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Revised Iranian Water Quality Index (RIWQI): a tool for the assessment and management of water quality in Iran

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Abstract Water quality indices use biological, chemical, and physical data and information to classify the condition of surface waters, ultimately contributing to their management. We used multicollinearity and principal components analyses to develop the Revised Iranian Water Quality Index (RIWQI) as an indicator of agricultural and urban effects in the Karun River Basin of southwestern Iran. Seasonal sampling and analysis of water quality parameters from 54 sites across 18 rivers of the Karun River Basin include fecal coliform, total dissolved solid, phosphate, biological and chemical oxygen demand, nitrate, dissolved oxygen saturation, turbidity, pH, and water temperature. This study updates the previous version of Iranian Water Quality Index (IWQI) by differentially weighting individual variables, refining the main sub-indices, adding phosphate (PO_4^-), biological oxygen demand (BOD), chemical oxygen demand (COD), and temperature (T), and improving the aggregation calculation. Sensitivity testing of the RIWQI resulted in a mean value for discrimination efficiency (DE) > 85.6%, the highest of other indices calculated with the same dataset.

Keywords Karun River Basin · PCA · Rating curves · Freshwater ecosystem monitoring

Introduction

Freshwater plays a vital role in supporting the environment, society, and economy (UN Water, 2015). Good water quality is crucial for river ecosystems and biotic communities, but also for most human uses of the water (Sutadian et al., 2018). Large-scale monitoring programs

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aim at identifying trends in water quality, detecting point and non-point anthropogenic pollution (Bartram & Ballance, 1996), inferring consequences on aquatic organisms (Amoatey & Baawain, 2019; Shukla Devangee et al., 2017; Tejerina-Garro et al., 2005), and guiding management actions. They classify the integrity of surface waters based on a range of biological, chemical, and physical parameters in order to plan and manage water uses and allocations (Boyacioglu, 2007, 2010; Khalil et al., 2011). A large range of these parameters are affected by human activities and might in turn be reflected—and measured—in water quality monitoring. Water Quality Indices (WQIs) have been developed to reduce the complexity arising from the number of potentially relevant parameters (Horton, 1965; Kachroud et al., 2019) and used to evaluate water quality in various regions around the globe (Brown et al., 1970; Dinius, 1987; Dojlido et al., 1994; Liou et al., 2004; Said et al., 2004; Hülya Boyacioglu, 2010). WQIs usually report higher scores for more pristine water quality (excellent or good) and lower scores for degraded water quality (poor or very poor) (Lumb et al., 2011). To use several parameters in the calculation of a single index value, they must be weighted, scaled, and aggregated (Kachroud et al., 2019). Most WQIs are thus based on four analytical steps: (i) selection of the specific water quality variables to be included; (ii) transformation of the raw values of the variables to a common scale; (iii) definition of the respective assigned weights (AW) and relative weights (RW) of the parameters; and (iv) specification of the aggregation function to calculate the final water quality index (Gupta et al., 2007; Kachroud et al., 2019; Paun et al., 2016; Uddin et al., 2021).

Variable selection is the first step for defining a WQI and has great importance, because partly redundant parameters in the index cause rigidity problems (Sutadian et al., 2018). Unnecessary parameters also decrease the magnitude of the aggregated index, potentially resulting in ambiguity issues (Swamee & Tyagi, 2007). The next step is rating curves (generation of the sub-indices) that are the essence of the development of this index and needs to be defined in a transparent manner for each parameter (Almeida et al., 2012; House, 1989). Then, parameters are assigned weightings depending on their significance to the assessment (Uddin et al., 2021). The aggregation process is the final step of the WQI model. It is applied to aggregate the parameter sub-indices into a single water quality index score (Sutadian et al., 2016). Therefore, the results should be checked with different formulas (additive functions, multiplicative functions, and combination of the additive and multiplicative functions) to select the best one for calculating the new index. The best version must be chosen based on its sensitivity to reduced or degraded water quality, and on its performance to show differences between sites and seasons. Because, one source of uncertainty problem in WQI models is the use of inappropriate mathematical functions in the aggregation step, which affects the final index values (Juwana et al., 2016; Sutadian et al., 2016). An inappropriate aggregation function might artificially change the value of the water quality index so that it does not exactly reflect the real water quality (Swamee & Tyagi, 2007).

Uncertainty problem in WQI models can be caused by inappropriate selection of parameters, the sub-indexing techniques, weighting of parameters, and aggregation functions. Moreover, eclipsing problem can also be caused by inappropriate weighting and the sub-indexing techniques (Juwana et al., 2016; Sutadian et al., 2016; Uddin et al., 2021). The Delphi method (researcher's opinion) which has been widely employed in other indices is a subjective approach due to the selection and weighting of parameters by experts (Harkins, 1974; Tirkey et al., 2015), and causes reduction of objectivity and comparability. However, subjectivity in developing WQI can be further reduced by parameter selection based on statistical approaches. These can also be used to identify most informative variables in determining the water quality as well as the extent of their significance (Terrado et al., 2010; Tirkey et al., 2015). In some indices, statistical approaches such as cluster analysis (CA), discriminant analysis (DA), analytic hierarchy process (AHP), factor analysis (FA), and principal components analysis (PCA) are used to evaluate structure and relationships among multivariate data and to assist in different steps of index development (Kung et al., 1992; Tirkey et al., 2015; Uddin et al., 2021). Using more quantitative statistical approaches (such as CA and PCA) thus can reduce reliance on subjective assumptions, improve accuracy of WQI, and increase reliability compared to individual opinions (Tirkey et al., 2015; Uddin et al., 2021).

In Iran, environmental water quality assessment and classification of river's integrity were commonly performed by the National Sanitation Foundation Water Quality Index (NSFWQI) and non-Iranian WQIs (Babaei Semiromi et al., 2011). In recent years, various WQIs that take into account local environmental characteristics have been developed by researchers in different regions of Iran (Babaei Semiromi et al., 2011; Karbassi et al., 2011; Nikoo et al., 2011). These indices are based on the analytical hierarchy process method (AHP) and experts' opinions (EO). The Iranian Water Quality Index (IWQI) is one of these indices that commonly used for water quality assessment in Iran (Babaei Semiromi et al., 2011). The IWQI was developed based on the Delphi method (consultation of 180 experts in water quality management), which defined the most influential variables and their weights, followed by the sub-indices' determination based on the opinion of seven experts. This has resulted in the six parameters (oxygen saturation (%DO), turbidity (NTU), nitrate (NO_3), fecal coliform (FC), total dissolved solids (TDS), and pH) that are included in the IWQI. However, some important variables such as chemical oxygen demand (COD), biological oxygen demand (BOD), phosphate (PO_4^-), and temperature (T) are not considered in the IWQI.

Our study aimed at evaluating the WQI commonly used for surface water monitoring in Iran and improving it by using objective techniques of parameter selection and weighing. We proposed our modifications based on the results obtained and analysis performed on a large dataset of the Karun River Basin, Iran. With the size of its catchment and the range of tributaries of different characteristics, the Karun River Basin is representative of many semi-arid river systems in Iran and elsewhere and thus provides a very useful case study. We identified dominant alterations of surface water quality in 54 sites in four seasons; determined the most influential parameters and their weights using multicollinearity analysis and PCA; created rating curves and sub-indices using Iranian and world standards, and other global indices; and developed the Revised Iranian Water Quality Index (RIWQI).

Material and methods

Study area

The Karun River Basin is the largest freshwater resource in Iran, with a drainage area of 67,000 km^2 covering seven provinces in southwestern Iran between 48° 00′ to 52° 30′ E and 30° 00′ to 34° 05′ N (Fig. 1). The Karun is the longest (950 km) and the only navigable river in Iran, draining the Zagros mountain range (max. altitude > 4400 m.a.s.l., average slope 3%), of which approximately 74.6% is characterized as mountains and foothills, and 25.4% as high plains (Bakhshipour et al., 2019). Its collection of rivers flows through various landscapes and mesohabitats, eventually discharging into the Persian Gulf (21×10^9 m^3/year) (Afkhami et al., 2007; Bagherian Marzouni et al., 2014). The rivers of the Karun Basin play important roles in Iran as valuable sources of water and serve multiple and often competing anthropogenic uses. These rivers are the main source of drinking water for 16 cities and numerous villages, irrigate thousands of hectares of agricultural lands, and support industries and several large hydropower plants, resulting in diverse pollution and other alterations of the river (Naddafi et al., 2007; Sabbaghi & Masihi, 2012).

Sampling

The dataset used to develop RIWQI is based on a range of ecological surface water quality parameters sampled in four seasons of 2018–2019 at 54 sites on 18 rivers in the Karun River Basin in south western Iran (Fig. 1). Surface water samples were collected in triplicates at a depth of 10–15 cm with pre-washed (2% HCl) plastic containers. The bottles were rinsed again with river water and the water samples were collected securely, sealed, and labeled. The water samples were transported on ice to the laboratory at IUT for analysis within 24 h. We used a portable multiparameter probe (Oxi, 3205, WTW Weilheim, Germany) for in situ measurements of dissolved oxygen (DO) concentrations and water temperature (T) at 10 transects per site.

Methodology of developing the RIWQI

We took the average of each variable between all seasons on each site. Then, we used statistical techniques (multicollinearity analysis and PCA) for selecting water quality variables, their importance degree (assigned weight), and their coefficient values (Relative Weight). Sub-indices for selected parameters and qualitative classification table for the final index were developed based on a large-scale Delphi method. Final index was developed and chosen based on testing of different functions (formulas), and discrimination efficiency (DE) analysis, respectively. Statistical analysis was performed using Excel 2016, SPSS v. 22, R software (v. 4.0.4, R Core Team, 2020), and vegan (2.5–6) and ggplot2 (v. 2.2.0) packages. Flowchart of RIWQI development is presented in Fig. 2.

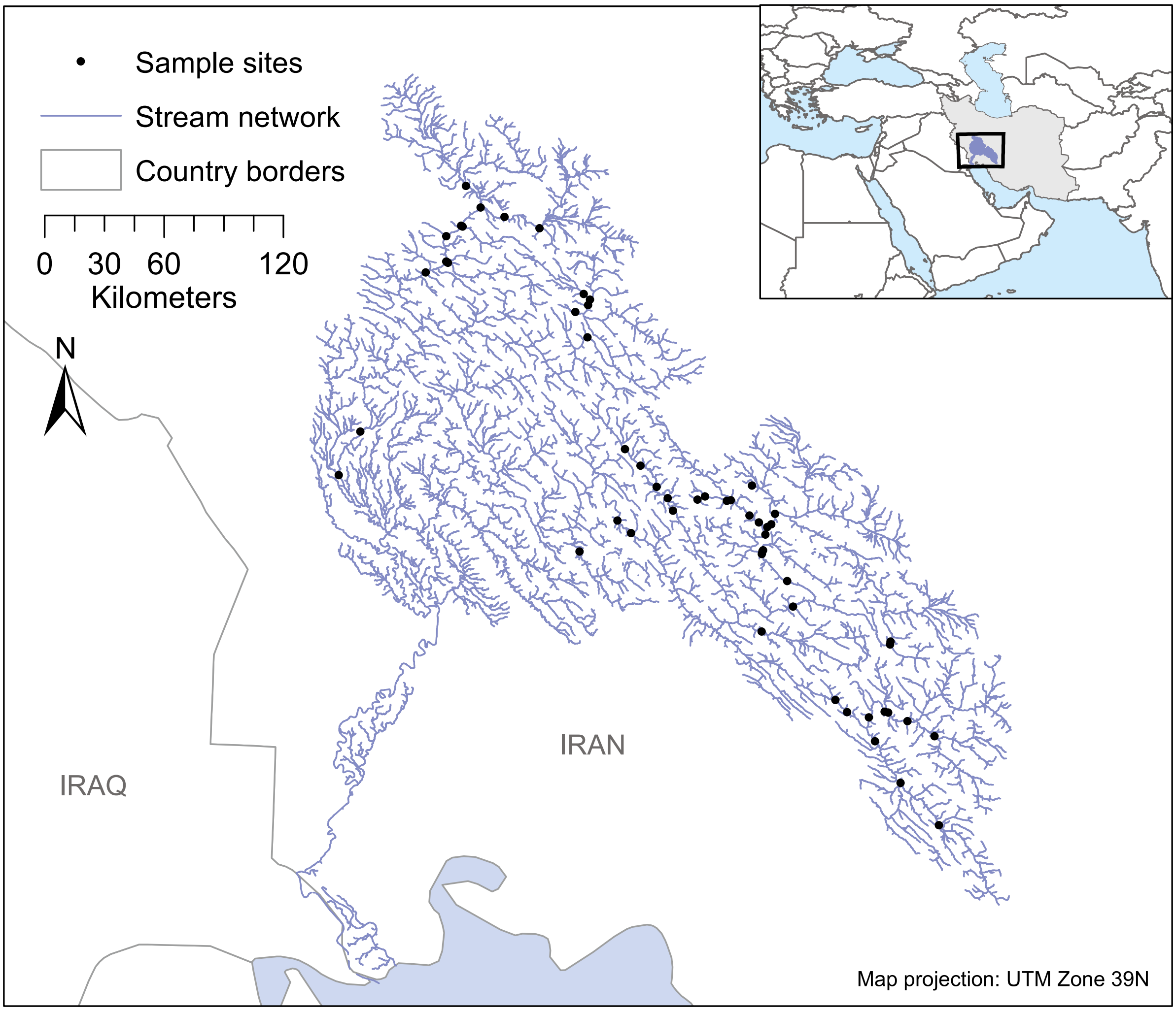


Fig. 1 Location of the sampling sites in the Karun River Basin, Iran

Variables screening and selection

From the samples, we analyzed 22 variables (Table 1) using standard methods (APHA et al., 2017). Before running PCA, we performed variable screening and checked normality of data by one-sample Kolmogorov–Smirnov tests ($p > 0.05$). Because some data were not normally distributed, we used common log- and box-cox transformations for further analysis. Multicollinearity analysis as a redundancy analysis was used to measure correlation among the variables and identify correlated variables. In case of correlated variables ($R^2 \geq 0.7$), we removed one of them chosen based on redundancy and efficiency of measurement. This resulted in twenty-two physico-chemical variables measured, of which nine correlated variables were removed (Table 1). PCA was then used for both reducing the number of variables (by identifying redundant variables) and identifying and selecting the most influential variables. The set of most influential variables identified by PCA provides the means to explain the variability in environmental characteristics of the study system (Ellison et al., 2012; Legendre, 1998; Robertson et al., 2001). We ran PCA with 13 variables, after which three additional variables were removed (NO_2, TH, and TA) based on their low eigenvalues on PC1 (Fig. 3). To support their selection and inclusion in the RIWQI (Table 1), we compared the candidate variables (FC, TDS, PO_4^-, BOD, COD, NO_3, DO%, NTU,

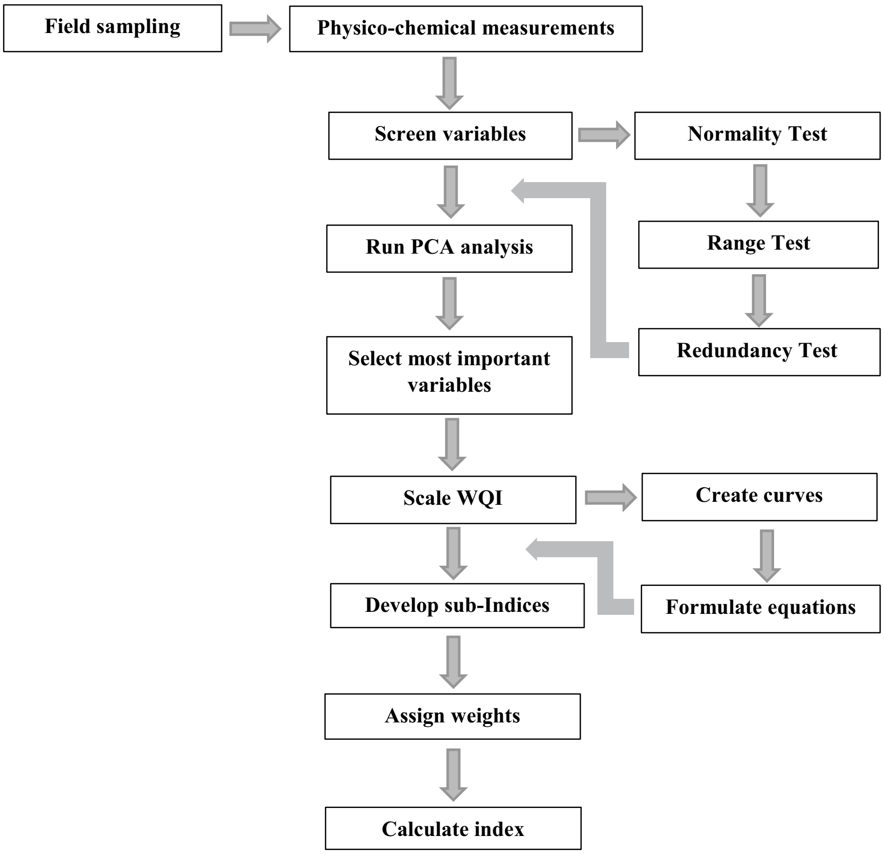


Fig. 2 Process followed in developing the Revised Iranian Water Quality Index (RIWQI)

pH, T) with 15 published WQIs (Horton, 1965; Brown et al., 1970; Deininger & Maciunas, 1971; Prati et al., 1971; MCDuffie & Haney, 1973; Oconnor, 1973; Tyson & House, 1989; Paulic et al., 1996; SAFE, 1996; Cude, 2001; CCME, 2003; Sarkar & Abbasi, 2006; Hulya Boyacioglu, 2007; Shuhaimi-Othman et al., 2007; Babaei Semiromi et al., 2011; Almeida et al., 2012).

Definition of the RIWQI scale

We scaled the RIWQI (Table 2) based on Iranian and world standards (CCME, 2003; House, 1989; ISIRI, 2010; USEPA, 1986; WHO, 2004) from 0 to 100, with a score of 0 reflecting extremely polluted (very poor) waters and 100 reflecting excellent waters (Almeida et al., 2012). We categorized the RIWQI according to possible water uses including drinking, recreational, aquaculture, agriculture, and industrial uses (Table 2).

Threshold values of the variables (desirable, minimum, moderate, maximum, and undesirable) to develop and classify the RIWQI were also determined based on Iranian and world standards (CCME, 2003; House, 1989; ISIRI, 2010; USEPA, 1986; WHO, 2004) (Table 3).

Developing Q-value rating curves and sub-indices

The concentration values of parameters to create rating curves were drawn from Iranian and world standards. Rating curves and sub-indices were developed by averaging both expert opinions on water quality levels in Iranian and world water quality standards (CCME, 2003; ISIRI, 2010; USEPA, 1986; WHO, 2004) and expert opinions on sub-indices of universal and Iranian WQIs (Brown et al., 1970; Tyson & House, 1989; Paulic et al., 1996; SAFE, 1996; Cude, 2001; Sarkar & Abbasi, 2006; Boyacioglu, 2007; Babaei Semiromi et al., 2011). This technique represents a large-scale Delphi method and can reduce

Table 1 List of physico-chemical variables measured in study area and those selected through the screening procedures. Column A is the list of variables resulting from the first screen; B is the final list of variables

Candidate variables	Symbol	Unit	Method	A	B
Biochemical oxygen demand	BOD	(mg/L)	Incubation	BOD	BOD
Chemical oxygen demand	COD	(mg O_2/L)	COD digester	COD	COD
Escherichia coli	*E. coli*	(n/100 ml)	Membrane filtration	FC	FC
Fecal coliform	FC	(n/100 ml)	Membrane filtration	TH	pH
Electrical conductivity	EC	(μmho/cm)	Conductivity meter	pH	PO_4
Total hardness	TH	(mg/l $CaCO_{3)}$	Complexometric titration	TA	NO_3
pH	pH	-	pH meter	PO_4	TDS
Total alkalinity	TA	(mg/l $CaCO_3$)	Acid–Base titration	NO_3	NTU
Phosphate	PO_4	(mg/L)	Spectrophotometric	NO_2	T
Total phosphate	TP	(mg/L)	Ascorbic acid method	TDS	DO%
Nitrate	NO_3	(mg/L)	UV spectrophotometric	NTU	-
Nitrite	NO_2	(mg/L)	UV spectrophotometric	T	-
Total ammonia nitrogen	TAN	(mg/L)	Kjeldahl method	DO%	-
Total Kjeldahl nitrogen	TKN	(mg/L)	Macro Kjeldahl method		-
Total nitrogen	TN	(mg/L)	Kjeldahl method	-	-
Total dissolved solid	TDS	(mg/L)	Gravimetric method	-	-
Total suspended solid	TSS	(mg/L)	Gravimetric method	-	-
Total solid	TS	(mg/L)	Gravimetric method	-	-
Turbidity	NTU	(mg/L)	Digital nephelometer	-	-
Water temperature	T	°C	Thermometer	-	-
Oxygen saturation	DO%	%	Oxygen meter	-	-
Dissolved oxygen	DO	(mg/L)	Oxygen meter	-	-

eclipsing and uncertainty problems and improve the final index. The rating curves reflect waters which are ideally suited (1), of reasonable quality (2), or of dubious quality for a particular use and require

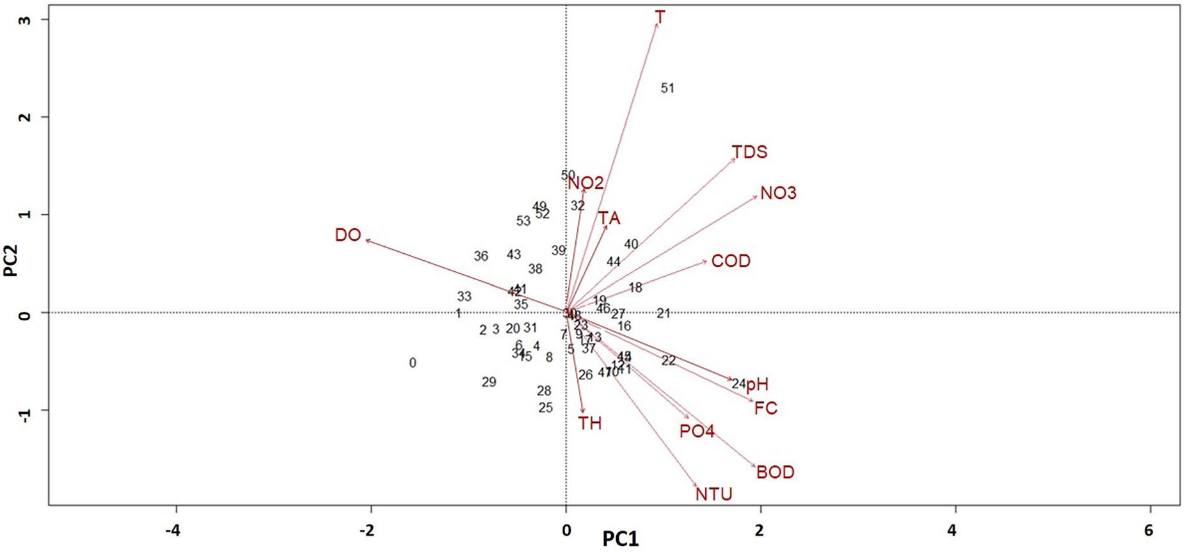


Fig. 3 Biplot of the PCA on sampling sites and 13 environmental variables left after removing nine correlated variables in the Karun River Basin. Abbreviations as in Table 1

Table 2 The interpretation and classification of the RIWQI scale (CCME, 2003; House, 1989; ISIRI, 2010; USEPA, 1986; WHO, 2004)

RIWQI class	RIWQI range	Interpretation
I	90–100	The best water quality and suitable for drinking water supply. Water quality is protected with a virtual absence of treat or impairment
II	70–89	The high water quality and good source for drinking water supply that is protected with only a minor degree of treatment or impairment. A good source for recreational uses which water contact needed. Game fisheries and high-quality industrial abstractions at low cost
III	50–69	Reasonable water quality and moderate treatment are needed for drinking water. Good coarse fisheries, indirect contact sports, and most industrial abstractions at moderate cost
IV	25–49	The polluted water quality and advanced treatment are needed for drinking water. Suitable for drainage uses. Fishery water for the propagation and growth of fish and other aquatic resources
V	0–24	The highly polluted water quality is almost always threatened or impaired. It is suitable for agriculture, irrigation, and livestock watering. Use generally restricted to non-contact recreational uses, sewage transport, and navigation

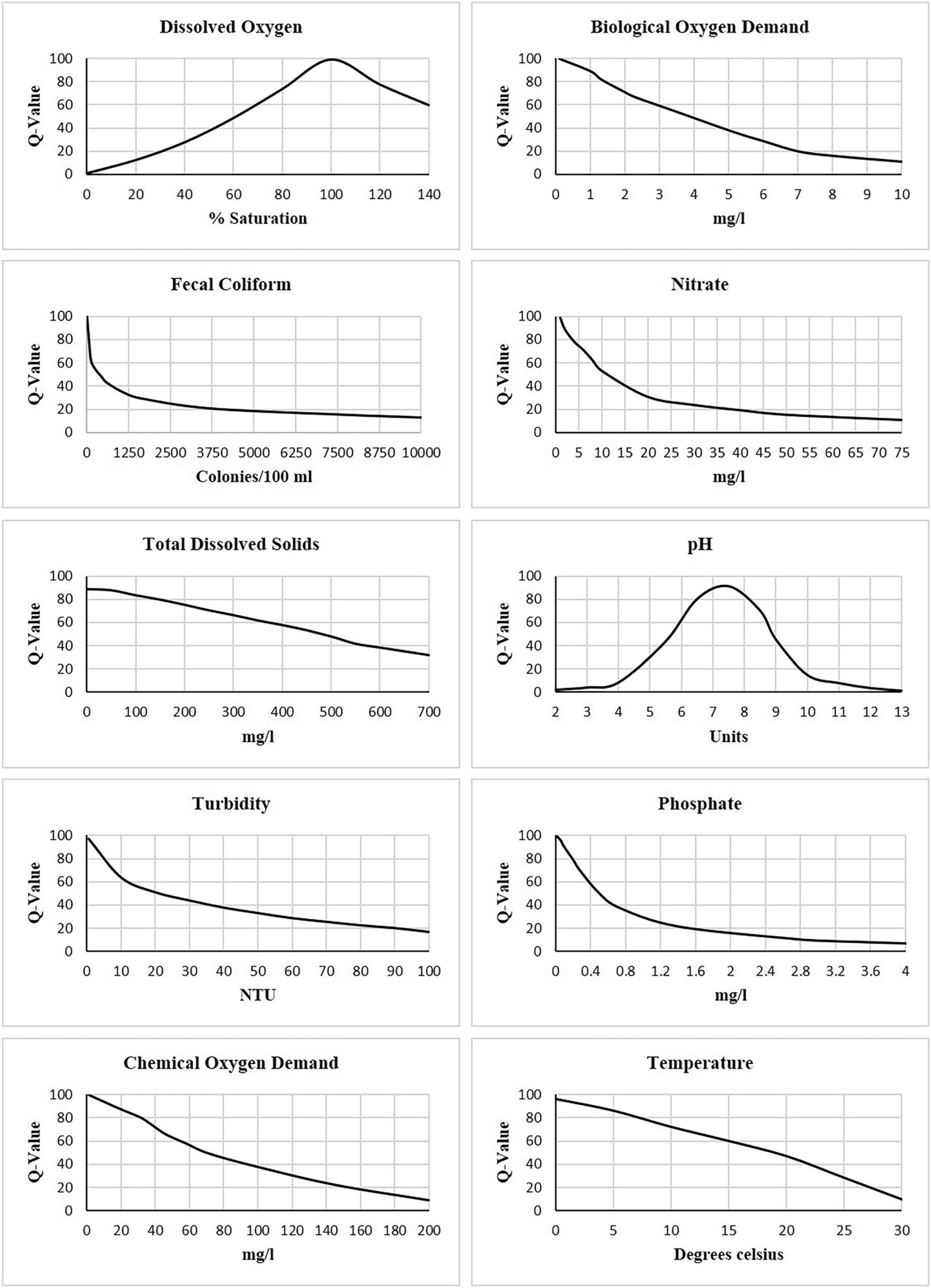
careful monitoring (3) (House, 1989). After developing sub-indices and fitting their exponential, linear, logarithmic, polynomial, or power relationships ($R^2 \geq 0.98$), new graphs (Fig. 4) were created. Sub-indices or Q-values were calculated using mathematical equations (Table 4) and the final curves and equation were drawn using Excel (version 2016).

Assignment of weights

Weighting of variables is necessary because variables have unequal importance for water quality (Almeida et al., 2012). The statistical methods (such as PCA and AHP) are appropriate techniques for weighting WQI parameters objectively. These approaches can reduce subjective assumptions and allow determination of the most appropriate weightings for given parameters that are reflective of their influence on overall water quality (Abbasi & Abbasi, 2012). Parameter weight values can strongly influence the final index value and WQI model robustness is enhanced by using an unequal parameter weighting system and assigning the most appropriate weighting values to parameters. This technique also reduces the eclipsing and uncertainty in the WQI model and helps improving model integrity (Uddin et al., 2021). PCA was run again for the ten selected variables and PCA axis 1 (PC1) was chosen, as it explained most of the variation (about 33%) in the data, i.e., dissimilarity between the sampling sites (Fig. 5).

Table 3 Threshold values of the variables to develop RIWQI according to the Iranian and world standards (CCME, 2003; ISIRI, 2010; USEPA, 1986; WHO, 2004)

Variables	Thresholds				
	Desirable (class I)	Minimum (class II)	Moderate (class III)	Maximum (class IV)	Undesirable (class V)
DO%	93–108	78–93 and 108–128	61–78 and 128–140	36–61 and > 140	0–36
NO_3	0–2.1	2.1–5.9	5.9–11	11–27.9	> 27.9
BOD	0–0.8	0.8–2.1	2.1–3.7	3.7–6.5	> 6.5
FC	0–25	25–85	85–375	375–2100	> 2100
pH	7.3–7.6	6.4–7.3 and 7.6–8.3	5.5–6.4 and 8.3–9	4.6–5.5 and 9–9.7	> 2–4.6 and 9.7– > 13
TDS	0–10	10–255	255–490	490–700	> 700
COD	0–15	15–42	42–75	75–130	> 130
NTU	0–2	2–8.5	8.5–19	19–72	> 72
PO_4	0–0.1	0.1–0.28	0.28–0.51	0.51–1.13	> 1.13
T	0–3	3–11	11–18	18–26	> 26


Dissolved Oxygen
Q-Value
100
80
60
40
20
0
0 20 40 60 80 100 120 140
% Saturation
Biological Oxygen Demand
Q-Value
100
80
60
40
20
0
0 1 2 3 4 5 6 7 8 9 10
mg/l
Fecal Coliform
Q-Value
100
80
60
40
20
0
0 1250 2500 3750 5000 6250 7500 8750 10000
Colonies/100 ml
Nitrate
Q-Value
100
80
60
40
20
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75
mg/l
Total Dissolved Solids
Q-Value
100
80
60
40
20
0
0 100 200 300 400 500 600 700
mg/l
pH
Q-Value
100
80
60
40
20
0
2 3 4 5 6 7 8 9 10 11 12 13
Units
Turbidity
Q-Value
100
80
60
40
20
0
0 10 20 30 40 50 60 70 80 90 100
NTU
Phosphate
Q-Value
100
80
60
40
20
0
0 0.4 0.8 1.2 1.6 2 2.4 2.8 3.2 3.6 4
mg/l
Chemical Oxygen Demand
Q-Value
100
80
60
40
20
0
0 20 40 60 80 100 120 140 160 180 200
mg/l
Temperature
Q-Value
100
80
60
40
20
0
0 5 10 15 20 25 30
Degrees celsius

◂**Fig. 4** The Q-value rating curves for ten variables used in RIWQI

The variables were sorted based on the rank of their eigenvalues on PC1. Eigenvalues of the variables on PC1 ranged from 0.58 (water temperature) to 1.31 (dissolved oxygen concentration). We scaled the eigenvalues from 1 to 4 that the scores "1" and "4" were assigned to lowest and highest eigenvectors of PCA axis 1, respectively (Mahajan et al., 1976) and weighed them based on a regression model (Eq. 1: x = eigenvalues) and calculated the relative weights (RW) of variables (Eq. 2: RW = relative weight, AW = assigned weight). The eigenvalues, assigned

Table 4 Equations formulated for the sub-index of each variable

Variables	Range	Sub-index function	R square
DO%	$X \leq 100$	$Y = 0.0049x^2 + 0.5044x + 0.5929$	$R^2 = 0.9995$
	$100 < X \leq 140$	$Y = 0.0048x^2 - 2.1353x + 264.37$	$R^2 = 1$
	$X > 140$	$Y = 50$	
BOD	$X < 0.2$	$Y = 100$	
	$0.2 \leq X \leq 10$	$Y = 0.7859x^2 - 17.108x + 103.11$	$R^2 = 0.9985$
	$X > 10$	$Y = 5$	
Fecal coliform	$X < 2$	$Y = 100$	
	$2 \leq X \leq 250$	$Y = 0.001x^2 - 0.4354x + 100.13$	$R^2 = 0.9963$
	$250 < X \leq 10000$	$Y = 528.2x^{-0.398}$	$R^2 = 0.9924$
	$X > 10000$	$Y = 10$	
NO_3	$X \leq 1$	$Y = 100$	
	$1 < X \leq 10$	$Y = 103.7e^{-0.066x}$	$R^2 = 0.9931$
	$10 < X \leq 75$	$Y = 330.72x^{-0.788}$	$R^2 = 0.9960$
	$X > 75$	$Y = 5$	
pH	$X < 2$	$Y = 0$	
	$2 \leq X \leq 4$	$Y = 1.13x^2 - 3.66x + 5.04$	$R^2 = 1$
	$4 < X \leq 7.5$	$Y = -1.7479x^2 + 44.845x - 144.25$	$R^2 = 0.9789$
	$7.5 < X < 10$	$Y = -3.1167x^2 + 23.279x + 92.915$	$R^2 = 0.9865$
	$10 \leq X \leq 13$	$Y = 1.1575x^2 - 31.088x + 210.06$	$R^2 = 0.9999$
	$X > 13$	$Y = 0$	
TDS	$X < 0$	$Y = 100$	
	$0 \leq X \leq 700$	$Y = -1E-05x^2 - 0.0792x + 90.841$	$R^2 = 0.9967$
	$X > 700$	$Y = 20$	
Turbidity	$X < 0$	$Y = 100$	
	$0 \leq X < 30$	$Y = 0.0699x^2 - 3.8644x + 98.007$	$R^2 = 0.9914$
	$30 \leq X \leq 100$	$Y = -22.03\ln(x) + 119.3$	$R^2 = 0.9989$
	$X > 100$	$Y = 5$	
COD	$X < 3$	$Y = 100$	
	$3 \leq X \leq 200$	$Y = 0.0019x^2 - 0.8415x + 102.38$	$R^2 = 0.9962$
	$X > 200$	$Y = 5$	
PO_4	$X < 0.02$	$Y = 100$	
	$0.02 \leq X \leq 0.73$	$Y = 57.799x^2 - 131.9x + 102.52$	$R^2 = 0.9985$
	$0.73 < X \leq 4$	$Y = 28.357x^{-1.011}$	$R^2 = 0.9962$
	$X > 4$	$Y = 5$	
TEM	$X < 0$	$Y = 100$	
	$0 \leq X \leq 30$	$Y = -0.0325x^2 - 1.8851x + 96.236$	$R^2 = 0.9989$
	$X > 30$	$Y = 0$	

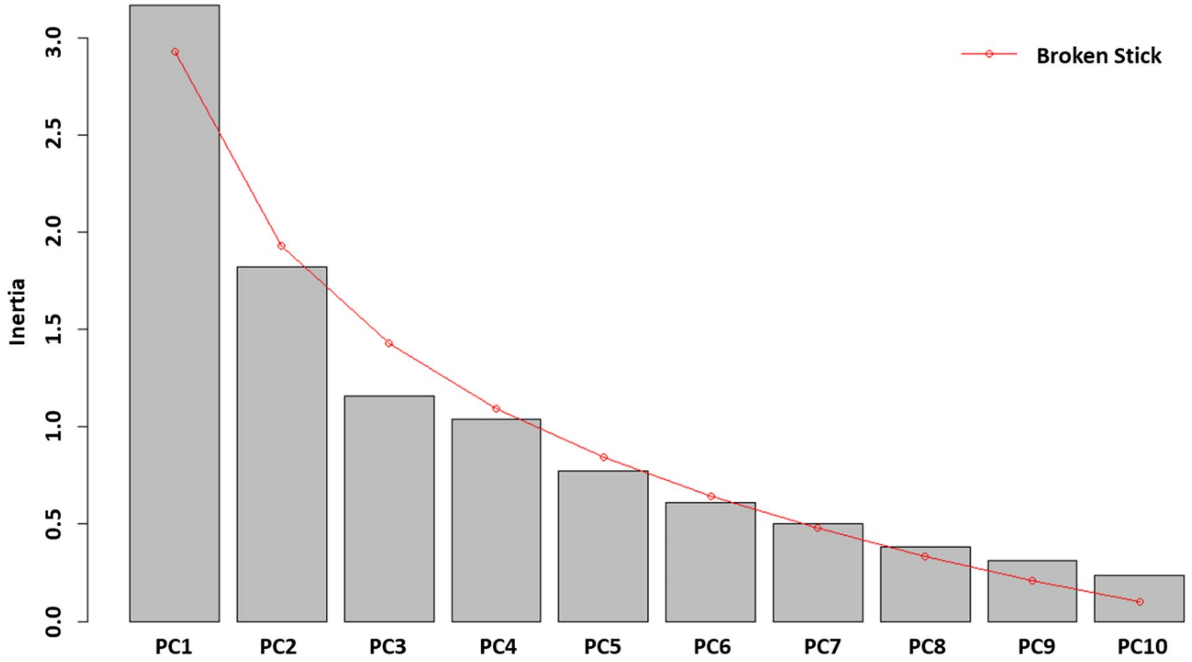


Fig. 5 Scree plot of the principal components of the PCA of physico-chemical measurements in the Karun River Basin

weight (AW), and relative weight (RW) that we determined are shown in Table 5.

$$\text{Assignedweight} = 4.0661x - 1.3409 \quad (1)$$

$$RW = {}^{AW} / _{\sum AW} \quad (2)$$

Overall index calculation

The functions needed to aggregate the sub-indices were drawn from valid global WQIs. We used some additive formulas (e.g., Horton index, Scottish Research Development Department (SRDD) index, NSFWQI (earlier version), House index, and Malaysian index), multiplicative formulas (e.g., the NSFWQI (second version), Dinius index, West Java index, and Almeida index), and combination formulas (e.g., Oregon index and Dojlido index) (Horton, 1965; Brown et al., 1970, 1973; Dinius, 1987; House, 1989; Dojlido et al., 1994; Cude, 2001; Shuhaimi-Othman et al., 2007; Almeida et al., 2012; Sutadian et al., 2016, 2018; Uddin et al., 2021) to calculate final RIWQI. We evaluated the performance of 11 different formulas based on their ability to detect changes in water quality among the sites and seasons. Among the additive models, the mathematic equation of NSFWQI (earlier version); among the multiplicative models, the mathematic equation of NSFWQI (second version); and among the combination models, the mathematic equation of Oregon index showed the best results. These three formulas were reported in Table 6 as a reprehensive of three different types of

Table 5 Eigenvalue, assigned weight (AW), and relative weight (RW) of the selected variables

Variables	Eigen value	AW	RW
DO%	1.3135	4	0.145
NO_3	1.2024	3.55	0.128
BOD	1.1918	3.51	0.127
FC	1.1800	3.46	0.125
pH	1.1104	3.17	0.115
TDS	1.0641	2.99	0.108
COD	0.8661	2.18	0.079
NTU	0.8213	1.99	0.072
PO_4	0.7696	1.79	0.065
T	0.5757	1	0.036

mathematical models. We selected the best formulae based on our results from DE (Table 6) and those in similar studies (Gupta et al., 2007; Sutadian et al., 2016; Uddin et al., 2021).

Testing of RIWQI performance using discrimination efficiency (DE)

We classified the sites as low, moderate, and high water quality sites by defining a disturbance gradient using PCA and selecting the high water quality sites from that gradient (Blocksom & Johnson, 2009; Zare Shahraki et al., 2021). Then, we measured DE as the percent of the sites that were inferred to be in low and moderate water quality based on our index. We defined low and moderate water quality values as index values that fell below the 25th percentile of the sites with high water quality values (Hawkins et al., 2010; Jones et al., 2016). We calculated DE to determine which formulas and indices differed significantly in sensitivity from one another, using Eq. 3:

$$DE = \frac{a}{b} \times 100 \tag{3}$$

where a represents the number of degraded sites scoring below the 25th percentile of metrics in the least disturbed sites, and b, the total number of degraded sites determined by PCA. A higher DE represents a better or more efficient index in distinguishing between degraded and non-degraded sites (Bressler et al., 2006).

Results

Our results showed that a multiplicative formula first presented by Brown et al. (1973) was found to produce the best results in the study area with four-season mean DE > 85.6% (Table 6) and used in the calculation of the RIWQI (Eq. 4).

$$OIWQI_m = \prod_{i=1}^{n} Q_i W_i \tag{4}$$

where Q_i is the sub-index of variable i and W_i is the relative weight for variable i ($\Sigma W_i = 1$). Therefore, each analytic value is converted to a non-dimensional value or quality level (Q_i) by a mathematical equation (Table 4) or via its corresponding graphical representation (Fig. 4). The RIWQI is computed by the multiplication of the products of relative weights and sub-index values (Q_i^{Wi}).

In our study, RIWQI using an additive formula classified most of the sites in all seasons as good, whereas using a combination formula classified all the sites in all seasons as medium. The multiplicative formula showed some differences between the sites and seasons, and classified them in different (medium and good) classes (Table 6). On the other hand, DE showed that additive and combination formulas have poorer performance to detect disturbance compared to multiplicative formula (Table 6). Arithmetic or additive formulae, although easy to understand and calculate, lacked sensitivity in terms of the effect a single bad parameter value on the WQI (Brown et al., 1973). Moreover, WQIs based on multiplicative formulae seem to agree with experts' opinion better than those based on additive ones (Gupta et al., 2007; Lumb et al., 2011). Although additive and multiplicative functions have been most popular, computer-based techniques like fuzzy interface systems and artificial neural networks have been used recently to further reduce uncertainty resulting from the final aggregation process (Uddin et al., 2021).

The water classification table (Table 7) was defined according to the average of water classification in previous studies (Brown et al., 1970; Tyson & House, 1989;

Table 6 Result of evaluation of water quality (WQ) and discrimination efficiency (DE) in the Karun River Basin based on RIWQI calculated by different formulas. Good (G) and medium (M) are narrative categories of the acceptability of WQ conditions

	Additive		**Multiplicative**		**Combination**	
	WQ	**DE**	**WQ**	**DE**	**WQ**	**DE**
Autumn	G (71.7)	82.5	M (68.7)	85	M (58.8)	82.5
Winter	G (74.8)	80	G (72.1)	82.5	M (63.7)	77.5
Spring	G (69.3)	87.5	M (65.6)	92.5	M (54.2)	82.5
Summer	G (70.2)	80	M (67.1)	82.5	M (56.5)	70
Mean		**82.5**		**85.6**		**78.1**

Table 7 Scaled narrative categories of the RIWQI scoring system

WQ class	RIWQI value
Excellent	90–100
Good	70–89
Medium	50–69
Poor	25–49
Very poor	0–24

Paulic et al., 1996; SAFE, 1996; Cude, 2001; Sarkar & Abbasi, 2006; Hulya Boyacioglu, 2007; Babaei Semiromi et al., 2011). The RIWQI is a number between 0 and 100, where values close to 0 and 100 represent worst and best water quality, respectively (Table 7).

The RIWQI, other indices such as NSFWQI (Brown et al., 1970), OWQI (Cude, 2001), FWQI (SAFE, 1996), CPCBWQI (Sarkar & Abbasi, 2006), and IWQI (Babaei Semiromi et al., 2011) were applied and compared to assess the water quality status at the Karun River Basin (our dataset) (Table 8). In addition, the ability of all indices to detect disturbance and pollution was compared based on DE (Table 8).

We also checked and compared the changes of 22 water quality parameters measured in the Karun River Basin among different seasons (Table 9). The result showed that most of them were significantly different among seasons ($p < 0.01$) which it caused to change the water quality at some sites.

Discussion

The variables used to develop the RIWQI

We used ten variables to develop the RIWQI that includes a combination of physical, chemical, and microbiological parameters which have been shown to efficiently discriminate sites of contrasting water quality in our study.

(a) Physical parameters

Temperature and turbidity represent physical characteristics of the habitat. Temperature is a critical parameter for ecological health as it governs the kinds and types of aquatic life, regulates the maximum dissolved oxygen of the water, and affects physical, chemical, and biological processes in water bodies (Chapman et al., 1996; Rai et al., 2012). Turbidity is caused by suspended particles of clay, silt, other small inorganic and organic particles, dissolved colored organic compounds, and microscopic organisms (Swenson & Baldwin, 1965). It is an important parameter for drinking water and aquatic life. Excessive turbidity in drinking water presents a health concern. Turbidity can provide food and shelter for pathogens in the water, leading to waterborne disease outbreaks, which have caused significant cases of intestinal sickness throughout the world (EPA, 2020; Peterson & Gunderson, 2008). Additionally, high turbidity is often used to indicate the influence of wastewater discharge (Sutadian et al., 2018). Another physical parameter included in the RIWQI is total dissolved solids (TDS) that represents the total concentration of dissolved substances in water (CCME, 2003). TDS concentration is affected by industrial effluent, changes to the water balance (by limiting inflow, by increased water use or increased precipitation), or salt-water intrusion. Total dissolved solids lead to toxicity via increases in salinity, changes in the ionic combination of the water, and toxicity of single ions (Weber-Scannell & Duffy, 2007). TDS can be applied to establish potential water usage or to assess the quality of supplied water; it affects

Table 8 Evaluation of water quality (WQ) and discrimination efficiency (DE) in the Karun River Basin based on mean values of the different WQI across all sites. Good (G), medium (M), and poor (P) are narrative categories of the acceptability of WQ conditions

Seasons	NSF WQI	DE	OWQI	DE	FWQI	DE	CPCB WQI	DE	IWQI	DE	RIWQI	DE
Autumn	M (64.2)	70	P (76.8)	45	M (47.1)	82.5	G (78.7)	62.5	G (40)	67.5	M (68.7)	85
Winter	M (69.3)	65	M (84.9)	60	G (44.3)	55	G (82.8)	60	G (34.6)	70	G (72.1)	82.5
Spring	M (67.4)	80	P (73.6)	72.5	M (53.9)	65	G (79.2)	72.5	G (37.9)	57.5	M (65.6)	92.5
Summer	M (65.9)	85	P (73.4)	72.5	M (52.8)	40	G (77.6)	67.5	G (36.6)	35	M (67.1)	82.5
Mean		**75**		**62.5**		**60.6**		**65.6**		**57.5**		**85.6**

Table 9 Mean and standard deviation of water quality parameters across 54 sampling sites during four seasons in the Karun River Basin

Variable	Season			
	Autumn	Winter	Spring	Summer
BOD	2 ± 1.2	1.9 ± 0.7	3.7 ± 1.6	3.6 ± 0.8
COD	17.7 ± 15.9	24.4 ± 19	39.8 ± 13.5	24.1 ± 12.2
E. coli	123.9 ± 304	111 ± 189.2	68 ± 94.7	93.4 ± 285.5
FC	198.9 ± 576.6	127.2 ± 208.8	84.6 ± 107.3	141.3 ± 294
EC	500.9 ± 279.6	472.2 ± 297.2	390.5 ± 317.9	470.5 ± 279.3
TH	192.1 ± 61.7	181.5 ± 49.4	167.6 ± 78.9	187 ± 52.2
NO_3	7.9 ± 2.7	9.1 ± 3.3	7.3 ± 2.6	6.5 ± 2.3
NO_2	0.07 ± 0.07	0.07 ± 0.06	0.07 ± 0.07	0.1 ± 0.13
pH	8.1 ± 2.8	7.7 ± 0.2	7.7 ± 0.2	7.9 ± 0.3
PO_4	0.32 ± 0.34	0.15 ± 0.16	0.22 ± 0.12	0.22 ± 0.13
TP	1.4 ± 0.98	0.48 ± 0.43	1.2 ± 0.77	1.8 ± 0.88
TA	193.5 ± 33.1	213 ± 23.6	162.1 ± 28.8	155.3 ± 34.7
TAN	0.05 ± 0.06	0.9 ± 1.9	0.02 ± 0.02	0.05 ± 0.08
TKN	0.12 ± 0.13	1.9 ± 2.5	0.08 ± 0.06	0.14 ± 0.13
TN	8.1 ± 2.8	11.1 ± 4.6	7.5 ± 2.6	6.8 ± 2.4
TDS	368.7 ± 291.9	354.2 ± 228.5	408.3 ± 177.5	359.2 ± 226.4
TSS	149.9 ± 70.7	158.9 ± 83.8	225.3 ± 150.1	186.3 ± 147.5
TS	518.6 ± 293.2	513.2 ± 251.3	633.7 ± 204.3	545.5 ± 306.4
NTU	36.7 ± 12.6	38.3 ± 14.9	51.4 ± 26.4	43.2 ± 26.2
T	12.1 ± 2.5	9.7 ± 2.7	14.8 ± 3.5	18.7 ± 4.1
DO%	96.4 ± 11.2	102.9 ± 3.3	95.9 ± 6.2	99.4 ± 7.2
DO	8.7 ± 1	9.9 ± 0.4	8.2 ± 0.7	8.5 ± 0.9

everything that consumes, lives in, or uses water. High levels of TDS can be a sign of other detrimental pollutants; it is easily measured and can act as an early alarm signal for pollution (Ewaid et al., 2020).

(b) Chemical parameters

The level of pH is an important indicator of water that is altered chemically and pH can control the availability of nutrients, biological functions, microbial activity, and the behavior of chemicals. Furthermore, low levels of pH may indicate the presence of other detrimental pollutants in the water. Also, pH is easily measured and may therefore act as an early alarm signal for pollution (Ewaid et al., 2020).

Chemical oxygen demand (COD), biological oxygen demand (BOD), and dissolved oxygen saturation (%DO) are indicative of oxygen depletion. BOD represents the content of oxygen consumed by bacteria and other microorganisms while they decompose organic matter under aerobic conditions, thus providing an estimate of the intensity of organic pollution. Factors such as discharge, water velocity, temperature, substrate, and also the concentration of wastewater can affect BOD (Susilowati et al., 2018). COD also provides an indication discharged wastewater. Higher COD levels indicate a greater amount of oxidizable organic matter, which can reduce dissolved oxygen levels and it acts precise to describe water health and quality with organic content. Therefore, it is important to measure both BOD and COD for water quality assessment (Heng et al., 2015). DO is an important indicator of river water quality (Sutadian et al., 2018), as pollution from industrial development, fertilizer use, and human waste can lead to oxygen limitation. Low DO can lead to anaerobic conditions, which is deleterious to higher forms of aquatic life (Kannel et al., 2007).

Nitrate (NO_3) and phosphate (PO_4^-) were selected in our study as representative of the nutrients group. Organic and synthetic fertilizers in agricultural systems are the main sources of NO_3 in surface waters and can lead to eutrophication (Dragon et al., 2016; Harter et al., 2002). Nitrate in drinking water can lead to significant harm to human health, including cancer, methemoglobinemia, enlargement of the thyroid gland, and diabetes mellitus (Parvizishad et al., 2017; WHO, 2011). Phosphate also contributes to eutrophication, entering waterways from phosphorus-rich bedrock, human and animal waste, urban and industrial effluents, and fertilizer runoff. Increased PO_4^- supply may initially enhance biomass and diversity of biotic communities ("subsidy effects"), while longer-term exposure may act as a stressor by stimulating algal growth and potentially oxygen depletion through eutrophication (Stockner et al., 2000).

(c) Microbiological parameter

Fecal coliform (FC) was selected to represent microbial pollution, as coliform bacteria can cause serious illnesses, such as gastroenteritis and diarrhea, and compromise the safety of water for recreation or drinking (Seo et al., 2019). As FC are bacteria that originate in the intestinal gut of warm-blooded animals, high values of FC in a waterbody indicate the presence of fecal material and thus of elevated risk of pathogenic contamination from untreated sewage or damaged septic tanks. Understanding the origin of fecal contamination is paramount in assessing associated health risks as well as identifying the actions necessary to remedy the problem (Scott et al., 2002). As a result, numerous methods have been developed to identify fecal contamination as well as differentiate between these sources of pollution. Accurately identifying these sources can help to facilitate the elimination of waterborne microbial disease as a leading threat to public health (Simpson et al., 2002).

Comparing the performance of the RIWQI with existing WQIs

The purpose of this comparison was to evaluate the accuracy, validity, and sensitivity of the RIWQI to detect disturbance compared to IWQI and other WQIs. We also examined the similarity of classifications obtained with RIWQI and that of other indices. The results suggest better performance of RIWQI to detect disturbance compared to that of other WQIs (Table 8). Furthermore, application of RIWQI to the dataset of the Karun River Basin showed that its results are more similar to those of indices such as NSFWQI, OWQI, and FWQI, which all consider more variables than CPCB WQI and IWQI.

Our variable selection approach identified several additional and potentially important variables compared to those used for calculating IWQI. These include COD, BOD, phosphorus, and temperature. COD and BOD are important variables to describe the degree of organic pollution (Ewaid et al., 2020), where COD describes the total (inorganic plus organic) oxygen demand and BOD the biological oxygen demand, i.e., the amount of oxygen required to degrade organic matter by microorganisms (Sawyer et al., 1988). Phosphorus is a key element necessary for plant growth. However, too much PO_4^- in water can promote excessive growth of algae and weeds, thus reducing dissolved oxygen levels and potentially causing harm to aquatic life (Tang et al., 2020). Water temperature is an important variable for biochemical reactions and health of aquatic life. Consequently, it is considered in other WQI such as Horton WQI, NSFWQI, FAWLWQI, OWQI, House WQI, and River Pollution Index. The IWQI does not consider these variables (Babaei Semiromi et al., 2011).

Moreover, the calculation of the IWQI is based on an additive formula and thus lacks sensitivity to the effect of single potentially detrimental parameters (Lumb et al., 2011). Therefore, the IWQI might not be sensitive enough to adequately assess water quality. These limitations are also relevant for the CPCB WQI, which is based on four variables only (DO, pH, BOD, and FC) and calculated with an additive formula. In the RIWQI, the mentioned variables (COD, BOD, PO_4^-, and temperature) were considered and a multiplicative formula was used. This formula avoids problems of ambiguity and eclipsing related to the number of water quality variables needed to be aggregated in a certain index. If a sub-index value is zero, RIWQI will become zero automatically (Tirkey et al., 2015). In addition, weight factor of variable allows obtaining large changes in the final index with little variations for each one of different variables. Since, this formula is sensitive to small changes of individual variables (Table 8), thus enhancing its overall sensitivity and efficacy for freshwater ecosystem management (Tirkey et al., 2015). Moreover, the results of multiplicative formulation are closer to many experts' opinion (Gupta et al., 2007; Lumb et al., 2011). Our result showed that the ability of multiplicative formulae to detect changes in water quality was acceptable (Table 8).

Applying the RIWQI to the Karun River case study

The Karun River Basin is made up of many different subwatersheds that respond to human-induced impacts to which they are exposed. Our results showed that water quality was different among sampling sites and seasons. In this study, results produced within sampling sites highlighted the advantages of using RIWQI for water quality management. Mean values of the RIWQI across all sites in the Karun River Basin resulted in classifications of the study sites as medium class for autumn, spring, and summer, and good class for winter (Table 8). Water quality was evaluated as being better in winter, mainly due to a decrease in BOD, phosphorus concentrations, and temperature (Table 9). Lower BOD and phosphorus values in winter can result from seasonal reduction of agricultural and livestock activities in the Karun River Basin. Similarly, Fathi et al. (2016) reported a reduction of BOD and phosphorus levels due to decline in agricultural and livestock activities in winter. Moreover, the expansion of agricultural and livestock land use is a major threat to water quality and can cause to increase BOD and phosphorus (Shuhaimi-Othman et al., 2007).

Water quality variables of the Karun River Basin compared to standard levels

Study of water quality variables across 54 sampling sites during four seasons in the Karun River Basin (Table 8) showed that the average of turbidity across all sites was above threshold in all seasons and did not match with levels recommended by world and Iran standards for drinking water (CCME, 2003; Gray, 2008; ISIRI, 2010; WHO, 2004). Sand extraction from the riverbed, agricultural runoff, floods, and precipitation all contribute to high turbidity in the Karun River Basin. Consequently, turbidity was highest in spring in many sites because of strong precipitations and floods. The averages of pH and TDS across all sites during four seasons were in the range of world and Iran standards for drinking water (CCME, 2003; Gray, 2008; ISIRI, 2010; WHO, 2004). If the TDS passes 1000 mg/l, water becomes less usable and it is no longer potable for human consumption and above 3000 mg/l, it is not suitable for most municipal or agricultural usages (Al-shujairi, 2013). The average of BOD across all sites during four seasons was less than world standard range for drinking water, and since non-polluted waters are likely to have a BOD value less than 3 mg/l (Fathi et al., 2016), the range of BOD was in acceptable range (WHO, 2004). The averages of DO and DO saturation across all sites during four seasons were high and in acceptable range of standards (CCME, 2003; Gray, 2008; Lumb et al., 2002; WHO, 2004) and it was suitable for human consumption (swimming, bathing, and drinking) and many aquatic organisms (Fathi et al., 2016; Hammer, 1976; Wilcock et al., 1995). The average of COD across all sites during four seasons was higher than the acceptable range of COD for drinking water that is 10 mg/l (WHO, 2004). Chemical discharges caused from industry as well as pesticides and fertilizers used in agriculture can contribute to the high levels of COD in the Karun River Basin. The average of nitrate across all sites during four seasons was in the reported range by world and Iran standards for drinking water (CCME, 2003; Gray, 2008; ISIRI, 2010; Lumb et al., 2002; WHO, 2004). The possible sources of nitrate in surface water are mainly from atmospheric depositions, surface runoff, sewage discharges, agricultural fertilizers, and organic wastes (WHO, 2004). The European Union, World Health Organization, and Iran standard have determined the maximum permissible concentration of nitrates in drinking water at 50 mg NO_3/l (11.3 mg N–NO_3/l) (Gray, 2008; WHO, 2004). The average of phosphate across all sites during four seasons was not in the reported range by world standards for drinking water (USEPA, 2002; WHO, 2004) and many sampled rivers have exceeded recommended water quality criteria for phosphate. It should be noted that the effects of phosphate vary by region and depend on physical factors such as the size, hydrology, and depth of rivers. Also, nuisance algal growth in rivers is another reason to change phosphate concentration (Dodds & Welch, 2000). Finally, the average of fecal coliform across all sites during four seasons was higher than standards for drinking water (CCME, 2003; Gray, 2008; ISIRI, 2010; WHO, 2004). The World Health Organization has reported that total coliform for drinking water should be zero (0). Discharge of waste water and livestock around the Karun River can increase the level of fecal coliform. Therefore, treatment is urgently needed for drinking water in many rivers of the Karun River Basin.

Conclusion

Water quality indices serve to reduce complex and diverse data into more simple and understandable expressions of monitoring data, and if properly revised and calibrated for specific uses, they will be valuable tools for assessing and managing water quality. To protect and preserve freshwater ecosystems and their services in the Karun Basin, long-term monitoring and assessment strategies need to be designed. The proposed RIWQI and its composites provide useful and comparable information to guide management actions. The performance assessment of the RIWQI suggests good formulation of the physical, biological, and chemical parameters. This index can thus address and improve some of the limitations of the currently used index in Iran (IWQI), which lacked parameters of the local conditions and some important water quality variables, including PO_4^-, BOD, COD, and temperature. We used a set of statistical and weighting procedures to identify the most important variables and establish rating curves and a classification table. The RIWQI was developed using four basic steps: (1) the selection of variables based on a statistical assessment (PCA) for parameter redundancy; (2) developing rating curves and classification table using researcher's opinions taken from other indices and standards; (3) establishing parameter weights based on statistical analysis (eigenvalue in PCA); and (4) aggregation of sub-indices to produce the final index using the weighted geometric method. The RIWQI was tested and compared with other indices used worldwide. Our result showed that the RIWQI is more compatible with other indices than the IWQI. Therefore, the RIWQI can have better accuracy and performance in the analysis, as shown in its application to the rivers in the Karun system. We applied the RIWQI to the Karun River Basin as the largest freshwater resource in the south west of Iran to demonstrate its effectiveness and applicability as a decision-making tool for river water quality evaluation and zoning. It seems that RIWQI can serve the relevant authorities in Iran and elsewhere for evaluating more accurately the general status of river water quality. The RIWQI can be used for the following: (1) to characterize river water quality status and trends in a straightforward manner, (2) to highlight the rivers which have shown a change in water quality, (3) to reflect both clean and polluted conditions and indicating of spatial variations in water quality, (4) to indicate possible water use in terms of world standards of water quality.

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Declarations

Conflict of interest Not applicable.

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