Applied Water Science (2024) 14:66
https://doi.org/10.1007/s13201-024-02122-5

REVIEW ARTICLE

Watering Sundarban's fields: a systematic review of groundwater and surface water suitability for irrigation

Monika[1] · **Dimple**[1] · **Sunil Kumar**[2] · **Arup Giri**[1]

Received: 19 October 2023 / Accepted: 30 January 2024 / Published online: 7 March 2024

Abstract

The Sundarban region—located from the Hooghly River in India's state of West Bengal to the Baleswar River in Bangladesh—renowned for its distinctive ecosystem and agricultural techniques, heavily depends on groundwater for irrigation purposes. However, concerns arise regarding the suitability of groundwater for sustainable agriculture in this vulnerable coastal zone. This systematic review aims to comprehensively evaluate the quality and appropriateness of groundwater and surface water for irrigation in the Sundarban region. By extensively searching scientific databases and relevant literature, we identified eighteen studies meeting our inclusion criteria. These studies encompassed hydrological, hydrochemical, and agronomic parameters, facilitating a thorough assessment of groundwater quality and its potential impacts on crop productivity. The review evaluates key parameters such as total hardness, residual sodium carbonate, potential salinity, permeability index, Kelly's ratio, sodium absorption ratio, corrosivity ratio, and chloroalkaline indices. The results revealed that irrigation water displays an alkaline nature, and both surface water and groundwater were unsuitable for irrigation due to exceedingly high-quality parameters beyond the standard limits. Nevertheless, groundwater exhibited favorable physiochemical properties. The review identifies critical research gaps and proposes future directions to enhance the understanding of groundwater suitability for irrigation in the Sundarban region. The findings emphasize the necessity of a multidisciplinary approach to ensure sustainable agricultural practices and safeguard the delicate ecosystem of the Sundarban region.

Keywords Agronomic parameter · Corrosivity ratio · Hydrochemical parameter · Kelly's ratio · Water quality

Introduction

The Sundarban, a tide-dominated wetland, forms a complex network of estuaries, tidal inlets, creeks, and islands. The region is crisscrossed by numerous rivers, giving rise to a tidal river system and estuaries (Chatterjee et al. 2013). Nestled in the deltaic floodplains of the Ganges and Brahmaputra rivers, the Sundarban region is renowned for its unique mangrove ecosystem. It is a vital agricultural zone in South Asia (Manna et al. 2010). Spanning parts of Bangladesh and India, the Sundarbans are home to a significant rural population whose livelihoods heavily depend on agriculture. Major rivers within the Indian Sundarban, such as Hooghly and Muriganga, are connected to the Himalayan glaciers through the Ganges. However, the Saptamukhi, Thakuran, Matla, Gosaba, and Harinbhanga rivers, being tide-fed, have lost their upstream connections with the Ganges due to siltation and waste disposal from nearby urban centers (Mondal et al. 2013). Regrettably, the once productive Bidyadhari River, a branch of the Bhagirathi in the fifteenth and sixteenth centuries, is now heavily silted up and functions mainly as a sewage and excess precipitation outlet from Kolkata (Banerjee 2013).

Tidal water level variations have been observed across different stations, covering more than 3600 km^2, including the Saptamukhi, Thakuran, Matla, Bidya, Gomdi,

✉ Arup Giri
arupsatadal@gmail.com

Monika
monikarohilla988@gmail.com

Dimple
dimpleparashar00@gmail.com

Sunil Kumar
sunilevs@yahoo.com

[1] Department of Zoology, Baba Masthnath University, Asthal Bohar, Rohtak, Haryana 124021, India

[2] Department of Environmental Sciences, Maharshi Dayanand University, Rohtak, Haryana 124001, India

Harinbhanga, and Raimangal estuaries in the Indian Sundarbans (Chatterjee et al. 2013).

Agriculture in this region relies heavily on groundwater resources for irrigation due to the limited availability of surface water (Jain et al. 2021). Groundwater, primarily extracted from shallow aquifers, raises concerns about its suitability for irrigation due to its complex hydrogeological characteristics and natural and anthropogenic contaminants in the area (Sahoo et al. 2021).

The hydrogeochemistry of the Sundarbans region emerges as a crucial factor in understanding the intricate interplay between groundwater composition, aquifer properties, and regional influences. Groundwater quality, a product of hydrogeochemical processes (Lakshmanan et al. 2003), is shaped by factors such as geochemistry (Mukherjee and Fryar 2008), aquifer characteristics (Verma et al. 2019; Kumar et al. 2022), and human activities (Zahid et al. 2006; Shamsudduha et al. 2009; Tauqeer et al. 2021). A study reported that the dominance of Ca-Mg-HCO_3-rich waters in unconfined aquifers (Type I) contrasts with the Na-Cl hydrogeochemical facies prevalent in semiconfined (Type II) and nearly confined multilayered aquifer subsystems (Type III) (Chakraborty et al. 2022). Noteworthy studies suggest that the hydrogeochemistry within the delta is governed by carbonate dissolution, silicate weathering, and cation exchange processes (Mukherjee and Fryar 2008). However, a gap persists in understanding the regional-scale hydrogeochemical evolution pathways across the delta (Sikdar et al. 2001). The chemical composition of groundwater in the Sundarbans is intricately tied to rock–water interactions, seasonal variations, and anthropogenic activities. Processes, such as carbonate and silicate weathering, ion exchange, seawater intrusion, and anthropogenic influences, contribute to dynamic hydrogeochemistry (Mukherjee and Fryar 2008; Tauqeer et al. 2021; Kumar et al. 2022). This region exhibits dominant geochemical activities, with carbonate weathering, silicate weathering, and ion and cation exchange playing pivotal roles. The major ion chemistry, characterized by $Ca^{2+} > HCO_3^- > Cl^- > Na^+ > Mg^{2+} > SO_4^{2-}$, underscores the complexity of hydrogeochemical interactions. Moreover, anthropogenic causes, including the agricultural practices and industrial waste, significantly impact groundwater geochemistry. The use of diverse fertilizers alters the chemical composition during percolation, influencing concentrations of sulfate, halite, and gypsum in the aquifer (Refat Nasher and Humayan Ahmed 2021).

With this hydrogeochemistry, one of the primary challenges for agriculture in the Sundarban region, especially in cultivating rabi rice and other crops, is the scarcity of fresh surface water for irrigation, leading to extensive reliance on shallow tube wells (STWs) to extract groundwater. Surveys conducted between 2000 and 2014 have focused on STWs in the South and North 24 Parganas districts (Burman et al. 2015). Similarly, in the Sundarban region of Bangladesh, tube wells are typically installed between 150 and 350 m deep. The interface between fresh and saline groundwater is usually between 200 and 300 m below ground level in the Khulna region, with the upper aquifer containing brackish to salty water (Worland et al. 2015). Additionally, saline pockets can be found in both shallow and deep aquifers due to the presence of paleo-brackish water trapped during rapid regressive events that occurred between 12,000 and 10,000 years ago, following a transgression period between 18,000 and 12,000 years ago (Jahan et al. 2022).

The proper management and conservation of groundwater resources in the Sundarban region are essential to sustain agriculture and support the livelihoods of the local population while also ensuring the protection of the delicate mangrove ecosystem.

In recent years, growing concerns have emerged regarding the deteriorating quality of groundwater and surface water in the Sundarban region, characterized by elevated levels of salinity, iron, chloride, and other chemical parameters, as documented by several studies (Okereafor et al. 2020; Ghirardelli et al. 2021). The intrusion of saline water from seawater, combined with the region's geological and hydrological factors, has led to the infiltration of saline water into aquifers, adversely impacting water quantity and quality (Hajji et al. 2022). Anthropogenic activities, including agricultural practices, industrial discharge, and improper waste management, have further contributed to groundwater and surface water contamination with various chemicals (Khalid et al. 2018).

The unsuitability of groundwater and surface water affects crop productivity and yield and impacts soil health, water use efficiency, and overall agricultural system sustainability. The heavy reliance on contaminated water sources for irrigation exacerbates these challenges, resulting in reduced crop production, heightened vulnerability to climate change, and potential long-term environmental degradation (Borsato et al. 2020).

To address these concerns and promote sustainable agricultural practices regarding groundwater and surface water quality, it is essential to evaluate the levels of various ions such as Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, and HCO_3^-, which influence parameters such as total hardness (TH), residual sodium carbonate (RSC), potential salinity (PS), permeability index (PI), Kelly's ratio (KR), sodium absorption ratio (SAR), sodium percentage (Na%), corrosivity ratio (CR), and chloroalkaline indices (CAI). A comprehensive assessment of hydrogeological, hydrochemical, and agronomic parameters can provide valuable insights into the current state of groundwater quality and its implications for irrigation practices (Chen et al. 2020).

This review aims to address this knowledge gap by systematically analyzing the available literature on the suitability of groundwater for irrigation in the Sundarban region. It aims to synthesize and analyze previous research findings, assess the impact of groundwater quality on agricultural productivity, identify existing challenges, and propose potential mitigation strategies (Nath et al. 2021). By understanding the present state of groundwater and surface water suitability for irrigation and addressing knowledge gaps, this review will contribute to developing sustainable water management practices and enhancing the resilience of agriculture in the Sundarbans. It will also provide valuable guidance to policymakers, researchers, and practitioners on the importance of integrating hydrological, hydrochemical, and agronomic perspectives to ensure the long-term sustainability of agriculture in this ecologically fragile and socioeconomically significant region.

Materials and methods

Study area

Research articles have been reviewed that were carried out in the Sundarban region of India and Bangladesh for groundwater and surface water analysis (as shown in Fig. 1). The neglected sections of the lower deltaic plain were extensively developed into the Sundarban mangroves, starting from 1770 AD, by the rulers of British India's East India Company, aiming to profit from agricultural activities. The Sundarban in Bangladesh has been designated a UNESCO World Heritage Site and is situated in the southwestern part of the country, between latitudes 21° 39′ and 22° 30′ N and longitudes 89° 01′ and 89° 52′ E, as per the International Union for Conservation of Nature (IUCN) in 1997. The total area of the Sundarban is 10,000 km^2, with 60% (6000 km^2) falling within Bangladesh. Among its total area,

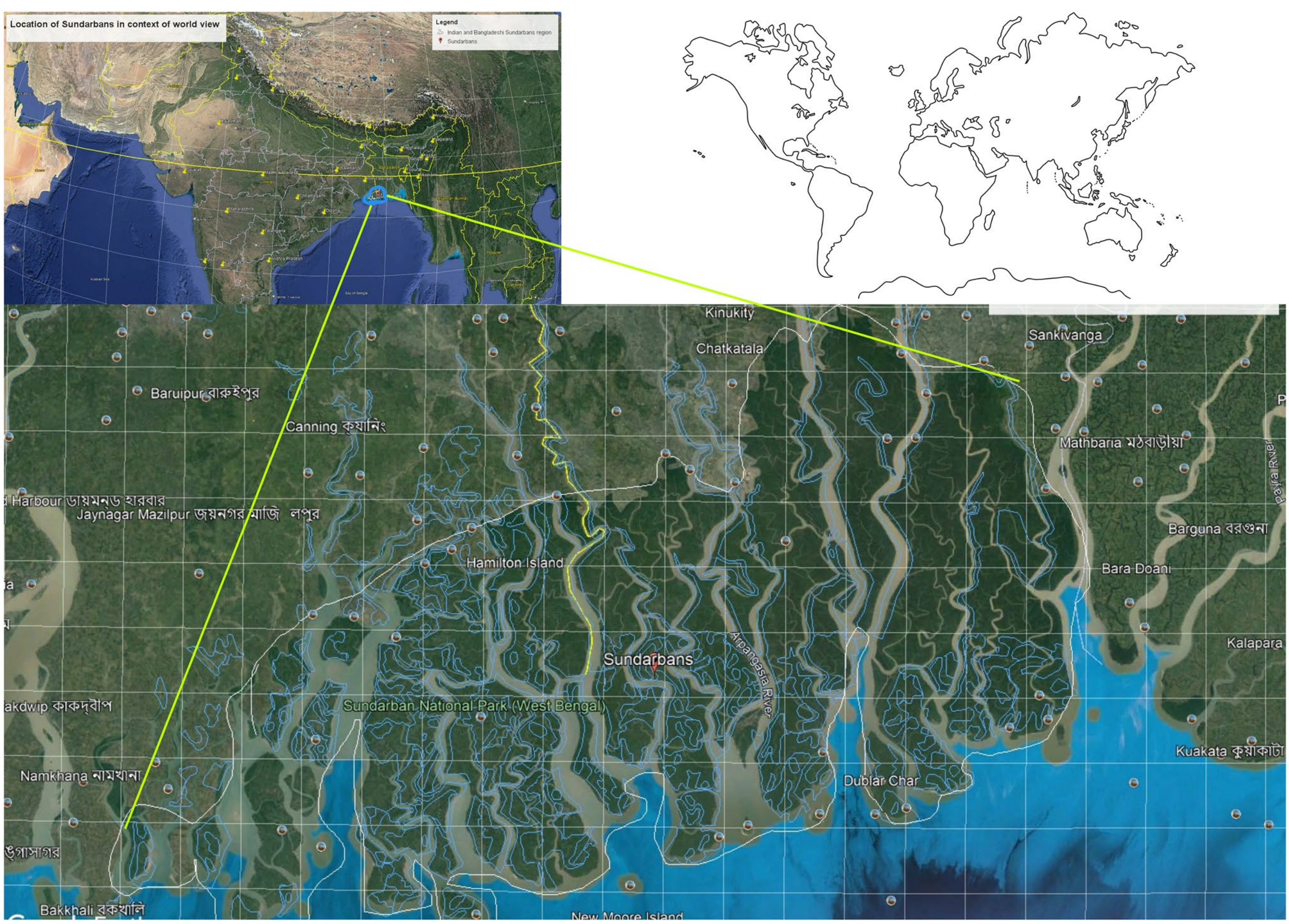

Fig. 1 Research data collection sites of Indian and Bangladesh Sundarban. The white lines encircling islands denote the geographic boundaries, clearly illustrating the location of the Sundarban region. The inclusion of this map is integral to our study, as it visually contextualizes the source of research data on groundwater and surface water quality that was considered for this systematic review

the Sundarban comprises 187,413 ha of aquatic bodies and 414,259 hectares of land, accounting for 70% of the overall expanse.

Data search strategy, database, and keywords used

A comprehensive search of the literature was conducted to identify relevant studies on the suitability of groundwater and surface water for irrigation in the Sundarban region. The data search was performed using electronic databases, including "Google Scholar," "ScienceDirect," and "PubMed" to enhance the search precision. The keywords used for data collection included "Sundarban," "water resources," "water quality," "groundwater," "surface water," "physiochemical properties," and "hydrochemical." The collected articles were limited to those published between 2011 and 2023 to ensure the relevance of the data. Included studies focused on water quality assessment, physiochemical analysis, hydrochemical analysis, and agrochemical characteristics of groundwater and surface water in the Sundarban region. Articles lacking proper data or full-text accessibility were excluded. Additionally, studies published before 2011 and those solely used for literature review without data analysis were not included.

Data collection and selection

The PRISMA chart was followed to meet the criteria of this systematic review (Heasley et al. 2021) (Fig. 2). Initially, approximately 250 articles were retrieved from the data search. After removing 40 duplicated downloads, 70 articles were excluded based on the initial screening as they did not contain relevant data related to the physiochemical properties of water in the Sundarban region. The remaining 140 articles underwent a thorough review, and 122 of them were excluded due to insufficient or insignificant data. Finally, 18 articles were identified as primary sources for the study, containing valuable data related to water quality, physiochemical analysis, hydrochemical analysis, and agrochemical characteristics of water. Supplementary files have been documented with all the primary data (Tables S1–S3).

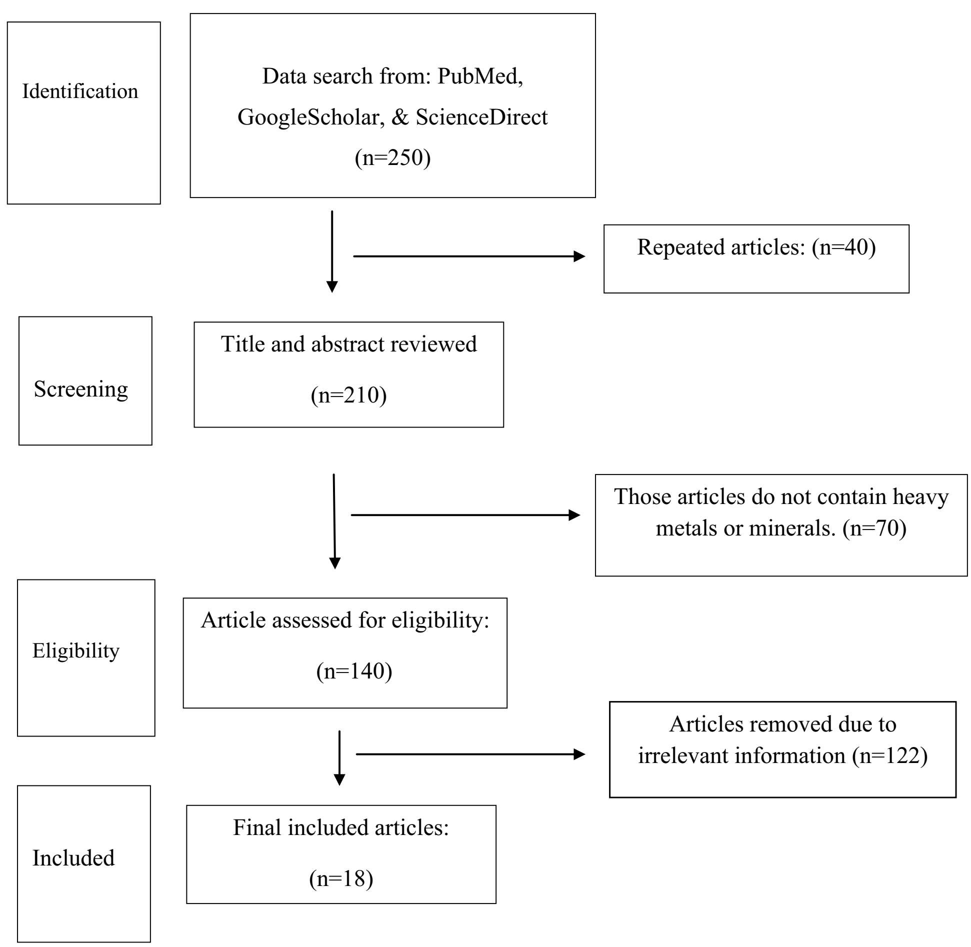

Fig. 2 Flow diagram (PRISMA chart) showing the selection and search process for data collection. Approximately 250 articles were retrieved from the data search. After removing 40 duplicated downloads, 70 articles were excluded based on the initial screening as they did not contain relevant data related to the physiochemical properties of water in the Sundarban region. The remaining 140 articles underwent a thorough review, and 122 of them were excluded due to insufficient or insignificant data. Finally, 18 articles were identified as primary sources for the study

Data organization

Data synthesis and analysis

The selected articles were thoroughly analyzed and synthesized to extract relevant information on the suitability of groundwater and surface water for irrigation in the Sundarban region. The extracted data were then organized in tables (Tables S1–S3) to facilitate data presentation and comparison.

Quality assessment

The quality of the included studies was assessed to ensure the reliability and validity of the data. Quality assessment criteria included study design, sample size, data collection methods, and reporting clarity. Studies that met rigorous quality standards were given higher consideration in the data synthesis.

Data interpretation and conclusion

The findings from the selected articles were interpreted and discussed to provide a comprehensive review of the suitability of groundwater and surface water for irrigation in the Sundarban region. The conclusions drawn from the data synthesis will shed light on the current state of water resources and their implications for sustainable agricultural practices in the Sundarban region (Table 1).

Classification of water quality based on different parameters

The classification used in this study, indicating the suitability of groundwater and surface water for irrigation, is presented in Table 2. Several parameters are used for the classification.

Results and discussion

Physicochemical characteristics of groundwater and surface water for irrigation purposes

Various parameters were employed to assess the physiochemical properties of irrigation water, including pH, electrical conductivity (EC), total dissolved solids (TDS), and chemical compositions determined by major ions and heavy metals. In this study, we specifically analyzed the physiochemical properties of water with a focus on major cations, anions, pH, EC, and TDS.

The pH values of groundwater samples in the study area ranged from 3.52 to 9.99 mg/L, while surface water samples exhibited a broader pH range of 12.09 to 15.25 mg/L, as presented in Table 3. Notably, surface water displayed

Table 1 Different indices/parameters used for the evaluation of water quality

S. no.	Index	Symbol	Equation	Sources
1	Total Hardness (mg/L)	TH	$TH = (2.5 \times Ca^{2+}) + (4.2 \times Mg^{2+})$	Todd and Mays (2005)
2	Residual Sodium Carbonate (meq/L)	RSC	$RSC = (CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+})$	Eaton et al. (1995)
3	Potential Salinity (meq/L)	PS	$PS = Cl^- + (0.5 \times SO_4^{2-})$	Doneen (1964)
4	Permeability Index (all the ion concentrations are expressed in meq/l)	PI	$PI = \frac{Na^+ + \sqrt{HCO_3^-}}{Ca^{2+}+Mg^{2+}+Na^+} \times 100$	Doneen (1964)
5	Kelly's Ratio (all the ion concentrations are expressed in meq/l)	KR	$KR = \frac{Na^+}{Ca^{2+}+Mg^{2+}}$	Kelley (1963)
6	Magnesium Hazard (all the ion concentrations are expressed in meq/l)	MH	$MH = \frac{Mg^{2+}}{Ca^{2+}+Mg^{2+}} \times 100$	Szabolcs (1964)
7	Sodium Percentage (all the ion concentrations are expressed in meq/l)	Na%	$NA(\%) = \frac{Na^+ + K^+}{Ca^{2+}+Mg^{2+}+Na^+ + K^+} \times 100$	Todd and Mays (2005)
8	Sodium Absorption Ratio (Na^+, Ca^{2+} and Mg^{2+} are in meq/L)	SAR	$SAR = \frac{Na^+}{\sqrt{\frac{1}{2}(Ca^{2+}+Mg^{2+})}}$	Allison (1964)
9	Corrosivity Ratio (all the ion concentrations are expressed in meq/l)	CR	$CR = \frac{(Cl^-/35)+2(SO_4^{2-}/96)}{(CO_3^{2-}+HCO_3^-/100)}$	Balasubramanian (1986)
10	Choroalkaline indices 1 (meq/L)	CAI1	$CAI1 = \frac{Cl^- - (Na^+ + K^+)}{Cl^-}$	Schoeller (1977)
11	Choroalkaline indices 2 (meq/L)	CAI2	$CAI2 = \frac{Cl^- - (Na^+ + K^+)}{SO_4^{2-}+(CO_3^- + NO_3^-)}$	Schoeller (1977)

Concentrations of all the ions expressed in meq/l

Table 2 Classification of surface water and groundwater suitability for irrigation purposes based on different water quality indices (Kelley 1940; Wilcox 1948; Thorne 1954; Todd and Mays 1980). Table adapted from Giri et al. (2022)

S. no.	Index	Class											
		Exc	Go	Perm	Dou	Su	UnSu	REP	DEP	Soft	Mode	Hard	V.Hard
1	pH	–	6.5–8.4	–	–	–	–	–	–	–	–	–	–
2	EC	< 250	250–750	750–2250	–	–	–	–	–	–	–	–	–
3	TDS	< 450	450–2250	–	–	–	> 2000	–	–	–	–	–	–
4	TH	–	–	–	–	–	–	–	–	0–60	60–120	120–180	> 180
5	RSC/RA	–	< 1.25	–	1.25–2.5	–	> 2.5	–	–	–	–	–	–
6	PS	–	–	–	–	< 3	> 3	–	–	–	–	–	–
7	PI	–	25–75%	–	–	> 75%	< 25%	–	–	–	–	–	–
8	KR/KI	–	–	–	–	< 1	> 1	–	–	–	–	–	–
9	MAR/MH	–	–	–	–	< 50	> 50	–	–	–	–	–	–
10	%Na	< 20	20–40	40–60	60–80	–	> 80	–	–	–	–	–	–
11	SAR	< 10	10–18	–	18–26	–	> 26	–	–	–	–	–	–
12	CR	–	–	–	–	< 1	> 1	–	–	–	–	–	–
13	CAI1	–	–	–	–	–	–	– tv	+ tiv	–	–	–	–
14	CAI2	–	–	–	–	–	–	– tv	+ tiv	–	–	–	–

Exc. Excellent, *Go.* Good, *Perm.* Permeability, *Dou.* Doubtful, *UnSu* Unsuitable, *REP* Reverse exchange process, *DEP* Direct exchange process, *V.* Hard very hard, *TH* Total hardness, *RSC* Residual sodium carbonate, *PS* Potential salinity, *PI* Permeability index, *KR* Kelly's ratio, *SAR* Sodium absorption ratio, *MH* Magnesium hazard, *NA%* Sodium percentage, *CR* Corrosivity ratio, *CAI1* Chloroalkaline indices 1, *CAI2* Chloroalkaline indices 2

an alkaline nature, as evidenced by its high pH level. Conversely, groundwater was deemed suitable for irrigation in this investigation. The alkaline nature of water corresponds to a higher pH level, which occurs when there is a significant concentration of hydroxide ions present in the water sample.

Electrical conductivity (EC) is a crucial factor for evaluating the suitability of irrigation water, as it reflects the presence of salts in the water, which can impact crop yield (Ayers and Wescott 1985; Bauder and Brock 2001). In this study, the EC values for surface water ranged from 3.27 to 3567.95 µS/cm, while for groundwater, the range was 0.30 to 270.50 µS/cm as presented in Table 3. According to the classification, irrigation water with an EC of 250 µS/cm is considered excellent, 250–750 µS/cm is considered good, and 750–2250 µS/cm is still acceptable (Ayers and Wescott 1985) (Table 2). The findings of this study indicate that groundwater falls within the good category concerning EC, while surface water falls into the unsuitable category, making it unsuitable for irrigation due to its higher EC levels.

Another important component affecting water quality in agriculture is total dissolved solids (TDS), which depend upon minerals and ions such as Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, CO_3^{-}, HCO_3^{-}, Cl^{-}, SO_4^{2-}, and PO_4^{3-} (Giri et al. 2022). The classification of water quality based on TDS is as follows: excellent for irrigation at less than 450 mg/L, good within 450–2000 mg/L, and unsuitable greater than 2000 mg/L (EPA 2014) (Table 2).

The total dissolved solids (TDS) content in surface water ranged from 1.32 to 2922.72 mg/L, while in groundwater, it ranged from 0.54 to 215.45 mg/L, as indicated in Table 3. The study findings demonstrated that groundwater exhibited chemical ion concentrations within the excellent quality range for irrigation water. Conversely, surface water was deemed unsuitable for irrigation due to its TDS value exceeding the permissible limit. The higher TDS in surface water can be attributed to elevated concentrations of Na^{+}, Cl^{-}, and HCO_3^{-}, surpassing the acceptable thresholds.

The measured concentrations of chloride, sulfate, phosphate, bicarbonate, and nitrate in surface water samples ranged from 35.20–572.36 mg/L, 55.50–57.37 mg/L, 1.15–1.47 mg/L, 0.03–419.83 mg/L, and 2.73–8.26 mg/L, respectively, as presented in Table 3. For groundwater samples, the concentrations of chloride, sulfate, phosphate, carbonate, bicarbonate, and nitrate were found to be within the ranges of 9.97–49.08 mg/L, 0.24–1.79 mg/L, 0.100–14.92 mg/L, 0.0–0.35 mg/L, 0.23–141.26 mg/L, and 0.15–1.84 mg/L, respectively, as shown in Tables 3 and 4.

As per the standards set by the World Health Organization, the allowable limits for Cl^{-}, SO_4^{2-}, PO_4^{3-}, HCO_3^{-}, and NO_3^{-} in irrigation water are 250 mg/L, 200 mg/L, 10 mg/L, 200 mg/L, and 50 mg/L, respectively, as shown in Table 2 (World Health Organization 2006). The study's results revealed that concentrations of salt ions in groundwater samples were within these established permissible limits. However, in surface water samples, the concentrations of Cl^{-} and HCO_3^{-} exceeded the standard permissible values set by the World Health Organization (2006) (Table 2).

Table 3 Mean physiochemical and mineral (mg/L) contents in groundwater and surface water in the Sundarban region

Location	pH	Temp	EC	Salinity	TDS	TCC	DOC	Na	Ca	Mg	CO_3^{2-}	HCO_3^-	Si	NO_3^-	Cl^-	F
Surface water																
Indian Sundarban	15.25	4.16	3.27	9.87	1.32	13.21	0.00	27.11	37.46	48.23	0.00	0.03	5.66	2.73	35.28	0.28
Bangladesh	12.09	22.61	3567.95	0.08	2922.72	0.00	15.34	276.11	47.58	48.39	0.00	419.83	0.00	8.26	572.36	0.07
Groundwater																
Indian Sundarban	9.99	0.00	270.50	2.84	215.45	7.51	1.53	41.85	33.65	32.33	0.35	141.26	0.00	1.84	49.08	0.21
Bangladesh	3.52	0.00	0.30	1.04	0.54	0.00	13.50	0.25	0.01	0.04	0.00	0.23	0.00	0.15	0.17	0.00

pH Power of hydrogen, *Temp.* Temperature, *EC* Electrical conductivity, *TDS* Total dissolved solids, *TCC* Total cation concentration, *DOC* Dissolved oxygen concentration, *Na* Sodium, *Ca* Calcium, *Mg* Magnesium, CO_3^{2-} Carbonate, HCO_3^- Bicarbonate, *Si* Silica, NO_3^- Nitrate, Cl^- Calcium, F^- Fluorine

The concentrations of Ca^{2+}, Mg^{2+}, and Na^+ in surface water samples ranged from 37.46–47.58 mg/L, 48.23–48.39 mg/L, and 27.11–276.11 mg/L, respectively. In groundwater samples, the corresponding ranges were 0.01–33.65 mg/L, 0.04–32.33 mg/L, and 0.25–41.85 mg/L, respectively, as presented in Table 3. For irrigation purposes, the acceptable limits for Ca^{2+}, Mg^{2+}, and Na^+ are 75 mg/L, 30 mg/L, and 200 mg/L, respectively, as per (Singh et al. 2020). The data indicate that all the various salt ion concentrations are within the standard permissible limits, except for Na^+, which slightly exceeds the prescribed value.

Evaluation of the suitability of groundwater and surface water for irrigation purposes

This review employed various parameters, including TH, RSC, PI, KR, SAR, CAI1, and CAI2, to evaluate the suitability of groundwater and surface water for irrigation. The total hardness (TH) of water is influenced by the concentrations of calcium and magnesium in both groundwater and surface water (Sengupta 2013). According to EPA (2014) classifications, water can be categorized as soft (0–60 mg/L), moderately hard (60–120 mg/L), hard (120–180 mg/L), or very hard (greater than 180 mg/L) (Table 2).

The study found that the TH values of surface water ranged from 296.21 to 322.21 mg/L, while groundwater TH varied from 219.9 to 0.21 mg/L (Table 5). Notably, the present study demonstrated that the total hardness (TH) values fell under the hard category, with collected water samples containing elevated levels of Ca^{2+} and Mg^{2+} ions. These findings indicate that the water's hardness makes it unsuitable for irrigation purposes. In contrast, the groundwater in the Sundarbans region of Bangladesh exhibited a TH value falling in the soft category, rendering it suitable for irrigation purposes.

Residual sodium bicarbonate (RSC) is a critical factor affecting the quality of irrigation water. When the concentration of carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) in water exceeds that of calcium (Ca^{2+}) and magnesium (Mg^{2+}), it can adversely impact water quality by promoting the precipitation of calcium and magnesium. This, in turn, affects the physical characteristics of soils, leading to the breakdown of organic substances within the soil. The study found that the levels of Na^+ were high in water with sodium carbonate (Eaton et al. 1995; Mousazadeh et al. 2019).

As per the EPA (2014) guidelines, water with RSC values below 2.50 meq/L is suitable for irrigation, while values above 2.50 meq/L are considered unsuitable (Table 2). Positive RSC values in water samples indicate that the concentrations of Ca^{2+} and Mg^{2+} are lower than those of CO_3^{2-} and HCO_3^-, while negative values indicate the reverse exchange process. The present study observed RSC values in surface water ranging from -85.65 to 323.86 meq/L, while in

Table 4 Mean values of heavy metals (mg/L) in groundwater and surface water in the Sundarban region

Location	K	Mn	Fe	Co	Cd	Cr	Ni	Ag	Zn	Cu	SO_4^{2-}	PO_4^{3-}	Pb
Surface water													
Indian Sundarban	3.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	55.50	1.15	0.00
Bangladesh	18.70	0.09	2.35	0.00	0.00	0.05	0.01	0.01	0.04	0.01	57.37	1.47	0.01
Groundwater													
Indian Sundarban	2.37	0.00	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.79	14.92	0.00
Bangladesh	0.16	70.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.10	0.00

K Potassium, *Mn* Manganese, *Fe* Iron, *Co* Cobalt, *Cd* Cadmium, *Cr* Chromium, *Ni* Nickel, *Ag* Silver, *Zn* Zinc, *Cu* Copper, SO_4^{2-} Sulfate, PO_4^{3-} Phosphate, *Pb* Lead

Table 5 Different water quality indices estimated in groundwater and surface water of the Sundarban region of India and Bangladesh

Location	TH	RSC	PS	PI	KR	SAR	MH	Na%	CR	CAI1	CAI2
Surface water											
Indian Sundarban	296.21	-85.65	63.02	24.20	0.31	0.99	56.28	26.60	7213.00	0.11	0.07
Bangladesh	322.21	323.86	601.04	79.71	2.87	9.99	50.42	75.44	3.86	1632.60	4.22
Groundwater											
Indian Sundarban	219.90	75.62	49.98	49.83	0.63	2.20	49.00	64.60	0.82	0.10	1.22
Bangladesh	0.21	0.18	0.29	239.13	5.00	1.78	81.93	195.23	4.26	-1.41	-1.60

TH Total hardness, *RSC* Residual sodium carbonate, *PS* Potential salinity, *PI* Permeability index, *KR* Kelly's ratio, *SAR* Sodium absorption ratio, *MH* Magnesium hazard, *Na%* Sodium percentage, *CR* Corrosivity ratio, *CAI1* Chloroalkaline indices 1, *CAI2* Chloroalkaline indices 2

groundwater; the range was 75.62 to 0.18 meq/L (Table 5). In the Indian Sundarbans region, the RSC value of surface water was negative due to the higher concentration of Ca^{2+} and Mg^{2+} compared to CO_3^{2-} and HCO_3^-, while in Bangladesh's Sundarban region, the surface water's RSC value was positive. The RSC values of groundwater were positive due to higher carbonate and bicarbonate ion concentrations. However, both surface and groundwater were found to be unsuitable for irrigation purposes.

Potential salinity (PS) is a crucial parameter used to assess the suitability of surface water and groundwater for irrigation, based on Cl^- and SO_4^{2-} concentrations (Tegegne et al. 2023). Salinity plays a significant role in soil quality; when it exceeds recommended levels, it adversely affects soil permeability, aeration, and structure, leading to soil hardening and directly impacting plant growth (Ramesh and Elango 2012; Singh et al. 2013). According to Doneen et al. (1964), a PS value less than 3 meq/L is suitable for irrigation, while values greater than 3 meq/L are considered unsuitable. In this study, the PS levels of surface water ranged from 63.03 to 601.04 meq/L, while groundwater PS levels varied from 49.98 to 0.29 meq/L (Table 5). The findings indicate that the PS value is higher than the permissible limit due to the high concentration of Cl^- and SO_4^{2-}, rendering the water unsuitable for irrigation.

Kelly's ratio (KR) is another vital water quality parameter used to assess the suitability of both groundwater and surface water for irrigation by comparing the levels of Na^+ against Ca^{2+} and Mg^{2+} ions. A KR value less than 1 is considered suitable, while a KR value greater than 1 indicates unsuitability for irrigation due to an excess of Na^+ in the collected samples (Kelley 1963). In this study, the KR levels of surface water ranged from 48.95 to 54.19, while the groundwater KR levels varied from 33.58 to 26.29. The findings reveal that the KR value in the collected water samples is greater than 1, rendering it unsuitable for irrigation due to the high concentration of Na^+.

The permeability index (PI) is a critical parameter for evaluating the quality of irrigation water in relation to soil for improved agriculture (Tegegne et al. 2023). According to (EPA 2014), water is categorized into Class I, Class II, and Class III based on the PI level, where Class I and II waters are considered good for irrigation with 75% or more maximum permeability, while Class III water is unsuitable with 25% maximum permeability (Table 2). In this study, the PI values for surface water ranged from 24.20 to 79.71%, and for groundwater, the PI was found to be in the range of 49.83% to 239.13% (Table 5). The findings demonstrate that both surface water and groundwater fall into the good category and can be utilized for irrigation purposes.

The magnesium hazard (MH) pertains to the proportion of magnesium absorption ratio (MAR) in water and indicates water quality in terms of magnesium content, which is crucial for agricultural activities (Ayers and Wescott 1985; Joshi et al. 2009). An MH value below 50 is considered suitable for irrigation, while values higher than 50 are deemed unsuitable for irrigation purposes (Ayers and Wescott 1985) (Table 2). MH levels in the surface water ranged from 56.28 to 50.42, whereas MH levels in the ground water varied from 49.00 to 80.00 (Table 5). The present study reveals unsuitability for irrigation due to the high concentration of magnesium (Mg^{2+}) in the collected water samples.

According to EPA (2014), the Na% was categorized into five classes: Class I (Excellent) with Na% less than 20, Class II (Good) with Na% between 20 and 40, Class III (Permeability) with Na% between 40 and 60, and Class IV (Unsuitable) with Na% greater than 80. The Na% levels in surface water ranged from 26.60 to 75.44, while groundwater Na% varied from 64.60 to 195.23 (Table 5). Increasing Na^+ levels can lead to soil becoming saline (due to Na^+ combining with Cl^-) or alkaline (due to Na^+ combining with HCO_3^-). This process, known as base exchange, removes Ca^{2+} and Mg^{2+} from clay particles and replaces them with Na^+, reducing soil permeability and promoting deflocculation (Kelley 1963; Joshi et al. 2009; Abderamane et al. 2013). The study indicates that surface water falls within the "good" category, making it suitable for irrigation. However, groundwater exceeds the permissible limit, rendering it unsuitable for irrigation purposes.

SAR (sodium absorption ratio) is another significant water quality parameter related to Na% in surface water and groundwater for irrigation purposes (Batarseh et al. 2021). According to EPA (2014), SAR can be classified into four categories: SAR less than 10 (Excellent), SAR 10–18 (Good), SAR 18–26 (Doubtful), and SAR greater than 26 (Unsuitable) (Table 2). The SAR values in surface water ranged from 0.99 to 9.99, while SAR in groundwater varied from 2.20 to 1.78. In the SAR parameter, higher Na^+ values replace Ca^{2+} and Mg^{2+} ions (Table 5). The study demonstrates that both surface water and groundwater were suitable for irrigation purposes.

The corrosivity ratio (CR) for surface water in this review ranges from 7213.00 to 3.86, while groundwater's CR varies from 0.82 to 4.26 (Table 5). CR is an important indicator to determine the feasibility of water transportation through metal pipes. For water transportation through pipes, a CR value less than 1 shows the feasibility of water transport through metal pipes, while for CR values greater than 1, water is not transported through the metal pipe due to increasing corrosion (Aravindan et al. 2004; Shankar et al. 2011; Giri et al. 2022). The present study showed that the CR value is less than 1 in the groundwater samples of India's Sundarbans region. In contrast, the remaining water samples have greater CR values, indicating that water should not be transported through the metal pipe.

The chloroalkaline index (CAI) is determined based on the chloride level (Cl^-), which plays a crucial role in regulating soil physical properties and photosynthesis in plants. However, elevated chloride levels beyond the optimal range can lead to soil degradation and plant toxicity (Giri et al. 2022). CAI1 and CAI2 indicate the ion exchange between water and rock. A positive CAI value suggests a direct exchange process between Na^+ and K^+ in water with Mg^{2+} and Ca^{2+} in rocks, while a negative value indicates the reverse process (Jafar Ahamed et al. 2013).

In surface water, CAI1 ranges from 0.11 to 1632.60 meq/L, while CAI1 in groundwater varies from 0.10 to − 1.41 meq/L (Table 5). For CAI2, surface water values range from 0.07 to 4.22 meq/L, and groundwater values vary from 1.22 to − 1.60 meq/L (Table 5). The study reveals that surface water has positive CAI1 and CAI2 values, indicating a direct exchange process between water and rock, with dissolved salts primarily originating from the host rock (Mousazadeh et al. 2019). However, in groundwater samples from the Bangladesh Sundarbans region, both CAI1 and CAI2 values are negative. In contrast, Indian Sundarbans groundwater samples have positive CAI1 and CAI2 values, indicating a similar direct exchange process.

The Sundarbans' generally saline groundwater is relatively deep and is impacted by saline water intrusion from the sea. Another issue is that the frequency of cyclones in the Sundarbans has been raised because of climate change and global warming, a continuing problem. Cyclones raise sea levels, which raise salinity levels in this region, impacting agriculture. On the other hand, the Sundarban salinity is significantly influenced by the amount of freshwater moving upstream (Neogi et al. 2017). The variation is dependent on the local tide characteristics. In 2001 and 2002, it was determined that the greatest salinity was approximately 26 psu and that the post-monsoon minimum salinity was approximately 5 psu. From the Sundarban east to the west, the soil's electrical conductivity rises spatially (Burman et al. 2019; Chowdhury et al. 2023).

Over the past three decades, the western sector of the mangrove-dominated Indian Sundarban has experienced a decline in the pH of surface water, decreasing at a rate of -0.015 per decade (Agarwal et al. 2023). This phenomenon is likely attributed to the increasing impact of anthropogenic factors in the region (Banerjee et al. 2017). On the other hand, in the eastern sector, water quality has shown significant changes, with increase in temperatures, salinity, density, and reduced clarity over the same period. The rise in salinity to the east can be attributed to freshwater scarcity and tidal water influence. The combined effects of these factors have contributed to variations in pH and dissolved oxygen levels observed in the region (Gobler and Baumann 2016).

Conclusion

The systematic review on groundwater suitability for irrigation in the Sundarban region provides a comprehensive assessment of hydrogeological, hydrochemical, and agronomic factors influencing groundwater quality and its impact on agricultural sustainability. The findings reveal that both the surface and ground water were unsuitable for irrigation purposes due to higher levels of TH, RSC, PS, KR, MH, and CR. Meanwhile, both surface and ground water were suitable for irrigation purposes for PI, Na%, and SAR parameters. However, as most of the parameters show the unsuitability of both water sources for irrigation purposes, both water sources are not suitable for irrigation purposes. This unsuitability impacts soil health, crop growth, and rural livelihoods. Mitigation measures may be explored, including rainwater harvesting, surface water reservoirs, and groundwater treatment techniques such as reverse osmosis and ion exchange. Agronomic practices, such as crop selection and irrigation scheduling, can enhance resilience to poor groundwater quality. Research gaps persist, necessitating long-term monitoring studies. Integrated water resource management strategies and site-specific decision support systems are vital for sustainable irrigation practices. The review underscores the urgent need for interdisciplinary approaches to safeguard the fragile ecosystem of the Sundarbans. Policymakers, researchers, and practitioners should collaborate on context-specific strategies, considering socioeconomic realities and environmental sensitivities. This review supports evidence-based policies that enhance agricultural system sustainability and preserve Sundarbans' unique ecological heritage by proposing practical solutions and bridging knowledge gaps. Prioritizing groundwater protection and restoration is imperative for securing local livelihoods and maintaining the region's ecological significance.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13201-024-02122-5.

Financial Disclosure statement The author(s) received no specific funding for this work.

Data availability All data collected, analyzed or generated during this study will be available from the corresponding author for reasonable scientific reasons.

Declarations

Conflict of interest The authors declare no competing interests.

References

Abderamane H, Razack M, Vassolo S (2013) Hydrogeochemical and isotopic characterization of the groundwater in the Chari-Baguirmi depression, Republic of Chad. Environ Earth Sci 69:2337–2350. https://doi.org/10.1007/s12665-012-2063-7

Agarwal S, Mukherjee P, Sinha M et al (2023) Anthropogenic climate change in the mangrove-dominated indian sundarbans: spatio-temporal analyses, future trends, and recommendations for mitigation and adaptation. In: Climate change management. Springer Science and Business Media Deutschland GmbH, pp 249–286

Allison LE (1964) Salinity in relation to irrigation. Adv Agron 16:139–180. https://doi.org/10.1016/S0065-2113(08)60023-1

Aravindan S, Manivel M, Chandrasekar SVN (2004) Groundwater quality in the hard rock area of the Gadilam River Basin, Tamil Nadu. J Geol Soc India 63:625–635

Ayers RS, Wescott DW (1985) Water quality for agriculture. FAO Irrigation and Drainage Paper no 29

Balasubramanian A (1986) Hydrogeological investigation of Tambraparani River Basin. University of Mysore, Mysore

Banerjee K (2013) Decadal change in the surface water salinity profile of Indian Sundarbans: a potential indicator of climate change. J Mar Sci Res Dev. https://doi.org/10.4172/2155-9910.s11-002

Banerjee K, Gatti RC, Mitra A (2017) Climate change-induced salinity variation impacts on a stenoecious mangrove species in the Indian Sundarbans. Ambio 46:492–499. https://doi.org/10.1007/s13280-016-0839-9

Batarseh M, Imreizeeq E, Tilev S et al (2021) Assessment of groundwater quality for irrigation in the arid regions using irrigation water quality index (IWQI) and GIS-Zoning maps: case study from Abu Dhabi Emirate, UAE. Groundw Sustain Dev 14:100611. https://doi.org/10.1016/j.gsd.2021.100611

Bauder JW, Brock TA (2001) Irrigation water quality, soil amendment, and crop effects on sodium leaching. Arid L Res Manag 15:101–113. https://doi.org/10.1080/15324980151062724

Borsato E, Rosa L, Marinello F et al (2020) Weak and strong sustainability of irrigation: a framework for irrigation practices under limited water availability. Front Sustain Food Syst 4:514751. https://doi.org/10.3389/fsufs.2020.00017

Burman D, Mahanta KK, Sarangi SK, Mandal S, Maji B, Mandal UK, Bandyopadhyay BK, Humphreys E, Sharma DK (2015) Effect of groundwater use on groundwater quality, piezometric level and boro rice productivity in the Sundarbans of West Bengal

Burman D, Mondal MK, Khan ZH et al (2019) Soil and water resources of Sundarbans. In: Coastal research library. Springer, pp 163–196

Chakraborty M, Mukherjee A, Ahmed KM et al (2022) Influence of hydrostratigraphy on the distribution of groundwater arsenic in the transboundary Ganges River delta aquifer system, India and Bangladesh. Bull Geol Soc Am 134:2680–2692. https://doi.org/10.1130/B36068.1

Chatterjee M, Shankar D, Sen GK et al (2013) Tidal variations in the Sundarbans estuarine system, India. J Earth Syst Sci 122:899–933. https://doi.org/10.1007/s12040-013-0314-y

Chen J, Qian H, Gao Y et al (2020) Insights into hydrological and hydrochemical processes in response to water replenishment for lakes in arid regions. J Hydrol 581:124386. https://doi.org/10.1016/j.jhydrol.2019.124386

Chowdhury MQ, Sarker SK, Sultana R et al (2023) Synergistic effects of climate and salinity on radial growth of *Excoecaria agallocha* L. in the Sundarbans world heritage mangrove ecosystem. Estuar Coast Shelf Sci 280:10818. https://doi.org/10.1016/j.ecss.2022.108181

Doneen LD (1964) Water quality in agriculture, water science and engineering

Eaton A, Clesceri L, Greenberg A (1995) Standard methods for the examination of water and wastewater, 19th edn. APHA, New York
EPA (2014) Test methods for evaluating solid waste: physical/chemical methods (SW-846). 0–27
Ghirardelli A, Tarolli P, Kameswari Rajasekaran M et al (2021) Organic contaminants in Ganga basin: from the Green Revolution to the emerging concerns of modern India. iScience 24
Giri A, Bharti VK, Kalia S et al (2022) Hydrochemical and quality assessment of irrigation water at the trans-Himalayan high-altitude regions of Leh, Ladakh, India. Appl Water Sci 12:1–20. https://doi.org/10.1007/s13201-022-01716-1
Gobler CJ, Baumann H (2016) Hypoxia and acidification in ocean ecosystems: coupled dynamics and effects on marine life. Biol Lett. https://doi.org/10.1098/rsbl.2015.0976
Hajji S, Allouche N, Bouri S et al (2022) Assessment of seawater intrusion in coastal aquifers using multivariate statistical analyses and hydrochemical facies evolution-based model. Int J Environ Res Public Health 19:155. https://doi.org/10.3390/ijerph19010155
Heasley C, Sanchez JJ, Tustin J, Young I (2021) Systematic review of predictive models of microbial water quality at freshwater recreational beaches. PLoS ONE 16:e0256785
Jafar Ahamed A, Ananthakrishnan S, Loganathan K, Manikandan K (2013) Assessment of groundwater quality for irrigation use in Alathur Block, Perambalur District, Tamilnadu, South India. Appl Water Sci 3:763–771. https://doi.org/10.1007/s13201-013-0124-z
Jahan K, Zahid A, Bhuiyan MAE, Ali I (2022) A resilient and nature-based drinking water supply source for saline and arsenic prone coastal aquifers of the Bengal Delta. Sustainability 14:6703. https://doi.org/10.3390/su14116703
Jain M, Fishman R, Mondal P et al (2021) Groundwater depletion will reduce cropping intensity in India. Sci Adv. https://doi.org/10.1126/sciadv.abd2849
Joshi DM, Kumar A, Agrawal N (2009) Assessment of the irrigation water quality of river Ganga in Haridwar district. Rasayan J Chem 2:285–292
Kelley WP (1963) Use of saline irrigation water. Soil Sci 95:385–391. https://doi.org/10.1097/00010694-196306000-00003
Kelley WP (1940) Permissible composition and concentration of irrigation water
Khalid S, Shahid M, Natasha et al (2018) A review of environmental contamination and health risk assessment of wastewater use for crop irrigation with a focus on low and high-income countries. Int J Environ Res Public Health 15:895
Kumar M, Patel AK, Singh A (2022) Anthropogenic dominance on geogenic arsenic problem of the groundwater in the Ganga-Brahmaputra floodplain: a paradox of origin and mobilization. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2021.151461
Lakshmanan E, Kannan R, Senthil Kumar M (2003) Major ion chemistry and identification of hydrogeochemical processes of ground water in a part of Kancheepuram district, Tamil Nadu, India. Environ Geosci 10:157–166. https://doi.org/10.1306/eg100403011
Manna S, Chaudhuri K, Bhattacharyya S, Bhattacharyya M (2010) Dynamics of Sundarban estuarine ecosystem: eutrophication induced threat to mangroves. Saline Syst 6:1–16. https://doi.org/10.1186/1746-1448-6-8
Mondal P, Bhowmick S, Chatterjee D et al (2013) Remediation of inorganic arsenic in groundwater for safe water supply: a critical assessment of technological solutions. Chemosphere 92:157–170
Mousazadeh H, Mahmudy-Gharaie MH, Mosaedi A, Moussavi Harami R (2019) Hydrochemical assessment of surface and ground waters used for drinking and irrigation in Kardeh Dam Basin (NE Iran). Environ Geochem Health 41:1235–1250. https://doi.org/10.1007/s10653-018-0214-9
Mukherjee A, Fryar AE (2008) Deeper groundwater chemistry and geochemical modeling of the arsenic affected western Bengal basin, West Bengal, India. Appl Geochem 23:863–894. https://doi.org/10.1016/j.apgeochem.2007.07.011
Nath A, Samanta S, Banerjee S et al (2021) Threat of arsenic contamination, salinity and water pollution in agricultural practices of Sundarban Delta, India, and mitigation strategies. SN Appl Sci 3:1–15
Neogi SB, Dey M, Kabir SL et al (2017) Sundarban mangroves: diversity, ecosystem services and climate change impacts. Asian J Med Biol Res 2:488–507. https://doi.org/10.3329/ajmbr.v2i4.30988
Okereafor U, Makhatha M, Mekuto L et al (2020) Toxic metal implications on agricultural soils, plants, animals, aquatic life and human health. Int J Environ Res Public Health 17:2204
Ramesh K, Elango L (2012) Groundwater quality and its suitability for domestic and agricultural use in Tondiar river basin, Tamil Nadu, India. Environ Monit Assess 184:3887–3899. https://doi.org/10.1007/s10661-011-2231-3
Refat Nasher NM, Humayan Ahmed M (2021) Groundwater geochemistry and hydrogeochemical processes in the Lower Ganges-Brahmaputra-Meghna River Basin areas, Bangladesh. J Asian Earth Sci X 6:100062. https://doi.org/10.1016/j.jaesx.2021.100062
Sahoo S, Chakraborty S, Pham QB et al (2021) Recognition of district-wise groundwater stress zones using the GLDAS-2 catchment land surface model during lean season in the Indian state of West Bengal. Acta Geophys 69:175–198. https://doi.org/10.1007/s11600-020-00509-x
Schoeller H (1977) Geochemistry of groundwater. In: Brown RH, Konoplyantsev AA (eds) Groundwater studies: an international guide for research and practice, 15th edn. UNESCO, Paris
Sengupta P (2013) Potential health impacts of hard water. Int J Prev Med 4:866–875
Shamsudduha M, Chandler RE, Taylor RG, Ahmed KM (2009) Recent trends in groundwater levels in a highly seasonal hydrological system: the Ganges-Brahmaputra-Meghna Delta. Hydrol Earth Syst Sci 13:2373–2385. https://doi.org/10.5194/hess-13-2373-2009
Shankar K, Aravindan S, Rajendran S (2011) Hydrogeochemistry of the Paravanar river sub-basin, Cuddalore district, Tamilnadu, India. E-Journal Chem 8:835–845. https://doi.org/10.1155/2011/107261
Sikdar PK, Sarkar SS, Palchoudhury S (2001) Geochemical evolution of groundwater in the quaternary aquifer of Calcutta and Howrah, India. J Asian Earth Sci 19:579–594. https://doi.org/10.1016/S1367-9120(00)00056-0
Singh K, Tewari G, Kumar S (2020) Evaluation of groundwater quality for suitability of irrigation purposes: a case study in the Udham Singh Nagar, Uttarakhand. J Chem. https://doi.org/10.1155/2020/6924026
Singh SK, Srivastava PK, Pandey AC, Gautam SK (2013) Integrated assessment of groundwater influenced by a confluence river system: concurrence with remote sensing and geochemical modelling. Water Resour Manag 27:4291–4313. https://doi.org/10.1007/s11269-013-0408-y
Szabolcs I (1964) The influence of irrigation water of high Sodium Carbonate content on soils. Agrokémia És Talajt 13:237–246
Tauqeer HM, Fatima M, Rashid A et al (2021) The current scenario and prospects of immobilization remediation technique for the management of heavy metals contaminated soils. In: Approaches to the remediation of inorganic pollutants. Springer, Singapore, pp 155–185
Tegegne AM, Lohani TK, Eshete AA (2023) Evaluation of groundwater quality for drinking and irrigation purposes using proxy indices in the Gunabay watershed, Upper Blue Nile Basin, Ethiopia. Heliyon 9:15263. https://doi.org/10.1016/j.heliyon.2023.e15263
Thorne DW (1954) Diagnosis and Improvement of Saline and Alkali Soils. Agron J 46:290–290. https://doi.org/10.2134/agronj1954.00021962004600060019x

Todd D, Mays L (2005) Groundwater hydrology, 3rd edn. Wiley, Hoboken

Todd D, Mays L (1980) Groundwater hydrology edition. sutlib2.sut.ac.th 29–55

Verma S, Mukherjee A, Mahanta C et al (2019) Arsenic fate in the Brahmaputra river basin aquifers: controls of geogenic processes, provenance and water–rock interactions. Appl Geochem 107:171–186. https://doi.org/10.1016/j.apgeochem.2019.06.004

Wilcox LV (1948) Classification and use of irrigation water. Agric Circ No 969,Washington, DC USDA 1–19. USDA Circular No. 969

Worland SC, Hornberger GM, Goodbred SL (2015) Source, transport, and evolution of saline groundwater in a shallow Holocene aquifer on the tidal deltaplain of southwest Bangladesh. Water Resour Res 51:5791–5805. https://doi.org/10.1002/2014WR016262

World Health Organization (2006) Guidelines for Drinking-water Quality first addendum to third edition volume 1 Recommendations WHO Library Cataloguing-in-Publication Data

Zahid A, Reaz S, Ahmed U (2006) Groundwater resources development in bangladesh: contribution to irrigation for food security and constraints to sustainability. Groundw Res Manag Integr Sci into Manag Decis Proc IWMI-ITP-NIH Int Work "Creating Synerg Between Groundw Res Manag South Southeast Asia" 27–46