Development of an integrated irrigation water quality index (IIWQIndex) model

Md. Shajedul Islam and M. G. Mostafa*
Institute of Environmental Science, University of Rajshahi, Rajshahi 6205, Bangladesh
*Corresponding author. E-mail: mgmostafa@ru.ac.bd

MSI, 0000-0003-4187-5674; MGM, 0000-0003-1709-769X

ABSTRACT

There are many irrigation water quality indices used to assess water suitability, despite some of their limitations. Hence, it is imperative to develop a water quality index to evaluate the irrigation water more accurately. This study has aimed to emerge an Integrated Irrigation Water Quality Index (IIWQIndex) using the sub-index and aggregated equations. This proposed index model was considered to be improved and updated in four aspects: the verified desirable and permissible value of parameters, maximum hazard class, used a modified rating system of parameters, and diversified parameters were considered. The proposed IIWQIndex model classified irrigation water into five categories, i.e., rejection, poor, moderate, good, and excellent. This model assessed two types of water to justify the model by categorizing the irrigation waters. The calculated results showed that the index values were 75.77 and 36.51, and the water category fell under ‘good’ and ‘rejected’ for the calcite (Ca-HCO₃) and sodic (Na-Cl) water, respectively. Besides, this index model satisfactorily evaluated different types of water datasets of eight geographic locations in the world. The study illustrated that the IIWQIndex evaluated values and water categories were rational and exhaustive to predict the suitability of irrigation water.

Key words: hazard class, irrigation water quality indices, soil structure, water quality parameter, water suitability, water type

HIGHLIGHTS

• Critically reviewed the previous irrigation water quality (IWQ) indices.
• Proposed a water quality index model (IIWQIndex) considering the maximum water quality parameters and hazard classes.
• Modify the rating value and acceptable limit of parameters.
• Evaluated the suitability and rationality of the index model for irrigation purposes.
INTRODUCTION

The groundwater quality largely depends on the dissolved solutes and trace metals in aquifers (Mostafa et al. 2017; Zaman et al. 2018). These substances come from weathering of rocks and the dissolution of the minerals such as calcite, dolomite, gypsum, lime, silicate, etc., in the aquifer basement and soil minerals (DANR-UC 2021). These minerals originated salts are spread to the water and kept on the soil or consumed by the plants. The harvesting problems associated with the overall salt content and specific management practices are needed for satisfactory crop growth and production. The suitability of water for irrigation uses is justified on the probable severity of hazard that can be predictable to develop during continuous use. The hazards that result differ both in kind and quantity and are adapted by soil, local climate, and plant, along with by the ability and knowledge of the irrigation activist (Islam & Mostafa 2021a; Rahim & Mostafa 2021). Thus, there is no usually bound on water quality; rather, its fitness for use is determined by the conditions of use that affect the accumulation of the water constituents and which may restrict crop yield. The soil hazard most come upon and used as a base to assess water quality are
those connected to salinity, sodicity, soil structure, water permeability, metal and ion toxicity, and other miscellaneous problems.

Irrigation water quality depends on the physical and chemical of soil properties, the nature of irrigation practice, firming management, and crop diversity. There is no single index model that could assess the water quality accurately. In addition, the potentiality of adverse effects of water components varies with crop variety and soil condition. Worldwide there were many water quality indices (IWQI) models developed to evaluate the irrigation water quality for better crop growths and productions (Wilcox 1948; Doneen 1964; Ayers 1977; Ayers & Westcot 1985; CCME 2006; Simsek & Gunduz 2007; Meireles et al. 2010; Bauder et al. 2011; Bozdag 2016; Arslan 2017; Hussain et al. 2018; Zaman et al. 2018; Singh et al. 2020). But those models have some limitations and are not able to accurately evaluate the irrigation water quality.

For instance, the Canadian water quality index (by the Canadian Council of Ministers of the Environment, CCME) was used to assess irrigation, aquatic culture, and drinking water quality in which has no hazard class, and particular parameters were not considered (UNEP-GEMS/Water 2007). Simsek & Gunduz (2007) have proposed a geographical information system (GIS) – based irrigation water quality model with specific geochemical parameters and some toxic metals to evaluate the water quality for irrigation of the Simav Plain in Turkey. Another new technique, proposed by Meireles et al. (2010), uses only four water quality criteria. Besides, Ashraf et al. (2011) established an IWQ index using GIS for calculating the sodium adsorption ratio (SAR), saturated sodium percentage (SSP), and residual sodium carbonate (RSC) with other parameters. Then, Romanelli et al. (2012) assessed IWQ by combining geological landscapes, water chemistry, and other indicators such as hydraulic conductivity, electrical conductivity, SAR, Na%, SSP, RSC, and aquifer width to assess water suitability for irrigation in Wet Pampa Plain, Argentina. Later, Bozdag (2016) used an analytic hierarchy process (AHP) to quantify the irrigation water suitability in central Anatolia, Turkey. Besides, Singh et al. (2020) developed the entropy weighted irrigation water quality index in Uttarakhand, India. These several diverse water quality strategies related to irrigating agriculture have some sort of suitability due to the inconsistency in cropland conditions and crops variety. Moreover, several limitations of these models were identified, including the limited number of parameters, hazard classes, and their rating, scoring, and weighting values. The present study proposed an indexing model that considered the maximum number of water quality parameters with a total of six hazard classes. Besides, modified rating values of water parameters and the weight factor of each hazard class are used. The proposed indexing model explores enough information on the suitability of various types of water for every irrigation practice. The procedures presented in this paper have improved to give more practical actions for assessing and managing water quality-related hazards of irrigated farming.

**LIMITATION OF EXISTING MODELS**

Several researchers have been working on agricultural water quality and suitability for irrigation purposes since 2000 (Eaton 1950; Wilcox 1955; Doonen 1962; Kelley 1963; Richard 1968; Hem 1970; UCCC 1974; Freeze & Cherry 1979; Todd 1980; Matthess 1982; Ayers & Westcot 1985; Raghunath 1987; Rhoades 1992; Gupta & Gupta 1998). However, few numbers water quality indices were developed after the 2000s (CCME WQI 2001; Simsek & Gunduz 2007; Meireles et al. 2010; Maia & Rodrigues 2012; Hussain et al. 2018). The existing indexing models considered only some selected and limited numbers of parameters. Since then, no one method was considered a combination of using the water quality parameter value, recognized permissible range of parameters, and various ratings with scoring values of parameters and hazard classes. For example, Simsek & Gunduz (2007) used only the scoring of parameters and weight factor of hazard class but not considered the concentration of parameters. Another index model developed by Meireles et al. (2010) used the value of a limited number of parameters, but the rating and weight factors were not included in their methods. Moreover, these models showed different indexing values and categories for the same water samples, i.e., one model exhibited the water quality category as good but, the other model showed it as poor for the same. Table 1 showed the diverse recognized index methods with the characteristics of their Equations for assessing the irrigation water quality. This Table displayed that the evaluation techniques of water categorization are different between these considered methods. Every method partially fulfilled the requirements of a well-fitted and complete indexing Equation. So, the ambiguity of water quality indexing encourages us to develop a diversified and improved model considering maximum parameters and hazard classes for getting the best solution to detecting irrigation water suitability.

Most of the index models considered the lowest rating value for the rejected category of the parameters was 1 (Ayers & Westcot 1985; Simsek & Gunduz 2007). But, this value of a parameter can affect the total index value. Hence, the lowest score of the parameter for the ‘rejected’ category should be zero. Besides, the acceptable and permissible ranges of water
quality parameters for irrigation are retroactive and not uniform. That is why, with views of recent research results, it should be modified the value of some parameter ranges and converted into a uniform pattern.

The contaminated surface water, including domestic and industrial wastewater, is used as irrigation water in many areas due to inadequate water resources that increase environmental hazards. The continuous use of this type of water in agricultural activities causes a substantial increase in the number of toxic metals in soils, and consequences increase risk in food safety. Existing methods are not well addressed the metal toxicity of irrigation water for calculating the indexing value. There should be lots of possibilities to be intoxicated with the foodstuffs through soil-crop-food transfer systems. Thus, the crops grown on the contaminated soils are the major routes of toxic hazards exposure to the human body. Several studies confirmed that a significant portion of toxic substances uptake by crops and the consequences are the bioaccumulation in the human body and livestock (Karim et al. 2008; Chauhan & Chauhan 2014; Leblebici & Kar 2018; Chaoua et al. 2019; Islam & Mostafa 2021b). This proposed indexing model considered all the toxic hazards in water and soils and then uptake by crops yield.

Table 1 | Indexing methods of irrigation water quality assessment

| Name of index | Final equation | Selected parameters | Sub-index used | Scoring/rating/weights used† | Aggregation method used |
|---------------|----------------|---------------------|----------------|-------------------------------|-------------------------|
| CCME WQI (2001) | CWQI = 100 − \left( \frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right) | • At least 4 parameters | No sub-Index used | • No scoring used | No aggregation method used |
| Simsek & Gunduz index (2007) | IWQ = \sum_{i=1}^{5} G_i | • 9 geochemical parameters and 17 trace metals | Mixed method | • Scoring factor used | Additive method |
| Meireles index (2010) | MWQI = \sum_{i=1}^{n} q_iw_i | • 5 parameters: SAR, EC, Na⁺, Cl⁻, and HCO₃⁻ | No sub-index used | • No scoring used | Additive method |
| Maia method (2012) | IWQI = \frac{1}{N} \sum_{i=1}^{N} \sqrt{Z_i^2} | • 9 parameters are used: SAR, Ca, Mg, Na, K, Cl, SO₄²⁻, and HCO₃⁻ CO₃⁻ | Parameters are directly taken as sub-index | • No scoring used | Additive method |
| Hussain method (2018) | IAWQ = \frac{C}{n} \sum_{i=1}^{n} (W_i × Y_i) | • 12 parameters are used: pH, EC, TDS, SO₄²⁻, Ca, Mg, Na, K, Cl, SAR, Na%, and TH. | Parameters are directly taken as sub-index | • No scoring used | Additive method |

†Scoring of hazard class; rating value of parameters in each hazard class; weight value of hazard class or parameters of groundwater samples.
The indexing method is a technique, approached to quantify the amount of change, if any, in the index. Besides, an index model is a popular tool for evaluating a physical state of a system. In water quality index model, it can explore the qualitative state of a water body. The study considered mathematical models, which are predictable to signify the physical problems with a rational level of accuracy.

There are four steps considered for developing any water quality index model. These are the selection of parameters, their weightage, sub-index, and aggregation of sub-index. Besides, the selection of hazard class, scoring and weight of the class, and rating value of each parameter are considered in the proposed IIWQ\textsubscript{Index}. A detail of these steps is discussed here.

**Hazard classes and parameters**

The selection of parameters is a vital step in the constituents of a water quality index. Traditionally, the indices have a different number of parameters, fluctuating from four (4) to twenty-six (26) (Dojlido \textit{et al.} 1994). Concerning the category of the system used for the choice of parameters, usually, it can be divided into three classes viz. fixed, open, and mixed types. The maximum WQIs studied have used a fixed number of parameters (Liou \textit{et al.} 2004; Almeida \textit{et al.} 2012). For the fixed and mixed types, the selection of parameters aims to choose the parameters which have the highest impact on the water quality. In this study, we have used the mixed type selection procedure of parameters. However, Abbasi & Abbasi (2011) stated that there was no way to get 100\% precision achieved by choosing the parameters.

The study considered six hazard classes, such as (1) salinity hazard, (2) sodicity problem, (3) permeability of the soil, (4) ions and trace metal toxicity to crop, (5) changing in soil structure, and (6) miscellaneous effects to plants (Table 2), where the hazard class, i.e., ‘changing in soil structure’ is incorporated with other hazard classes of existing models. A total of 27 irrigation water quality parameters is considered in those above-mentioned classes. The fixed system allows the parameters to choose the hazard classes, i.e., the salinity hazard, sodicity problem, the permeability of the soil, and changes in soil structure, and the open system allows to choose the ions and trace metal toxicity and miscellaneous hazard classes. Some parameters are commonly considered for different categories of hazard classes because of their harmful impacts differently. For this reason, these are involved as operating parameters to sub-index calculation in these hazard classes. A brief description of hazard classes and parameters and their relative impacts on soil, yield quality, and environment are stated below.

**Salinity hazard**

It was measured through EC and/or TDS (both are used if correlation matrix, $r<0.95$) and has given the highest score to calculate the index value that affected plants and led to saline soil condition. Saline soils usually have a pH value below 8.5 contain mainly Ca, Mg, and Na salt of Cl$^-$, SO$_4^{2-}$, CO$_3^{2-}$, HCO$_3^-$, NO$_3^-$, and PO$_4^{3-}$. A salinity hazard exists if salt accumulates in the crop root zone to a concentration that causes a loss in yield as roots of the plants are unable to uptake enough water to keep the plant hydrated in saline soil (Ayers & Westcot 1985).

**Sodicity hazard**

The sodicity problems are usually defined separately due to the specific harmful of Na$^+$ on the physical properties of soils and plants. It was given the second-highest score and usually measured by the values of Na\%, SSP, and SAR (or SAR\textsubscript{Adj}) that affected soils, and led to sodic soil conditions (Lesch & Suarez 2009).

**Water infiltration rate**

The infiltration rate was given the next priority to the sodicity hazards in scoring water quality index as it was considered to have a significant influence on the irrigation water quality index. The water quality infiltration rates depend on soil texture (the ratio of sand, silt, and clay in soil), organic/humic matter content, degree of compaction, and chemical make-up (USDA 2014).

**Toxicity to crop**

This hazard class is very flexible in choosing water quality parameters. It can be excluded or included any components relevant to toxic to crops for irrigation water if required. The proposed model considered some components, such as, Na$^+$, Cl$^-$, B, K, Fe, Mn, As, Cu, and Zn that are toxic to plants if they present in higher concentrations in water and soil. These metals...
Table 2 | Scoring of hazard class and rating of parameters in assuming the proposed model for irrigation water quality index

| Hazard class (Scoring value, s) | Parameter (Rating value, r) | Degree of restriction on use | Parameter (Rating value, r) | Degree of restriction on use |
|---------------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| (1) Salinity (s = 6)            | EC (μS/cm)                  | Excellent                   | Mn (mg/L)                   | Excellent                   |
|                                 |                             | 700–1,500 (r = 2)           |                             |                             |
| (2) Sodicity (s = 5)            |                             | Good                        |                             |                             |
|                                 |                             | >1,500–3,000 (r = 1)        |                             |                             |
| (3) Water infiltration rate     |                             | Faire                       |                             |                             |
|                                 |                             | >3,000 (r = 0)              |                             |                             |
| (4) Toxicity to plants (s = 3) |                             | Rejection                   |                             |                             |
| (5) Changing soil structure (s = 2) | TDS (mg/L)              | Excellent                   | Cu (mg/L)                   | Excellent                   |
|                                 |                             | <450 (r = 3)                |                             |                             |
|                                 |                             | Good                        |                             |                             |
|                                 |                             | >900–2,000 (r = 1)          |                             |                             |
|                                 |                             | Good                        |                             |                             |
| (6) Miscellaneous effect (s = 1) | Misc. effect             | Excellent                   | Zn (mg/L)                   | Excellent                   |
|                                 |                             | 0–20 (r = -3)               |                             |                             |
|                                 | %Na and SSP (%)             | Good                        |                             |                             |
|                                 |                             | >20 (r = -3)                |                             |                             |
|                                 |                             | Permissible                 |                             |                             |
|                                 |                             | >40 (r = -2)                |                             |                             |
|                                 |                             | Doubtful                    |                             |                             |
|                                 |                             | >80 (r = 0)                 |                             |                             |
|                                 |                             | Unsuitable/Rejection        |                             |                             |
| SAR (meq/L)                     |                             | 0.5–2 (r = 2)               | As (mg/L)                   | Suitable                    |
|                                 |                             | >2–3 (r = 1)                |                             |                             |
|                                 |                             | <3 (r = 0)                  |                             |                             |
|                                 |                             | 1–5 (r = 2)                 |                             |                             |
|                                 |                             | >5–15 (r = 1)               |                             |                             |
|                                 |                             | >15 (r = 0)                 |                             |                             |
|                                 |                             | 10–18 (r = 2)               |                             |                             |
|                                 |                             | >18–30 (r = 1)              |                             |                             |
|                                 |                             | >30 (r = 0)                 |                             |                             |
|                                 | SARa,li                     | 6.5–7; >8–8.5 (r = 1)       |                             |                             |
|                                 |                             | >6.5–pH>8.5 (r = 0)         |                             |                             |
|                                 |                             | pH                          |                             |                             |
|                                 |                             | >7.5 (r = 3)                |                             |                             |
|                                 |                             | >7.5–8 (r = 2)              |                             |                             |
|                                 |                             | >8–8.5 (r = 1)              |                             |                             |
|                                 |                             | >6.5–pH>8.5 (r = 0)         |                             |                             |
|                                 |                             | TH                          |                             |                             |
|                                 |                             | >75–150 (r = 2)             |                             |                             |
|                                 |                             | >50–Ca>150 (r = 1)          |                             |                             |
|                                 |                             | >400 (r = 0)                |                             |                             |
|                                 |                             | Ca                          |                             |                             |
|                                 |                             | >75–150 (r = 2)             |                             |                             |
|                                 |                             | >50–Ca>150 (r = 1)          |                             |                             |
|                                 |                             | >400 (r = 0)                |                             |                             |
|                                 |                             | Mg                          |                             |                             |
|                                 |                             | >10–20 (r = 3)              |                             |                             |
|                                 |                             | >20–30 (r = 2)              |                             |                             |
|                                 |                             | >10–Mg>60 (r = 1)           |                             |                             |
|                                 |                             | >60 (r = 0)                 |                             |                             |
| TH (mg/L)                       |                             | >75–150 (r = 2)             |                             |                             |
|                                 |                             | >50–Ca>150 (r = 1)          |                             |                             |
|                                 |                             | >400 (r = 0)                |                             |                             |
|                                 |                             | CO3<sup>2-</sup> (mg/L)    |                             |                             |
|                                 |                             | <1 (r = 3)                  |                             |                             |
|                                 |                             | 1–3 (r = 2)                 |                             |                             |
|                                 |                             | >3–15 (r = 1)               |                             |                             |
|                                 |                             | >15 (r = 0)                 |                             |                             |
|                                 |                             | 50–150 (r = 2)              |                             |                             |
|                                 |                             | >150–400 (r = 1)            |                             |                             |
|                                 |                             | >400 (r = 0)                |                             |                             |
|                                 |                             | HCO3<sup>-</sup> (mg/L)    |                             |                             |
|                                 |                             | <50 (r = 3)                 |                             |                             |
|                                 |                             | 50–150 (r = 2)              |                             |                             |
|                                 |                             | >150–600 (r = 1)            |                             |                             |
|                                 |                             | >600 (r = 0)                |                             |                             |
|                                 |                             | NO3<sup>-</sup> (mg/L)     |                             |                             |
|                                 |                             | <0.5 (r = 3)                |                             |                             |
|                                 |                             | 0.5–1 (r = 2)               |                             |                             |
|                                 |                             | >1–2 (r = 1)                |                             |                             |
|                                 |                             | >2 (r = 0)                  |                             |                             |

(Continued.)
directly affect the soil environment, plant growth, and the quality of yields, and through bio-accumulation, those are accumulated in the human body by the food chain (Saha et al. 2021).

**Changing soil structure**

Soil properties depend on the concentration of Na, Ca, Mg, organic matter, and micro-organisms in the soil mixture. The study observed that once the soil is irrigated with high Na in waters, by the ion exchange, Na potentially removes the Ca and Mg of soil which in turn deteriorates the soil structure.

**Miscellaneous**

A flexible hazard class named ‘miscellaneous’ included the rest of the water quality parameters such as pH, Ca, Mg, NO₃⁻, SO₄²⁻, PO₄³⁻, CO₃²⁻, HCO₃⁻ etc., considered less sensitive to crop and soil. This class includes irrigation water quality parameters such as TH, RSBC, RSC, and MAR. A report showed that TH increased the soil’s basicity and enhanced the micronutrient toxicity (Tan 1994).

**Establishing weights, scoring, and rating value**

The score of hazard classes and the rating value of parameters are important factors in the index calculation (Sutadian et al. 2016). The study followed the well-recognized analytic hierarchy process (AHP) to select the weight value of each hazard class. The proposed model is given a score from 1 to 6 for each hazard class considering their importance in the index model (Table 2). The salinity hazard is considered the most important issue in irrigation water quality evaluation, and its score is 6 ($s = 6$). Besides, The effects of miscellaneous hazard class on plants are considered to be the minor factor, and the score of this category is given one ($s = 1$). The scores for the remaining four hazard classes are set to 5, 4, 3, and 2 for sodicity hazard, the water infiltration rate of the soil, toxic to crops, and changing soil structure, respectively. The proposed model sets modified scoring and rating values for each hazard class and parameter, respectively, considering the FAO guidelines for agricultural water quality and other literature (Ayers & Westcot 1985; Fipps 2003; Hoffman 2010; Hussain et al. 2010; Bauder et al. 2014; Zaman et al. 2018). One can claim that these issues might show radical differences in topographical settings with different soil conditions and different crop patterns. Besides, the weight value of each class was measured by dividing by 21 (total score).

**Sub-index values**

This step aims to develop the water quality parameters into a scale where the actual values of the parameters are different units, and the ranges of parameters are varied (Abbasi & Abbasi 2011). In most of the WQIs, the parameters can only aggregate when they are on the same unit. Therefore, rescaling or normalizing to form sub-indices is necessary. Three different methods are commonly employed to establish the sub-index functions of parameters. Here, establishing rating curves or sub-index functions are presented based on the permissible limits from the legislated standards, such as technical regulations,
national water requirements, and WHO/FAO standards or international directives. Firstly, rating factors for each parameter are calculated in Step 1, and then the sub-index value is measured by Step 2.

**Step 1.** It is very tough to count the values of the parameters, permissible limits of parameters, and other related factors in the same Equation. In this step, the study calculated the rating factor through Equation (1), where the rating scores, rating coefficient, and three types of parameter values are considered simultaneously.

\[
Q_i = \frac{2V_i}{V_{\text{max}}} \times R_c \times \left| \frac{100 - V_{\text{min}}}{(V_i + V_{\text{max}})} \right| \times r_i \times 100
\]  

(1)

where,

- \(Q_i\) = rating factor of the \(i\)th parameter in each hazard class;
- \(r_i\) = rating score of \(i\)th parameters;
- \(R_c\) = rating coefficient;
- \(V_i\) = measured value of the parameter;
- \(V_{\text{min}}\) = maximum value of the parameter at \(r = 3\); and
- \(V_{\text{max}}\) = maximum value of the parameter at \(r = 1\).

The rating coefficient \((R_c)\) is the unitless and dimensionless factor. For \(r = 1, 2,\) and \(3; R_c\) are \(0.167, 0.333,\) and \(0.5,\) respectively, but at \(r = 0,\) it may exclude from the equation. In the case of TDS, \(488.5, 450,\) and \(2,000\) mg/L are the values of \(V_i, V_{\text{min}},\) and \(V_{\text{max}}\) (Tables 2 and 4); and \(R_c = 0.333.\) Any critical conditions such as heavy industrial discharge, lithological abnormality, abandoned mine, a radioactive substance that may present in water to a minimum of ten times higher than the usual level should be considered the \(r\)-value is \(-0.001\) instead of zero \((0)\) in Equation (1).

**Step 2.** In step 2, the rating factors of an individual parameter are aggregated and then multiplied by the weight value and scoring ratio of a hazard class. The sub-index value is obtained using the following Equation (2).

\[
S_i = \frac{s}{n} \times W_i \times \sum_{i=1}^{n} Q_i
\]

(2)

where,

- \(S_i\) = sub-index value of hazard class;
- \(s\) = scoring value of each class;
- \(n\) = number of parameters.

**Table 3** | Proposed irrigation water category

| IIWQ<sub>max</sub> value | Category/Suitability | Remarks |
|---------------------------|----------------------|---------|
| <40                       | Rejection            | Must be avoided this type of water for irrigation in any situation. In high sodic water, the permeability of soil must have very high (PI>80), and to avoid saltation surplus excess water should be used. The high SAR and low salt in water require gypsum or lime application in soil. Limited high salt tolerance crop tolerates this type of water. |
| 40 to <60                 | Poor                 | May be used in porous and sandy soils with high permeability. Heavy irrigation should be needed with high EC and SAR. Moderate to high salts tolerance crops may grow with special salinity control practices. |
| 60 to <70                 | Moderate             | May be used in soils with moderate to high infiltration rate with low leaching of salts. Crops with moderate tolerance to salts may be grown. |
| 70 to <80                 | Good                 | Irrigated soils with low clay level, moderate infiltration rate, recommended salt leaching, and light texture. Avoid very salt-sensitive crops. |
| ≥80                       | Excellent            | Except for extremely low permeability in soils, water is used for all types of soils with a low probability of causing salinity and sodicity problems. No toxicity/hazard risk for most crops. |
n = the number of parameters included in a class; and

\[ W_i = \text{weight value of } i\text{th hazard class.} \]

### Aggregation of sub-indices

An aggregate index is consisting of sub-indices for individual water quality variables. Index aggregation (addition) is made after the assignment of weights to get the final index value. Such additions may occur in consecutive stages if an index has aggregated sub-indices. In such cases, the combined subindices are again aggregated to obtain the final index value. The two most common aggregation methods for the sub-indices are the additive (arithmetic) and multiplicative (geometric) methods. Both methods are suffering from the eclipsing and the ambiguity problem (Swamee & Tyagi 2000; Juwana et al. 2012). To avoid these problems, Liou et al. (2004) proposed a mixed aggregation method (combination of additive and multiplicative methods), but this method is only for the indexing of drinking water. Here, the present study used a simple additive method shown in the following Equation (3).

\[
I_{WQIndex} = \sum_{i=1}^{n} S_i
\]

### WATER CLASSIFICATION

After getting the aggregated index value of water samples, it is essential to categorize the water quality status for irrigation suitability. The water samples are classified into five categories depending on the r-value between 0 and 3 (Table 3). The scoring values of the hazard classes and rating values of the parameters are shown in Table 2. The medians of these values are used to set the upper and lower limits used in each category. The IIWQ\_Index value less than 40 is considered to be rejected for irrigation water users (Table 3). Such waters could impair soil quality massively and result in production loss. If the index value is between 40 and <60, the suitability of the corresponding waters falls under the ‘poor’ category. When the index value is between 60 and <70, the water quality falls within the ‘moderate’ category indicating the crops are moderately tolerable for irrigation purposes. Besides, the score value is between 70 and <80, the water quality is considered to be ‘good’.
category. Finally, with a score of 80 and above, the water quality falls under the ‘excellent category. The waters usually obtained higher index values when most of the hazard classes, including the salinity, sodicity, and permeability of the soil found within the permissible limits.

**Evaluation of IIWQ\textsubscript{index}**

The proposed index model evaluates the irrigation water quality in such a way that helps to choose crop patterns and increase crop productions. The existing different water quality indices showed different suitability categories for the same water, attracting the water users for a unique index model. This study used different models, i.e., the CCME WQI (2001), Simsek & Gunduz (2007), Meireles \textit{et al.} (2010), and Maia & Rodrigues (2012) indices for a water parameter data set to evaluate the irrigation water quality suitability and found different categories for the same water. The calculated result of the CCME WQI revealed that about 65% of samples got the index value ranged from 70 to 84 and fell to a ‘good’ category, and about 35% of samples were found in the ‘fair’ category. The average value of this index was 71.52 with a standard deviation of ±4.56. The same samples were categorized as 97.5% in ‘excellent, and the rest of the samples are in ‘good’ classes using the Simsek & Gunduz index. Besides, the Meireles model classified as 32.5% of samples are in ‘no restriction’ and 67.5% are in ‘low restriction’ categories. Finally, 15.5% and 84.5% of samples were falling under the ‘excellent’ and ‘good’ quality using the Maia method. So, it is very crucial to constitute a suitable equation in which possible all water quality parameters, all-hazard classes, perfect ratting and scoring factors, etc., may include to avoid the dissimilarities in results. The present study established an indexing equation that included the maximum number of parameters and hazard classes for achieving the possible best results.

Another serious anomaly was observed in the limit value of selected water quality parameters in existing indexing methods. The minimum and maximum values of the parameters vary with permitted authorities and places. Different index models considered a different number of parameters and their limit values, so the final index value becomes different. Ayers & Westcott (1985) proposed the lowest rating value of parameters was one (1) and followed this by other recent index calculations for irrigation water suitability. However, the proposed model considered the lowest value of \( r \) is zero (0) for every parameter for the rejection category of water. If the \( r \)-value of all counted parameters is zero, then the final value of the IIWQ\textsubscript{index} becomes zero. The increased IIWQ\textsubscript{index} value indicates a better quality of water for irrigation (Table 3).

However, for any critical condition, if a highly hazardous substance has found a minimum of ten folds higher than the usual concentration of groundwater, then the \( r \)-value should be considered \(-0.001\) instead of 0 (rejection value) in Equation (1). According to Table 4, if the average arsenic (As) concentration in any groundwater samples was about 0.5 mg/L, then the calculated \( Q_i \) value would be \(-364\). In this case, the \( S_i \) value of the toxicity class obtained \(-3.52\) instead of 13.83, and the water quality of this study area ultimately fell under the ‘poor’ category.

There are four types of groundwater available for irrigation viz., calcite (Ca-HCO\(_3\)), calcite-dolomite (Ca-Mg-HCO\(_3\)), sodic (Na-Cl), and mixed type (Ca-Mg-Na-HCO\(_3\)-SO\(_4\)), and the proposed IIWQ\textsubscript{index} is equally suitable for those types of groundwater. Hence, the study considered two types of water viz., absolute calcite and sodic water to evaluate the suitability and fitness of this proposed method.

**For calcite water**

A total of 40 sampling stations of Kushtia District (the Ganges River basin area) situated in the middle-west part of Bangladesh (Figure 1(a)) were designated for this study as an example of calcite water. The concentration/value of analyzing geochemical is included in Table 4. Other parameters of irrigation water quality such as Na\%, SAR, SAR\(_{adj}\), SSP, MAR, RSBC, RSC, and PI were calculated from the usual methods (Richards 1954; Doneen 1962; Todd 1980; Gupta 1983; Raghunath 1987; Saha \textit{et al.} 2008). Studies illustrated that the groundwater of the study areas was highly mineralized, and almost 100% of samples were found calcite-type (Uddin \textit{et al.} 2011; Islam & Mostafa 2021c, 2021d). It was determined by Piper’s and Chadha’s diagram as well as other various statistical models. The parameter rating factor (\( Q_i \)), hazard sub-index (\( S_i \)), and integrated irrigation water quality index (IIWQ\textsubscript{index}) were calculated using Equations (1)–(3) and reported in the same Table. The aggregated index value for this type of water was 75.77 and fell under the ‘good’ category.

**For sodic water**

A total of 20 sampling sites of Chittagong District (the coastal belt) situated in the southeast part of Bangladesh (Figure 1(b)) were categorized as absolutely sodic water types. As the coastal part of the country, the groundwater samples were found highly sodic types with high EC, Na, and Cl\(^-\); and low Ca\(^{2+}\) and Mg\(^{2+}\) loads (Islam & Majumder 2020; Serder \textit{et al.} 2011; Chadha & Singh 2011; Islam & Mostafa 2021c, 2021d). Studies illustrated that the groundwater of the study areas was highly mineralized, and almost 100% of samples were found calcite-type (Uddin \textit{et al.} 2011; Islam & Mostafa 2021c, 2021d). It was determined by Piper’s and Chadha’s diagram as well as other various statistical models. The parameter rating factor (\( Q_i \)), hazard sub-index (\( S_i \)), and integrated irrigation water quality index (IIWQ\textsubscript{index}) were calculated using Equations (1)–(3) and reported in the same Table. The aggregated index value for this type of water was 75.77 and fell under the ‘good’ category.
The analysis results of the water samples are shown in Table 5. The parameter rating factor ($Q_i$), hazard sub-index ($S_i$), and IIWQ$_{Index}$ were calculated by the same procedure. The index value of this type of water was 36.51, which fell under the ‘rejection’ category.

Table 5 showed that several water parameters exceeded the maximum acceptable limit. In this case, the $r$-value became zero, and obviously, the $Q_i$ value obtained zero. The excess concentration of Na$^+$ (767 mg/L) and low concentration of Ca$^{2+}$ and Mg$^{2+}$ led to the higher value of Na%, SSP, and SAR, which made a lowering index value. This type of water is very harmful to both soil and crop growth, and hence, this water is completely unfit for irrigation purposes.

Table 5 | List of used parameters in each hazard class and calculated results of IIWQ$_{Index}$ for sodic water

| Hazard class | Parameter | Mean value | Rating limit | $Q_i$ | $S_i$ | Hazard class | Para. | Mean value | Rating limit | $Q_i$ | $S_i$ |
|--------------|-----------|------------|--------------|------|------|--------------|-------|------------|--------------|------|------|
| Salinity     | EC        | 1,407      | <700->3,000  | 8.50 | 13.09| Soil structure changes | SAR   | 25.22      | <10->30 | 0    | 0    |
|              | TDS       | 817        | <450->2,000  | 6.75 |       |              | SSP   | 92.6       | <20->80  | 0    |      |
| Sodicity     | %Na       | 93.77      | <20->80      | 0    | 0    | Miscellaneous Effect | Na%   | 92.45      | <20->80  | 0    |      |
|              | SSP       | 93.96      | <20->80      | 0    | 0    |              | pH    | 8.6        | >6.5->8.5| 0    | 1.95 |
|              | SAR       | 32.08      | <10->30      | 0    | 0    |              | NO$_3$| 9.69       | <2->30   | 106.4|      |
| Infiltration | SAR(EC)   | 32.08      | <10->30      | 0    | 0    |              | SO$_4$| 45.74      | <10->200 | 11.15|      |
| rates        | Na%       | 93.77      | <20->80      | 0    | 0    |              | PO$_4$| 3.67       | <0.5->20 | 102.8|      |
|              | PI        | 96.20      | >90->30      | 25.38|      |              | HCO$_3$| 134.9      | <50->600 | 2.04 |      |
|              | SSP       | 93.96      | <20->80      | 0    | 0    |              | CO$_3$| 1.67       | <1->15   | 132.8|      |
| Toxicity to  | Na        | 767        | <50->400     | 0    | 16.62|              | Ca    | 23.54      | >50->400 | 0.47 |      |
| crop         | Cl        | 389.5      | <30->3300    | 0    |      |              | Mg    | 12.96      | <10->60  | 35.30|      |
|              | B         | 2.61       | <0.5->2      | 0    |      |              | TH    | 112.7      | <75->300 | 3.06 |      |
|              | K         | 42.5       | <2->35       | 0    |      |              | RSC   | -0.03      | <0.5->2.5| 0    |      |
|              | Fe        | 7.31       | <2.5->30     | 84.81|      |              | RSRC  | 1.2        | <1->15   | 65.11|      |
|              | Mn        | 5.51       | <0.5->20     | 100.6|      |              | MAR   | 47.85      | <10->50  | 31.68|      |
|              | As        | 0.06       | <0->0.05     | 0    |      |              |       |            |      | 0    |      |
|              | Cu        | 4.81       | <2->25       | 84.20|      |              |       |            |      |      | 0    |
|              | Zn        | 6.74       | <3->30       | 79.00|      |              |       |            |      |      |      |

*The unit of all-metal, TDS, and ions is mg/L and other parameters are in usual units.*
Besides the two case studies of Bangladesh and eight water quality datasets of diverse geographical locations from seven countries were evaluated for the suitability of the proposed index IIWQ\textsubscript{Index} model. The water types, electrical conductivity (EC), and sodium adsorption ratio (SAR), and the calculated IIWQ\textsubscript{Index} values with water categories of the datasets are shown in Table 6. The sub-index values of salinity and sodicity hazard classes occupied the lion’s share of the total IIWQ\textsubscript{Index} value. Generally, these two classes are dependent mainly on the EC and SAR of water. EC counts the total dissolved solutes of water, such as Ca, Mg, and Na salt of Cl\textsuperscript{−}, SO\textsubscript{4}\textsuperscript{2−}, CO\textsubscript{3}\textsuperscript{2−}, HCO\textsubscript{3}\textsuperscript{−}, NO\textsubscript{3}\textsuperscript{−}, and PO\textsubscript{4}\textsuperscript{3−}. Heavy calcite and sodic water showed higher values of EC and TDS. A salinity hazard exists if salt accumulates in the crop root zone to a concentration that causes a loss in yield because the roots of the plants are unable to uptake enough water to keep the plant hydrated in saline soil. The reduced water uptake in crops hampered the growth rate of the crop (Ayers & Westcot 1985). SAR is an ideal index to evaluate the possibility of Na-alkali hazard because it measures the soil capacity to adsorb Na\textsuperscript{+} from irrigation water. Irrigation water with a higher SAR value can damage the soil structure by a cation-exchange reaction between Na\textsuperscript{+} in water and Ca\textsuperscript{2+} and Mg\textsuperscript{2+} in soil.

The IIWQ\textsubscript{Index} analysis results showed that very low or high concentrations of minerals in water samples were harmful to soil and plant health, which provided a lower index value. Therefore the concentration of the minerals should be within the permissible limit to get a suitable range of Qi and Si value as well the final index value. For example, in Ghana and Nigeria, the groundwater samples carry very few amounts of minerals with less than 20 mg/L of Ca\textsuperscript{2+}, Mg\textsuperscript{2+}, and Na\textsuperscript{+} and have very low EC and TDS values. For this reason, the index value was found relatively lower (Ghana: 72.11 and Nigeria: 63.06), though these waters were non-sodic than other countries included in Table 6. The low concentrations of all components present in water showed abnormal values of irrigation water quality parameters such as SAR, Na\text%\textsuperscript{+}, SSP, and others. So, this type of water did not present a suitable index value. For this reason, the study got the lower IIWQ\textsubscript{Index} for these above-mentioned places and the results get the acceptability of this proposed method. Besides, the calculated results showed that the absolute calcite or dolomite type water samples did not give the highest index value. The IIWQ\textsubscript{Index} values of different waters in Table 6 followed the order: sodic < calcite < calcite-dolomite < calcite-dolomite-Sodic. In Bangladesh (1), all water samples are calcite type (Ca-HCO\textsubscript{3}), and the calculated index value indicated the water was in a good category. In this case, high Ca\textsuperscript{2+} and HCO\textsubscript{3} concentration and the excessive hardness of water deducted some points from the excellent category’s index value (>80). Besides, the sodic type samples of the coastal belt areas of Bangladesh (2) showed a very low index value and were categorically unfit for irrigation uses. In China, Pakistan, and Morocco, the water samples are mixed type i.e., dolomite-calcite-sodic water with low SAR and medium values of EC and TDS. The concentrations of Ca\textsuperscript{2+}, Mg\textsuperscript{2+}, and Na\textsuperscript{+} in these waters were at a medium level that indicating the balanced constituents. These waters were of the excellent category (IIWQ\textsubscript{Index}>80) for irrigation uses. Due to the relatively high sodicity, SAR, and EC, the samples of India (1) were fallen under the ‘moderate’ category with an index value of 65.86. Instead, the mixed type water but with high EC in India (2) made it good quality water for irrigation. In addition, the study results revealed that the computed index values were apparently in reversely proportional to the EC and SAR (Figure 2 and Table 6). Several studies supported the present findings (Rhoades et al. 1992; Fipps 2003; Hoffman 2010). Hence, the calculated index values of the water of different locations support the acceptability of the proposed IIWQ\textsubscript{Index} model.

A recent study showed that climate change has greatly influenced both irrigation water quality and quantity (Serder et al. 2020). These impacts directly affected soil fertility and crops production as well. At extreme weather conditions, changes in the rainfall pattern, heavy drought, and variations of physicochemical parameters value of water collectively influence the rate of productivity. This proposed indexing model may measure the variations of irrigation water quality through climate change.

**CONCLUSION**

The irrigation water quality index (IWQI) is the tool that can evaluate water quality more accurately. Several established irrigation water quality indices are used, but most of the indices have some limitations. The present study critically reviewed the methods and identified the types and causes of that limitation. It proposed a new Integrated Irrigation Water Quality Index (IIWQ\textsubscript{Index}) using the precise sub-index and aggregated equations that included the maximum number and types of water parameters to evaluate irrigation water conveniently. This model evaluated two types of water to identify the suitability category for irrigation purposes. The results showed the index values were 75.77 and 36.51, and their water category fell under ‘good and rejected’ for the calcite (Ca-HCO\textsubscript{3}) and sodic (Na-Cl) type of water, respectively. The proposed IIWQ\textsubscript{Index} model was
| Sample source                              | References                  | Water type                               | EC    | SAR   | No of parameter used | Calculated IWIQ<sub>index</sub> value | Water category |
|-------------------------------------------|-----------------------------|------------------------------------------|-------|-------|----------------------|---------------------------------------|----------------|
| Muktsar, Punjab, India<sup>(2)</sup>      | Kumar et al. (2007)         | Na-Cl-SO<sub>4</sub>                      | 1.022 | 8.14  | 24                   | 65.86                                 | Moderate       |
|                                           |                             | Ca-Mg-HCO<sub>3</sub>-SO<sub>4</sub>     |       |       |                      |                                       |                |
|                                           |                             | Sodic (Major)                            |       |       |                      |                                       |                |
|                                           |                             | Calcite-Dolomite                        |       |       |                      |                                       |                |
| Kodavanar, Tamil Nadu, India<sup>(1)</sup>| Kalaivana et al. (2017)     | Ca-Mg-HCO<sub>3</sub>(50%)              | 1.818 | 3.5   | 20                   | 71.90                                 | Good           |
|                                           |                             | Na-K-Cl-SO<sub>4</sub>(40%)             |       |       |                      |                                       |                |
|                                           |                             | Calcite-Dolomite-Sodic                  |       |       |                      |                                       |                |
| Akure, Ondo State, Nigeria                | Falowo et al. (2019)        | Ca-Mg-HCO<sub>3</sub>                    | 189.8 | 0.087 | 19                   | 63.06                                 | Moderate       |
|                                           |                             | Calcite-Dolomite                        |       |       |                      |                                       |                |
| Near-suburb area, North China             | Xiao et al. (2020)          | Mg-Ca-HCO<sub>3</sub>(93%)              | 575   | 1.01  | 24                   | 97.31                                 | Excellent      |
|                                           |                             | Na-HCO<sub>3</sub>(7%)                  |       |       |                      |                                       |                |
|                                           |                             | Dolomite-Calcite-Sodic                  |       |       |                      |                                       |                |
| Beni Mellal city, Morocco                 | Baghdadi et al. (2019)      | Ca-Mg-HCO<sub>3</sub>-SO<sub>4</sub>     | 778.5 | 0.68  | 23                   | 90.37                                 | Excellent      |
|                                           |                             | Na-Cl (minor)                           |       |       |                      |                                       |                |
|                                           |                             | Calcite-Dolomite                        |       |       |                      |                                       |                |
|                                           |                             | Sodic                                   |       |       |                      |                                       |                |
| Talensi District, Northern Ghana          | Chegbeleh et al. (2020)     | Ca-Mg-Na-HCO<sub>3</sub>                 | 403.9 | 0.34  | 22                   | 72.11                                 | Good           |
|                                           |                             | Calcite-Dolomite-Sodic                  |       |       |                      |                                       |                |
| Sargodha District, Pakistan               | Siddique et al. (2020)      | Na-HCO<sub>3</sub>(42%)                 | 939   | 1.70  | 21                   | 94.18                                 | Excellent      |
|                                           |                             | Ca-Na-HCO<sub>3</sub>(37%)             |       |       |                      |                                       |                |
|                                           |                             | Sodic                                   |       |       |                      |                                       |                |
|                                           |                             | Calcite-Dolomite                        |       |       |                      |                                       |                |
| Calabria, South Italy                     | Vespasiano et al. (2021)    | Ca-Mg-HCO<sub>3</sub>(65%)              | 905   | 1.10  | 25                   | 80.76                                 | Excellent      |
|                                           |                             | Na-Cl(27%)                              |       |       |                      |                                       |                |
|                                           |                             | Calcite-Dolomite                        |       |       |                      |                                       |                |
|                                           |                             | Sodic                                   |       |       |                      |                                       |                |
| Kushthia District, Bangladesh<sup>(1)</sup>| This study                  | Ca-HCO<sub>3</sub>                      | 806.8 | 0.47  | 27                   | 75.77                                 | Good           |
|                                           |                             | Calcite                                 |       |       |                      |                                       |                |
| Chittagong coast, Bangladesh<sup>(2)</sup>| This study                  | Na-Cl                                   | 1,607 | 32.08 | 27                   | 36.51                                 | Rejection      |
|                                           |                             | Sodic                                   |       |       |                      |                                       |                |
justified using diversified water quality datasets of eight different geographical locations that showed satisfactory results. The index model has some flexibility which makes it better suitable. This indexing method is easy to compute and deliver practical information on the suitability of irrigation water and helping to decrease crop and soil damage from using worst-quality groundwater. The proposed index model is practical, precise, and applicable to all types of water in any topographical place and provided a simple analysis tool even for a non-technical decision maker and a farm manager.

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

REFERENCES
Abbasi, T. & Abbasi, S. A. 2011 Water quality indices based on basement: the biotic indices. Journal of Water And Health 9 (2), 330–348.
Almeida, C., González, S., Mallea, M. & González, P. 2012 A recreational water quality index using chemicals, physical and microbiological parameters. Environmental Science and Pollution Research 19 (8), 3400–3411.
Arslan, S. 2017 Assessment of groundwater and soil quality for agricultural purposes in Kopruoren Basin, Kutahya, Turkey. Journal of African Earth Sciences 131, 1–13.
Ashraf, M., Afzal, M., Ahmad, R. & Ali, S. 2011 Growth and yield components of wheat genotypes as influenced by Potassium and farmyard manure on a saline sodic soil. Soil and Environment 30, 115–121.
Ayers, R. S. 1977 Quality of water for irrigation. Journal of the Irrigation and Drainage Division 103 (2), 135–154.
Ayers, R. S. & Westcot, D. W. 1985 Water Quality for Agriculture, FAO Irrigation and Drainage Paper 29 Rev. I, UN Food and Agriculture Organization, Rome.
Baghdadi, E. M., Zantar, I., Jouider, A. et al. 2019 Evaluation of hydrogeochemical quality parameters of groundwater under urban activities-case of Beni Mellal city (Morocco). Euro-Mediterranean Journal for Environmental Integration 4 (1), 1–19.
Bauder, T. A., Waskom, R. M., Sutherland, P. L. & Davis, J. G. 2011 Irrigation water quality criteria. Colorado State University Extension Publication, Crop series/irrigation. Fact sheet no. 0.506, p. 4.
Bozdag, A. 2016 Assessment of the hydrogeochemical characteristics of groundwater in two aquifer systems in Çumra Plain, Central Anatolia. Environmental Earth Sciences 75 (674), 1–15.
Canadian WQI 2001 Canadian Water Quality Guidelines for the Protection of Aquatic Life. Canadian Environmental Quality Guidelines CCME Water Quality Index 1.0 Technical Report.
CCME 2006 A Sensitivity Analysis of the Canadian Water Quality Index. PN 1355, Gartner. Lee Limited 140 Renfrew Drive, Suite 102 Markham, Ontario L3R 6B3.
Chaoua, S., Boussaa, S., El Gharmali, A. & Boumezzough, A. 2019 Impact of irrigation with wastewater on accumulation of heavy metals in soil and crops in the region of Marrakech in Morocco. Journal of the Saudi Society of Agriculturalal Sciences 18 (4), 429–436.
Chauhan, G. & Chauhan, U. K. 2014 Human health risk assessment of heavy metals via dietary intake of vegetables grown in wastewater irrigated area of Rewa, India. International Journal of Scientific and Research Publications 4, 1–9.
DANR-UC 2021 Salinity Management. Division of Agriculture and Natural Resources, University of California.
Doljido, J., Raniszewski, J. & Woyciechowska, J. 1994 Water quality index applied to rivers in the Vistula river Basin in Poland. Environmental Monitoring and Assessment 33 (1), 33–42.
Doneen, L. D. 1964 Notes on Water Quality in Agriculture. Published as a water science and engineering. Paper 4001, Department of Water Sciences and Engineering, University of California.

Eaton, F. M. 1950 Significance of carbonates in irrigation waters. Soil and Science 69, 123–134.

Falowo, O. O., Amodu, M. B., Oluwasegunfunmii, V. et al. 2019 Groundwater evolution, hydrochemical facies and quality evaluation for irrigation use in Akure, Ondo State, Nigeria. Journal of Geoscience and Environmental Protection 7, 118–140.

Fipps, G. 2003 Irrigation Water Quality Standards and Salinity Management. Fact Sheet B-1667. Texas Cooperative Extension. The Texas A & M University System, College Station, TX.

Freeze, R. A. & Cherry, J. A. 1979 Groundwater. Prentice-Hall, Inc. Englewood Cliffs, New Jersey 07632.

Gazzaz, N. M., Yusufo, M. K., Aries, A. Z., Juahir, H. & Ramli, M. F. 2012 Artificial neural network modeling of The water quality index for Kinta River (Malaysia) using water quality variables as predictors. Marine Pollution Bulletin 64 (11), 2409–2420.

Gupta, U. C. & Gupta, S. C. 1998 Trace element toxicity relationships to crop production and livestock and human health: implications for management. Communications in Soil Science and Plant Analysis 29 (11–14), 1491–1522.

Hem, J. D. 1970 Study and Interpretation of the Chemical Characteristics of Natural Water, 2nd ed., US Geo Survey, Water Supply, Paper 1473.

Hoffman, G. J. 2010 Water Quality Criteria for Irrigation. University of Nebraska, Lincoln extension education Program. EC782.

Hussain, G., Aliquwaizany, A. & Al-Zarah, A. 2010 Guidelines for irrigation water quality and water management in the Kingdom of Saudi Arabia: an overview. Journal of Applied Sciences 10, 79–96.

Hussain, M. H., Salwan, S. A.-H. & Ayser, M. A.-S. 2018 Assessment of index for aquifer water quality for irrigation and livestock purposes of Dammam Aquifer in Najaf Area of Iraq. Journal of Karbala University 16 (3), 77–89.

Islam, M. S. & Majumder, S. M. M. H. 2020 Alkalinity and hardness of natural waters in Chittagong City of Bangladesh. International Journal of Science and Business 4 (1), 137–150.

Islam, M. S. & Mostafa, G. M. 2021a Groundwater suitability for irrigated agriculture in Alluvial Bengal delta plain: a review. International Journal of Advances in Applied Sciences 10 (2), 156–170.

Islam, M. S. & Mostafa, M. G. 2021b Meta-analysis and risk assessment of fluoride contamination in groundwater. Water Environment Research 93 (8), 1194–1216. doi: 10.1002/wer.1508.

Islam, M. S. & Mostafa, M. G. 2021c Hydro-geochemical evaluation of groundwater for irrigation in the Ganges river Basin areas of Bangladesh. Research Square (Preprint). http://doi.org/10.21203/rs.3.rs-161359/v1.

Islam, M. S. & Mostafa, M. G. 2021d Groundwater quality and risk assessment of heavy metal pollution in middle-west part of Bangladesh. Journal of Earth and Environmental Science Research 3 (2), 1–5. https://doi.org/10.47363/JEESR/2021 (3)143.

Juwana, I., Muttill, N. & Perera, B. J. C. 2012 Indicator-based water sustainability assessment – a review. Science of The Total Environment 438 (0), 357–371.

Kalaivanan, K., Gurugnanam, B., Pourghasemi, H. R. et al. 2017 Spatial assessment of groundwater quality using water quality index and hydrochemical indices in the Kodavanar sub-basin, Tamil Nadu, India. Sustain Water Resort Managua 4, 627–641.

Karim, R. A., Hossain, S. M., Miah, M. M. H., Nehar, K. & Mubin, M. S. H. 2008 Arsenic and heavy metal concentrations in surface soils and vegetables of Feni district in Bangladesh. Environmental Monitoring and Assessment 145, 417–425.

Kelley, W. P. 1963 Use of saline irrigation water. Soil and Science 95, 355–391.

Kumar, M., Kumari, K., Ramanathan, A. et al. 2007 A comparative evaluation of groundwater suitability for irrigation and drinking purposes in two intensively cultivated districts of Punjab, India. Environmental Geology 53, 553–574.

Leblebici, Z. & Kar, M. 2018 Heavy metals accumulation in irrigation water, and their daily intake in Nevşehir. Journal of Agricultural Science and Technology 20, 401–415.

Lesch, S. M. & Suarez, D. L. 2009 A short note on calculating the adjusted SAR index. American Society of Agricultural and Biological Engineers 52 (2), 493–496.

Liou, S. M., Lo, S. L. & Wang, S. H. 2004 A generalized water quality index for Taiwan. Environmental Monitoring And Assessment 96 (1–3), 35–52.

Maia, C. E. & Rodrigues, K. K. R. P. 2012 Proposal for an index to classify irrigation water quality: a case study in Northeastern Brazil. Revista Brasileira de Ciência do Solo 36 (36), 823–830.

Matthess, G. 1982 The Properties of Ground Water. John Wiley and Sons, New York, USA, p. 397.

Meireles, A., Andrade, E. M., Chaves, L. et al. 2010 A new proposal of the classification of irrigation water. Revista Ciencia Agronomica 41 (5), 349–357.

Mostafa, M. G., Helal Uddin, S. M. & Haque, A. B. M. 2017 Assessment of hydro-geochemistry and groundwater quality of Rajshahi City in Bangladesh. Applied Water Science (Springer Pub) 7 (8), 4663–4671. doi: 10.1007/s13201-017-0629-y.

Raghnunath, H. M. 1987 Groundwater. Wiley Eastern, New Delhi, India.

Rahim, M. A. & Mostafa, M. G. 2021 Impact of sugar mills effluent on environment around Mills area. AIMS Environmental Science 8 (1), 86–99. doi: 10.3934/envirosci.2021006.

Rhoades, J. D. 1992 Instrumental field methods of salinity appraisal. In: Advances in Measurements of Soil Physical Properties: Bringing Theory Into Practice (Topp, G. C., Reynolds, W. D. & Green, R. E., eds). SSSA Special Publication 30/ASA/CSSA/SSSA, Madison, pp. 231–248.

Richards, L. A. 1954 Diagnosis and Improvement of Saline and Alkaline Soils. US Department of Agriculture Hand Book, Washington, p. 60.
Romanelli, A., Lima, M. L., Londoño, O. M. Q. et al. 2012 A GIS-based assessment of groundwater suitability in irrigation purposes in flat areas of the wet Pampa Plain, Argentina. Environmental Management 50 (3), 490–503.

Saha, D., Dhar, Y. R. & Sikdar, P. 2008 Geochemical evolution of groundwater in the Pleistocene aquifers of South Ganga Plain, Bihar. Journal Geological Society of India 71, 475–482.

Saha, M. K., Sarkar, R. R., Ahmed, S. J., Sheikh, A. H. & Mostafa, M. G. 2021 Impacts of brick kiln emission on agricultural soil around brick kiln areas. Nepal Journal of Environmental Science 9 (1), 1–10. Available from: https://www.cdes.edu.np/njes/index.php/NJES/article/view/73.

Serder, S. M., Islam, M. S., Hasan, M. R., Yeasmin, M. S. & Mostafa, M. G. 2020 Assessment of coastal surface water quality for irrigation purpose. Water Practice & Technology 15 (4), 960–972. doi: 10.2166/wpt.2020.070960-972.

Singh, K. K., Geeta, T. & Suresh, K. 2020 Evaluation of groundwater quality for suitability of irrigation purposes: a case study in the Udham Singh Nagar, Uttarakhand. Journal of Chemistry 2, 1–15.

Sutadian, A. D., Muttil, N., Yilmaz, A. & Perera, C. 2016 Development of river water quality indices – a review. Environmental Monitoring and Assessment 188 (58), 1–33.

Tan, K. H. 1994 Environmental Soil Science. Marcel Decker, Inc., New York, Basel, Hong Kong.

Todd, D. K. 1980 Groundwater Hydrology. Wiley, New York.

UCCC 1974 Guidelines for interpretations of water quality for irrigation. University of California Committee of Consultants (UCCC), 3 USA. National field manual, US – Geological Survey.

Uddin, S. M. H., Mostafa, M. G. & Haque, A. B. M. H. 2011 Evaluation of groundwater quality and its suitability for drinking purpose in Rajshahi City, Bangladesh. Water Science and Technology: Water Supply 11 (5), 545–559. doi:10.2166/ws.2011.079.

UNEP-GEME Water 2007 United Nations Environment Programme; Global Environment Monitoring System (GEMS) for Water Programme; United Nations Water Assessment Programme.

USDA 2014 Soil Infiltration. Soil health- Guide for educators, NRCS-US Department of Agriculture.

Vespasiano, G., Muto, F. & Apollaro, C. 2021 Geochemical, geological and groundwater quality characterization of a complex geological framework: the case study of the Coreca Area (Calabria, South Italy). Geosciences 11 (3), 121.

Wilcox, L. V. 1955 Classification and Use of Irrigation Water. U.S. Department of Agriculture, Circular No. 969, Washington, DC, USA, p. 19.

Xiao, Y., Shiyang, Y., Qichen, H. et al. 2020 Hydrogeochemical appraisal of groundwater quality and health risk in A near-suburb area of Northern China. Journal of Water Supply Research and Technology-Aqua 69, 55–69.

Zaman, M., Shahid, S. & Heng, L. 2018 Irrigation water quality. Guideline for Salinity Assessment, Mitigation and Adaptation Using Nuclear and Related Techniques, 113–152.

First received 29 July 2021; accepted in revised form 25 October 2021. Available online 5 November 2021.