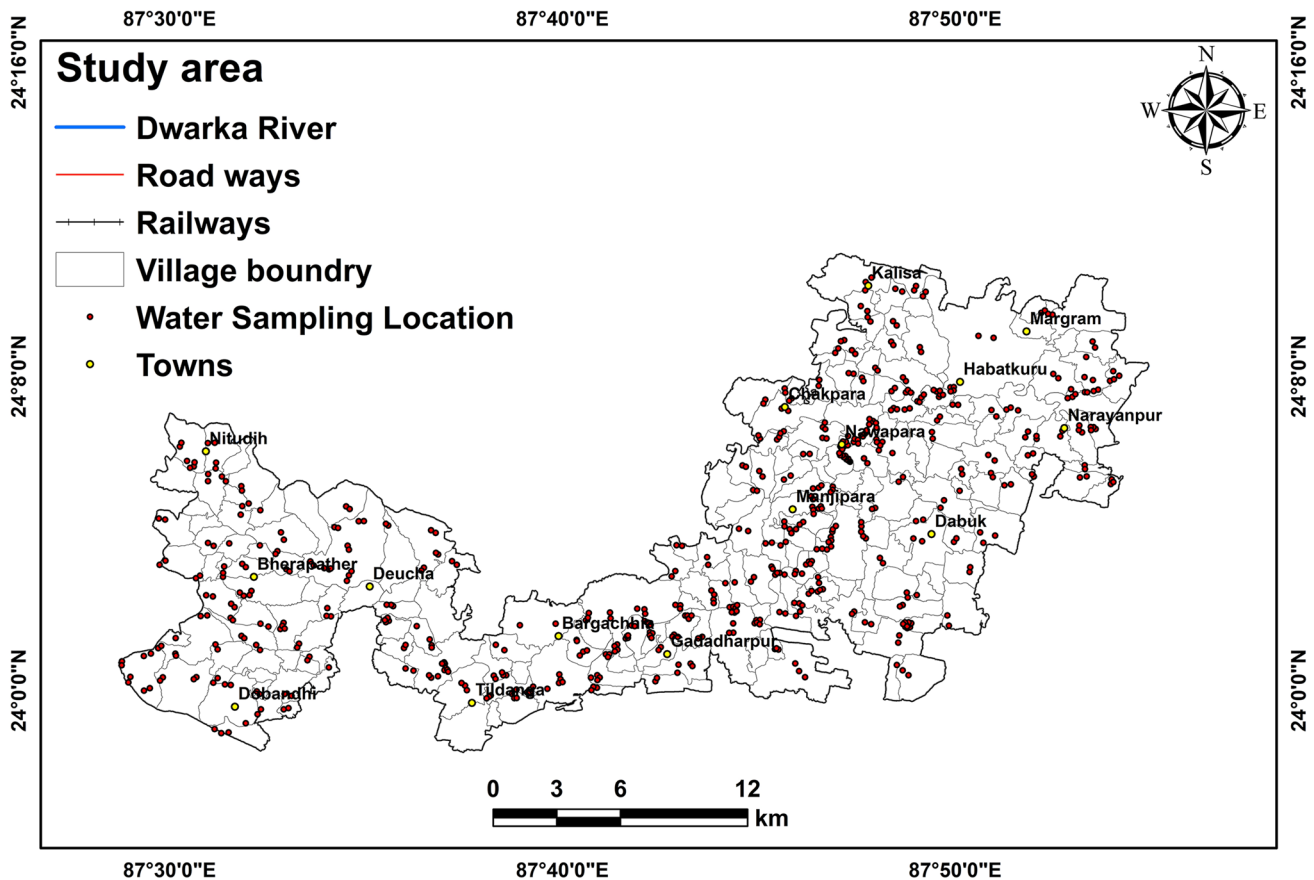
Fig. 1 Location map of the study area

dissolved solids (TDS), electrical conductance (EC) were measured in the field with the help of portable meters, and GPS. Analysis of major cation and anion in the water sample was carried out in Ion Chromatography (IC, Dionex make) in CSIR-National Geophysical Research Institute Laboratory (NGRI). Ion chromatography is based on the reversible exchange of ions in solution with ions electrostatically bound to an insoluble support media. For anions separation AS-14A Ion Pac 199 was used with 8.0 mM $NaHCO_3$ and 1.0 mM CO_3^{2-} as eluent and H_2SO_4 as regenerant with a mixed standard of F^-, Cl^-, NO_2^-, Br^-, NO_3^-, PO_4^{3-} and SO_4^{2-} made in the required proportions from the standards purchased from Merck, Germany. A CS-17 column was used for cation separation with 6 mM methanosulfonic acid as eluent, and a mixed standard of Li^+, Na^+, K^+, Mg^{2+} and Ca^{2+} prepared in accordance with the approximate sample values. The data quality was ensured with routine check on standards. Samples having TDS range above 600 mg/L were diluted prior to the measurement of ions concentration. To estimate the precision of cations and anions measurement in analyzed samples ionic balance error (IBE) was estimated. The IBE was computed between the cation concentration (Ca^{2+}, Mg^{2+}, Na^+, and K^+)

and the anion concentration (HCO_3^-, Cl^-, SO_4^{2-}, NO_3^{2-}, and F^-) expressed in meq/L and the value of IBE were within the desired limit of $\pm 10\%$ (Domenico and Schwartz 1990; Jabal et al. 2014). The total hardness (TH) of the water sample is expressed as total dissolved salts of calcium (Ca) and magnesium (Mg) according to the Eq. (1) (Todd 1980):

$$\text{Total Hardness (TH)} \left(CaCO_3 \right)/L = 2.49\,(Ca)\,mg/L + 4.1\,(Mg)\,mg/L. \tag{1}$$

The calculated concentration of parameters are converted from mg/L to meq/L and the equations implemented for the derivation of irrigation parameters are represented in the equations below (Eqs. 2–7):

$$\text{SSP} = \frac{\left(Na^+ + K^+\right)}{\left(Ca^{2+} + Mg^{2+} + Na^+ + K^+\right)} \times 100 \quad \text{(Todd 1980),} \tag{2}$$

$$\text{KR} = \frac{\left(Na^+\right)}{\left(Ca^{2+} + Mg^{2+}\right)} \quad \text{(Kelly 1963),} \tag{3}$$
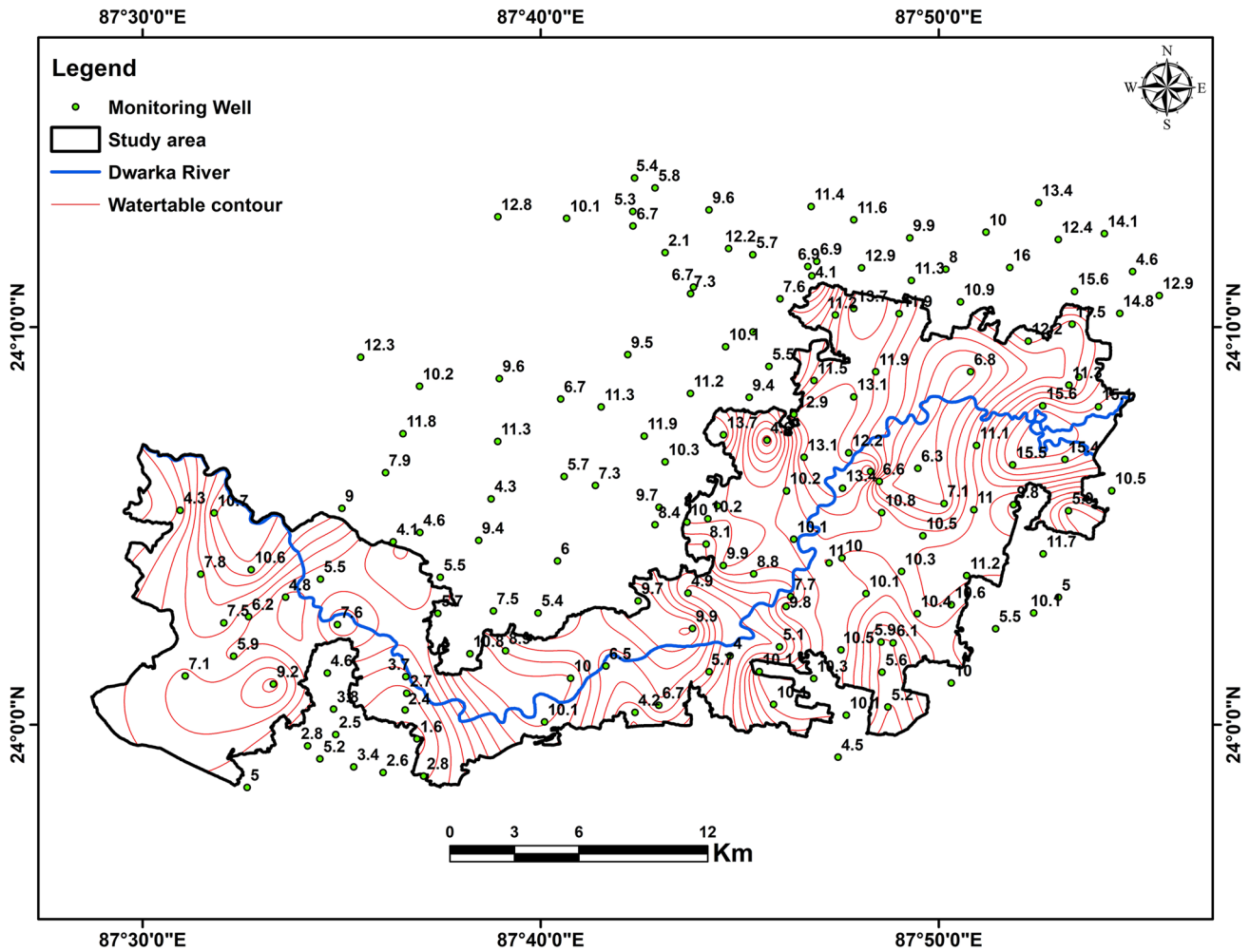
Fig. 2 Groundwater flow diagram within the study area

$$RSC = \left(CO_3^- + HCO_3\right) - \left(Ca^{2+} + Mg^{2+}\right) \quad \text{(Raghunath 1987),}$$
$$(4)$$

$$MAR = \frac{\left(Mg^{2+}\right)}{\left(Ca^{2+} + Mg^{2+}\right)} \times 100 \quad \text{(Raghunath 1987),} \quad (5)$$

$$SAR = \frac{\left(Na^+\right)}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \times 100 \quad \text{(Richards 1954),} \quad (6)$$

$$PI = \sqrt{\frac{\left(Na^+ + HCO_3\right)}{Ca^{2+} + Mg^{2+} + Na^+}} \times 100 \quad \text{(Doneen 1964).} \quad (7)$$

Development of irrigation water quality index (IWQI)

To execute the assessment of irrigation water quality suitability in the study area, nine parameters namely SAR, MAR, RSC, KR, SSP, PI, TH, EC and F^- were considered. In an attempt to develop an empirical formula to determine the IWQI, all the input parameters were classified into five different classes namely Class1, Class 2, Class 3, Class 4 and Class 5 where class 1 represents the very poor water quality and class 5 represents very good water quality for irrigation IWQI respectively. The classification was carried out based on literature survey (WHO 1984, 2008, 2011, BIS 2012, Brindha and Elango 2012; Dhanasekarapandian et al. 2016; Raj and Shaji 2017; Thapa et al. 2017e). In this method, all the input parameters were considered to have an equal impact on the overall IWQI. The ranks of each sample were assigned between '1' and '5' where '1' represents water with very poor quality and '5' represents excellent water (Table 1).
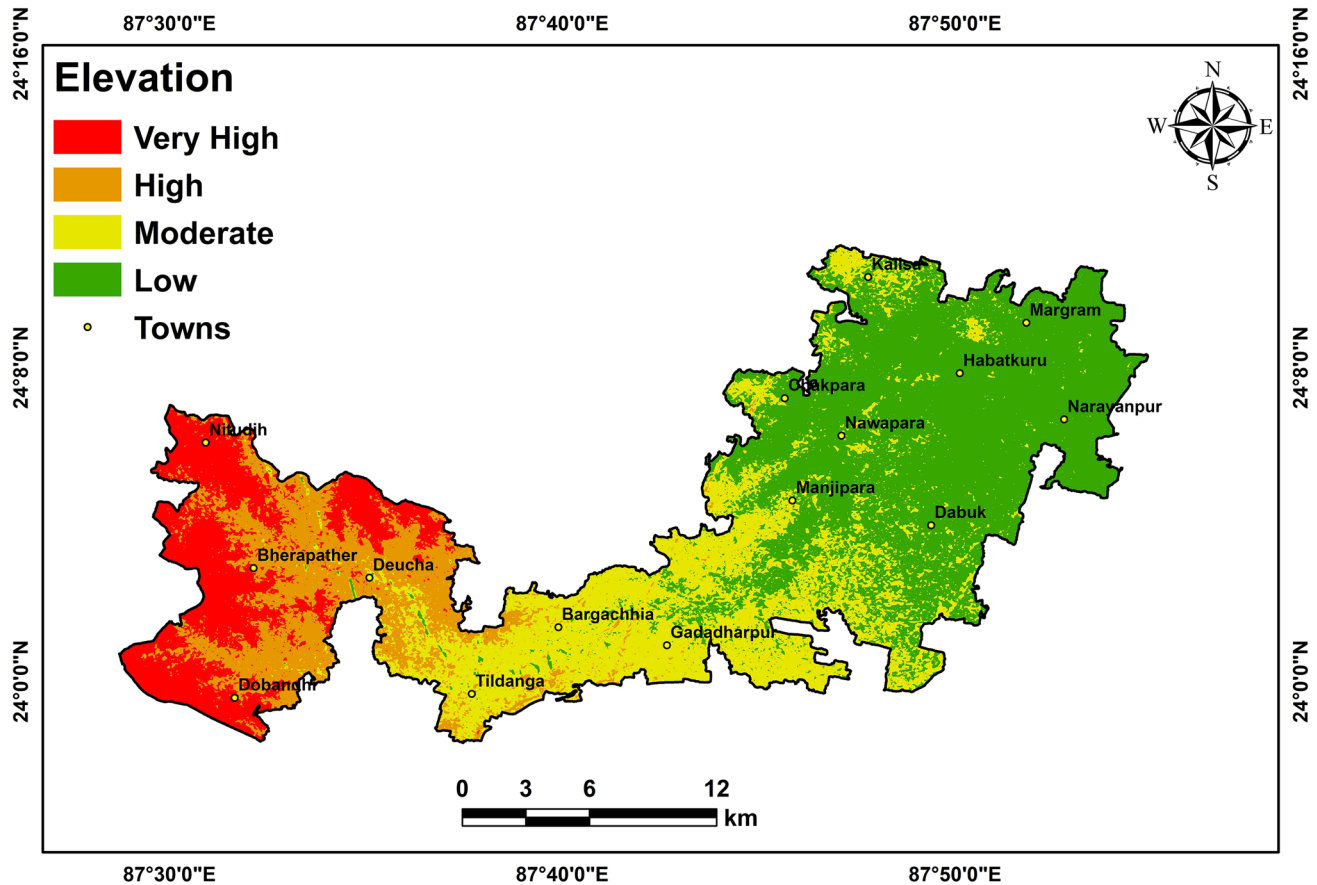
Fig. 3 Elevation map of the study area

The final IWQI in stretch Dwarka River basin was derived by summation of all the parameters that are classified into five classes each. The equation involved in the calculation of the IWQI has represented the equation below (Eq. 8):

$$\text{IWQI} = \sum_{i=1}^{n} \big(R_{\text{SAR}} + R_{\text{MAR}} + R_{\text{RSC}} + R_{\text{KR}} \\ + R_{\text{SSP}} + R_{\text{PI}} + R_{\text{TH}} + R_{\text{EC}} + R_{\text{F}} \big), \quad (8)$$

where, R is the rank of the parameter ranging from 1 to 5 depending upon the classification based on Table 1. IWQI generated is categorized into three different classes i.e., 0–15 (very poor), 16–30 (poor), and 31–45 (good). The class interval of each class is approximately equal to the number of parameters considered for the assessment multiplied by 5 (maximum rank) followed by division with 3. This method of class interval division has its superiority over other techniques is that it is dynamic and keeps changing with the number of input parameters without compromising the final irrigation water quality. This technique will highlight areas failing to meet the irrigation water suitability in the study area.

Results and discussion

Physicochemical analysis of water samples

The detailed physicochemical analysis results of the water sample are represented in Supplementary Table 1. The water sample of the study area indicates Ca–Mg–HCO$_3$ as the major water type. Apart from Ca–Mg–HCO$_3$ water type accounting for 76.61% of the total water samples other water types such as Ca–Mg–Cl–SO$_4$, Na–HCO$_3$–Cl, Na–Cl, Na–HCO$_3$ and Ca–Mg–SO$_4$ accounts for 12.69%, 5.12%, 2.47%, 2.14%, and 1% of the total sample respectively (Piper 1953). The order of abundance of cation are Ca^{2+} > Na$^+$ > Mg^{2+} > K$^+$ and abundance of anions is HCO$_3^-$ > CO$_3^-$ > F$^-$. Similar results have been reported by several researchers in their studies (Quddus and Zaman 1996; Mondal et al. 2014; Bodrud-Doza et al. 2016).

In the study area, according to SAR, all the water samples fall within a suitable range of irrigation water quality (Fig. 5a). Detail results of irrigation parameters of water samples in the study area are represented in Supplementary Table 2. The MAR of the water samples were categorised into five classes namely < 30, 30–40, 40–50, 50–60
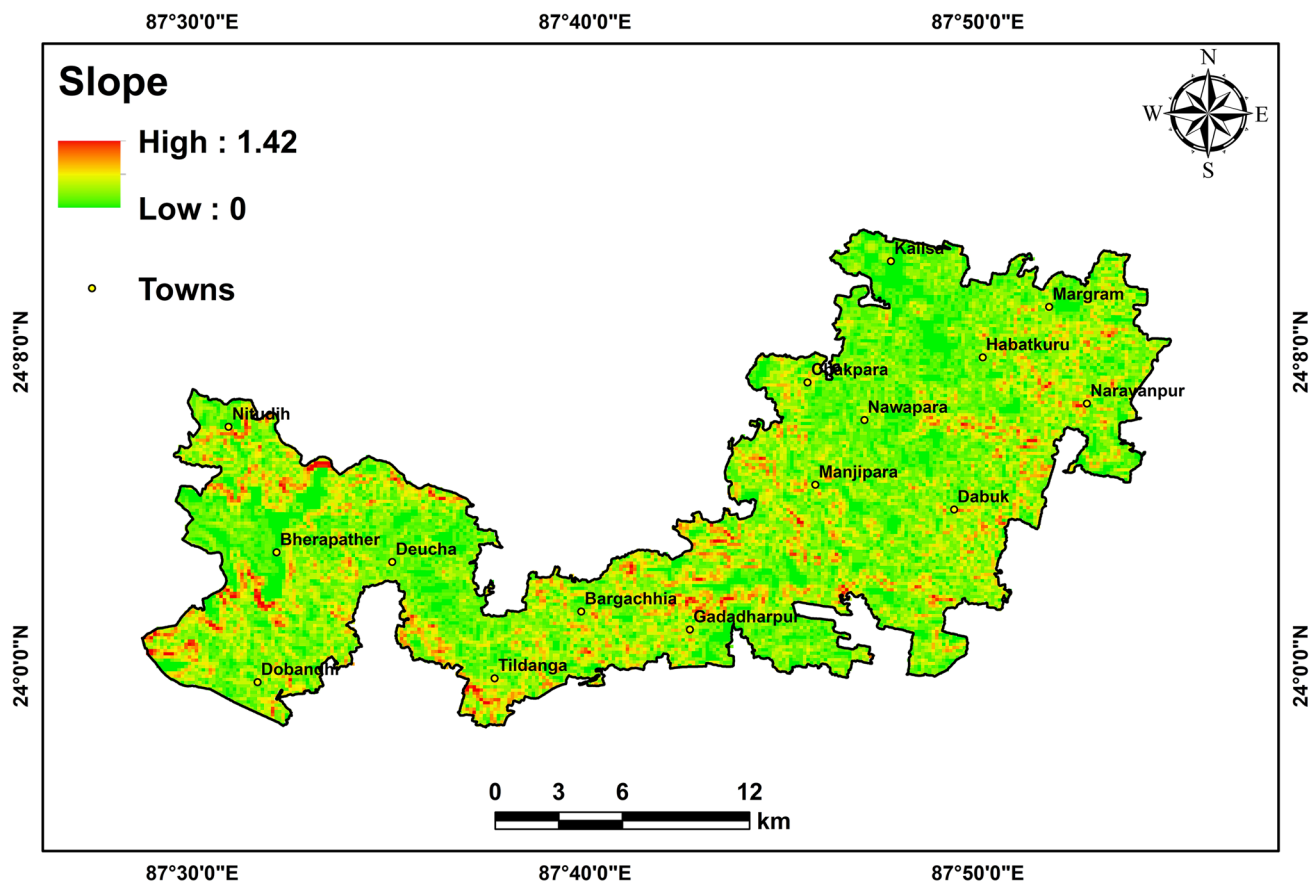
Fig. 4 Slope map of the study area

and > 60 with 467 (76.94%), 112 (18.45%), 22 (3.62%), 3 (0.49%) and 3 (0.49%) samples respectively (Fig. 5b). The RSC of the majority of samples 555 (91.43%) falls within 0.75 (Fig. 5c). Kelly's ratio of samples shows that 528 (86.99%), 27 (4.45%), 13 (2.14%), 5 (0.82%) and 34 (5.60%) falls under < 0.5, 0.5–0.75, 0.75–1.0, 1.0–1.25 and > 1.25, respectively (Fig. 5d). Majority of samples about 375 (61.78%) have SSP value < 30 followed by 109 (17.96%) falling in 30–40 class and 70 (11.53%) samples falling in 40–50 class (Fig. 5e). All water samples have PI value < 60 within the suitable irrigation limit (Fig. 5f). The hardness of the water sample in the study area is classified into five class namely very soft, soft, moderate, hard and very hard and it is observed that 11 (1.81%), 27 (4.45%), 137 (22.57%), 372 (61.29%) and 60 (9.88%) samples falls into each class respectively (Fig. 5g). EC in the water samples of study area ranges from 58 to 3200 µS/cm with an average value of 487 µS/cm. In the study area, 546 samples (90%) have EC value below 750 µS/cm indicating non-saline to averagely saline EC

(Fig. 5h). In the study area, about 1.3% (8 samples) of the total water samples have F⁻ content above 4 mg/L, 2.97% (18 samples) have F⁻ in the range of 2.5 and 4 mg/L, 3.79% (23 samples) have F⁻ value between 1–1.5 mg/L, the majority of the water sample 60.79% (369 samples) have F⁻ concentration ranging between 0.5–1.0 mg/L and 31.4% (189 samples) have F⁻ concentration below 0.5 mg/L.(Fig. 5i).

Irrigation water quality index (IWQI)

The IWQI for irrigation purpose was evaluated to determine the suitability of water for irrigation purposes. The IWQI was categorized into three classes. In the study area, approximately 95.38% (579 samples) of the total samples fall in 'good' category of IWQI indicating that the majority of water sample in the study area are good for irrigation purposes. About 4.61% (28 samples) of the total samples fall in 'poor' category of IWQI indicating poor quality unsuitable for irrigation. No sample falls in the very poor class of IWQI

Table 1 Weights and ranks assigned for irrigation water quality index (IWQI)

Sl no.	Parameter	Categories	Weights	Rank
1	SAR	<9	1	5
		9.0–18		4
		18–26		3
		26–35		2
		>35		1
2	MAR	<30	1	5
		30–40		4
		40–50		3
		50–60		2
		>60		1
3	RSC	<0.75	1	5
		0.75–1.0		4
		1.0–1.25		3
		1.25–2.5		2
		>2.5		1
4	KR	<0.5	1	5
		0.5–0.75		4
		0.75–1.0		3
		1.0–1.25		2
		>1.25		1
5	SSP	<30	1	5
		30–40		4
		40–50		3
		50–60		2
		>60		1
6	PI	<60	1	5
		60–70		4
		70–80		3
		80–90		2
		90–100		1
7	TH	<50	1	5
		50–75		4
		75–150		3
		150–300		2
		>300		1
8	EC	<750	1	5
		750–1000		4
		1000–1500		3
		15,000–2250		2
		>2250		1
9	F	Below 0.5	1	5
		0.5–1		4
		1–1.5		3
		1.5–4		2
		Above 4		1

suggesting that absence of areas with severe groundwater pollution. Nawapara with a population of 298 and about 0.35 sq.km area is among the most polluted irrigation water quality. Village wise population data of the year 2016–2017 is reported in supplementary Table (https://indiawater.gov.in). Nawapara has been reported to be endemic to fluoride-containing groundwater by several researchers. The IWQI value of Nawapara indicates it's unsuitable for usage in irrigation purposes which attributes to its high F^- content. Apart from high F^- content, Nawapara also has SSP, RSC, KR beyond the desired limit for irrigation. Similarly, in Junidpur with a total population of 205 and about 1.22 sq.km area IWQI is below 30 indicating poor water qualities which are due to the poor SSP, RSC, KR and TH in the study area. Chakpara and Bhelian show the poorest water quality with IWQI value of 26. Chakpara with a total population of 2451 and about 4.01 km^2 area has very poor SAR, RSC and KR. Bhelian with a total population of 1169 and about 1.34 km^2 show very poor RSC and MAR along with poor SSP, KR and TH. Villages such as Baharakunri, Gopalnagar, Chapadanga, Jayrampur, Shaikherdah, Bargachhia, Pachanpur, Andhargram, Kalitala, Abdarpur, Bishnupur and Bodmati indicate good quality of irrigation water with 44 value in IWQI since all the input parameter in these villages are within the permissible limit.

Conclusion

Throughout the study area, the water type is dominated by Ca^{2+} and $HCO_3^{\cdot-}$ ions except for a few patches where Na^+ is the dominant cation. The order of abundance of anions and cation in the study area are $HCO_3^- > Cl^- > CO_3^{-2} > SO_4^{2-} > F^-$ and $Ca^{2+} > Na^+ > Mg^{2+} > K^+$ respectively. In the majority of instances, the concentrations of parameters are under permissible limits. IWQI represents about 95.38% (579 samples) of the total samples fall in the good IWQI category and about 4.61% (28 samples) of the total samples fall in the poor category of IWQI. Except for a few villages namely Nawapara, Junidpur, Chakpara, Bhelian, Benechapar, Dasandaria, Habatkuru, Raghunathpur, Bilaspur, Habatkuru, etc. the water quality for irrigation purpose in the study area is generally good. The methodology applied classified the water samples into two groups and proven simple and efficient tool for quick analysis of water suitability and can be applied by the researcher with or without modification. The traditional water quality assessment represents the general water quality with respect to irrigation. The irrigation water
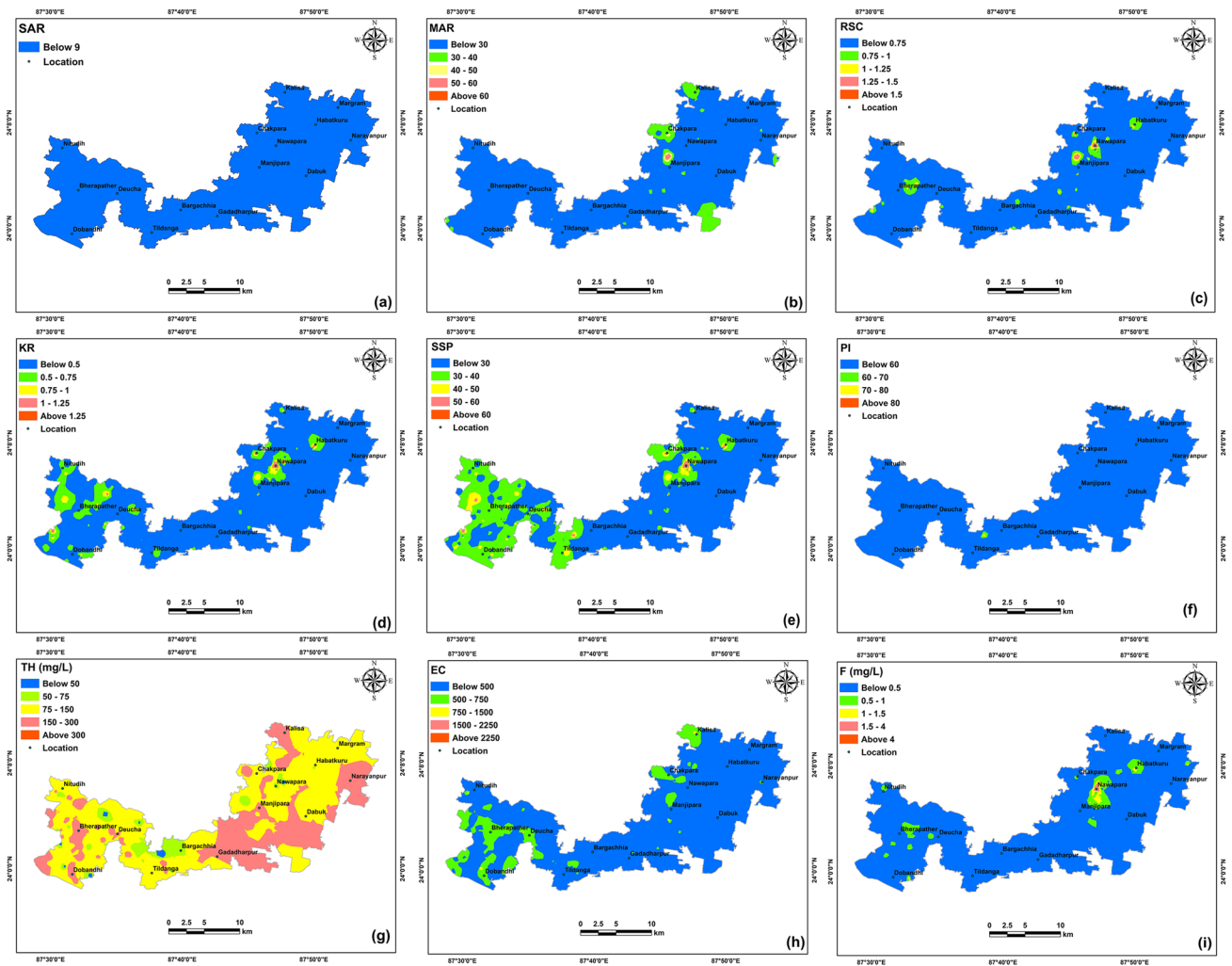
Fig. 5 Spatial distribution of parameters in the study area **a** SAR, **b** MAR, **c** RSC, **d** KR, **e** SSP, **f** PI, **g** TH, **h** EC and **I** F

quality index (IWQI) which gives equal rank from 1 to 5 to all the parameters underlines any parameter exceeding the permissible limit. However, it is important to note that mere exceeding the permissible limit not necessarily makes the water unsuitable for irrigation in all the cases. This method demarcates areas that exceed the permissible limit of water quality and can be very useful firsthand information to carry out further analysis. A detailed site-specific assessment can be further carried out to get an insight into the impact of irrigation water on soil, crops, and subsequently in the health of the population. Periodical monitoring of groundwater, rainwater harvesting, secondary uncontaminated water source, managed aquifer recharge, and public awareness can play a crucial role in the long run especially in the areas with unsuitable irrigation water quality.

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