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Comparison of surface water quality to land use: a case study from Tripura, India

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ABSTRACT

Land use pattern of a location is a key factor to determine the quality of water in that area. A case study was performed to understand the influence of land use on the quality of surface water. Water quality indices of surface water from different locations within study area were compared with the land use pattern of that location. Multi-criteria decision-making methods, like weighted sum method, weighted product method and grey relational analysis, were used to determine the priority values (PV) of the different water quality parameters on the basis of important criteria like hazard potential, cost of mitigation, utilization potential and popularity among the researchers. Water quality indices of the samples were calculated from those PV by weighted average method. The indices were then compared with respective land use pattern to assess the relation between land use pattern and water quality. The results suggest that dense settlement, moderate to low vegetation and dense cultivation is good for surface water, whereas low settlement, dense vegetation and moderate cultivation is bad for surface water. These findings may be useful for managers and policy makers to manage land use for maintaining the optimum quality of surface water.

Keywords: Water quality index; Multi-criteria decision-making; Weighted sum method; Weighted product method; Grey relational analysis; Tripura; India

1. Introduction

As land use stress has a direct impact on surface water quality [1], land use management is crucial for the maintenance of fair quality of surface water. Surface water is readily available and plays a key role in settlement sustenance [2] due to its impact on human health and economy [3]. However, surface water quality is affected more easily than groundwater by external factors [4] for being open to the environment [5]. Assessment of the impact of land use patterns on water quality is, therefore, useful for the managers and decision-makers for the optimum planning of land use in a location.

Water quality index (WQI) is a concise numerical representation of overall quality of water, which is easy to express and convenient to interpret [6,7]. WQI is essentially a function of the concentrations of the water quality parameters (WQP).

WQI is a function of parameters and their concentration is as follows:

$$\text{WQI} = f(C) \tag{1}$$

where C is the concentration of WQP and $C \in \Re \wedge C > 0$, $\Re$ being the set of real numbers.

A WQI can be subjective, that is, developed to use in a specific scenario (e.g., WQI for shrimp culture) or objective, that is, developed for general use (e.g., National Sanitation Foundation WQI [NSF WQI]). Several WQI were developed and still being developed to fulfil different purposes.

As different WQP have different degree of influence on overall water quality, the priority values (PV; i.e., importance with respect to the overall quality of water) of the WQP are required for calculating the WQI. In initial [8–10] and some later works [11,12] on WQI, the PV of WQP was determined from subjective opinions of the experts [13]. The criteria, on which the relative importance of the parameters was determined, were not mentioned explicitly in the expert survey.

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In more recent works, WQI became more general and objective in nature (e.g., British Columbia Water Quality Index [BCWQI], (Canadian Council of Ministers of the Environment) Water Quality Index [CWQI], Weighted Average Water Quality Index [WAWQI]) [14,15]. These WQI were calculated by quantifying the failure of the parameters to meet the target values, rather than weighted individual importance. Selection of parameters and target values, however, depends upon the purposes and considerations of the users. Therefore, these indices can still be subjective and biased [16].

Multi-criteria decision-making (MCDM) methods were developed for selecting the best among available alternatives, considering multiple criteria together. Weights can be assigned in MCDM to the available alternatives on the basis of some selected criteria. Several MCDM methods (e.g., analytic hierarchy process [AHP], fuzzy logic decision-making [FLDM], grey relational analysis [GRA], etc.) have been developed for use in different scenario. As for WQI, weights (relative influence on overall water quality) are required to be assigned to multiple WQP on the basis of their importance, MCDM can be used for this purpose.

The use of MCDM methods like weighted sum method (WSM) [17], GRA [18], FLDM [19], AHP [20] and their combinations [21,22] were found to be successful in determination of PV of WQP for achieving different decision-making goals in an objective and non-preferential manner.

In weight-based WQI, there are two primary concerns – to assign weights to the selected WQP according to their relative importance, and to assign weights to the concentrations of those WQP. In this study, such weights were assigned on the basis of important criteria, like hazard potential, cost of mitigation, utilization scope and popularity among the researchers of the WQP, to make it free from subjective judgements [23]. WSM, weighted product method (WPM), GRA and their combination were used in this study to determine the PV of the WQP to overcome the limitations of the individual methods and include their advantages as well [24].

WSM is a widely used MCDM method with minimum calculation process. In WSM, the importance of the criteria is assigned first, followed by assigning relative importance of all the alternatives with respect to each of the criteria. Finally, the weighted sums of the relative importance of the alternatives are taken as their final weights (Eq. (2)) [25]. However, WSM requires all the input data in same unit [26].

The WSM is as follows:

$$\mathrm{WSM} = \sum_{j=1}^{n} \mathrm{W}_j \mathrm{A}_{ij} \tag{2}$$

where W_j is the relative weight of importance of jth criteria; A_{ij} is the relative weight of importance of ith alternative with respect to jth criteria and n is the total number of criteria considered.

WPM is essentially a similar procedure but only weighted products of importance of the alternatives are considered (Eq. (3)) [27,28]. WPM involves more calculations than WSM, but it can handle dissimilar data [26] and can be used for indexing purpose [29]. However, WPM has a tendency to overrate the extreme values [30].

The WPM is as follows:

$$\mathrm{WPM} = \prod_{j=1}^{n} (\mathrm{A}_{ij})^{\mathrm{W}_j} \tag{3}$$

where W_j is the relative weight of importance of jth criteria; A_{ij} is the relative weight of importance of ith alternative with respect to jth criteria and n is the total number of criteria considered.

GRA can be applied where precise data is not available or data are qualitative or uncertain [31]. However, GRA is a more complex and involves much more calculations than WSM or WPM.

There are numerous works on the effect of land use, but modelling a WQI using land use as a predictor are limited [32], though it can be a useful tool in planning and management of land use.

A case study was, therefore, performed to assess the impact of different land use patterns on the overall quality of surface water by comparing WQI of samples with their respective land use.

2. Methodology

There were two primary steps for this study: (i) development of the WQI and (ii) comparison of water qualities with respective land use.

2.1. Determining the PV of WQP

For applying the MCDM methods, alternatives are required to be scored on the basis of some criteria. In this study, criteria were selected by expert survey and the WQP were taken as alternatives.

Four important criteria (viz., hazard potential, cost of mitigation, utilization potential and popularity among the researchers) were identified and their relative importance was determined by expert survey. WQP considered for this study were selected by literature survey.

The WQP were then scored on the basis of each of the criteria. The hazard potential and utilization potential of the WQP were determined by metastatic analysis of related literatures and reports. The most low cost practical treatment methods, which can be applied for natural water bodies, were considered to determine the cost of mitigation against each WQP. Popularity of the WQP among the researchers was determined by their frequency of use in related literature through extensive literature survey.

Finally, WPM, WSM and GRA were applied to calculate the PV of the selected WQP. The PV of the WQP was then scaled as per their weights in NSF WQI, so that the developed WQI may be in the same scale as in NSF WQI.

2.2. Development of WQI

WQI was developed, using the PV of the WQP, determined by MCDM methods, by weighted average method (Eq. (4)).

Calculation of WQI is as follows:

$$\mathrm{WQI} = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i} \tag{4}$$

where Q_i is the Q value for ith WQP as per NSF WQI; W_i is the weight associated with ith WQP and n is the total number of WQP considered.

2.3. Sensitivity analysis

Sensitivity of each of the WQP was assessed towards WQI, using Senslt Sensitivity Analysis Application, by Tornado model [33]. The sensitivity of the WQP towards WQI was then compared with their respective PV.

2.4. Comparison with an established WQI

The WQI, developed using different MCDM methods, were then compared with an already established WQI to check its accuracy. NSF WQI was selected for the purpose as:

- It is a well established general purpose WQI.
- All the WQP, selected for this study, are also used in NSF WQI.

2.5. Statistical validation

Mean average percentage deviation (MAPD) was calculated to assess the closeness of MCDM WQI with NSF WQI. Standard deviation, skewness, kurtosis and 85th percentile of the MCDM WQI were performed to check data reliability.

2.6. Comparison of WQI with land use

A very simple method was adopted for determining the land use patterns of the sampling locations. Different degrees (low, moderate and dense) of basic land uses (settlement, vegetation and cultivation) were taken as the primary land use patterns (Table 1) for this study. WQI of each of the samples was compared with the land use pattern of the sampling location to understand the relation between land use pattern and water quality.

Table 1
Estimation of densities of settlement, vegetation and cultivation in the study area

Densities	Description
Settlement density	
Low	Less than 250 persons per km^2
Moderate	300–400 persons per km^2
Dense	Greater than 400 persons per km^2
Vegetation density	
Low	Below 20% of the coverage area
Moderate	20%–40% coverage area
Dense	More than 40% coverage area
Cultivation density	
Low	Below 30% of the coverage area
Moderate	30%–50% coverage area
Dense	More than 50% coverage area

3. Results and discussion

3.1. Selection of parameters

Eight WQP were selected by metastatic literature survey, on the basis of their occurrence in the literature [34]. It was found that dissolved oxygen (DO) was considered in most of the literatures surveyed (59 out of 182 references) and turbidity occurred least (32 out of 182 references; Table 2).

3.2. Determination of the weights of the parameters

The PV of the WQP were determined using WSM, WPM, GRA and their combination. Criteria were ranked according to their relative importance as obtained from expert survey (Table 3).

The relative importance of hazard potential was found to be maximum, and that of popularity among researchers was found to be minimum.

Relative importance of the WQP was then calculated on the basis of those criteria using WSM, WPM and GRA (Table 4). The mean values of the importance scores of the

Table 2
Occurrence of different WQP in the literature surveyed

SL	Parameters	Occurrence in literature surveyed
1	DO	59
2	BOD	54
3	pH	49
4	Phosphate	43
5	Temperature	41
6	Nitrate	37
7	TS	36
8	Turbidity	32

Table 3
Scoring and ranking of criteria

Criteria	Score	Rank
Hazard potential	0.5872	1
Utilization potential	0.2179	2
Cost of mitigation	0.1228	3
Popularity among researchers	0.0722	4

Table 4
Relative PV of the WQP with respect to the criteria

Parameters	WSM	WPM	GRA	Combined
DO	0.20	0.19	0.21	0.20
BOD	0.14	0.14	0.13	0.14
pH	0.12	0.12	0.12	0.12
Phosphate	0.12	0.13	0.12	0.12
Temperature	0.11	0.11	0.11	0.11
Nitrate	0.12	0.13	0.11	0.12
Turbidity	0.11	0.10	0.11	0.10
Total solids	0.08	0.08	0.10	0.10

three MCDM methods were taken as the combined relative importance scores (Table 4).

For all the MCDM methods used, DO was found to be the most important WQP. Total solids (TS), on the other hand, were the least important WQP by all MCDM methods applied in this study. Such findings are also supported by other studies [35–37].

3.3. Development of MCDM WQI

As NSF WQI was the reference WQI for this study, the procedure of NSF WQI was followed to calculate the MCDM WQI. A correction factor (Eq. (5)) was applied to scale the PV of WQP as per their weights in NSF WQI.

Calculation of the correction factor is as follows:

$$C = \frac{\sum P_{\mathrm{NSF}}}{\sum P_{\mathrm{MCDM}}} \tag{5}$$

where P_{NSF} is the weights of the common parameters by NSF and P_{MCDM} is the weights of the common parameters in WQI.

The correction factor was found to be 0.84 (Eq. (5)) which is the sum of the weights of common parameters in NSF WQI. Therefore, 0.84 was multiplied with MCDM weights of the WQP to scale them as per the weights of WQP in NSF WQI (Table 5). The scaled MCDM scores were taken as the PV of the WQP in MCDM WQI.

Table 5
Weights of the parameters

Parameters	Corrected weights of the parameters				NSF WQI weights
	WSM	WPM	GRA	Combined	
DO	0.17	0.16	0.18	0.17	0.17
BOD	0.12	0.12	0.11	0.12	0.11
pH	0.10	0.10	0.10	0.10	0.11
Phosphate	0.10	0.11	0.10	0.10	0.10
Temperature	0.09	0.09	0.09	0.09	0.10
Nitrate	0.10	0.11	0.09	0.10	0.10
Turbidity	0.09	0.08	0.09	0.08	0.08
Total solids	0.07	0.07	0.08	0.08	0.07

3.4. Sensitivity analysis

The order of sensitivity of the WQP towards WQI was in parity to the order of the PV of WQP, determined by MCDM methods (Table 6).

3.5. Statistical analysis of the WQI data

All the WQI were found to be fairly close to NSF WQI (mean MAPD = 0.60%; Table 7). Among all the methods used, WSM WQI was found to be closest (MAPD = 0.42%) to NSF WQI, followed by combined WQI (MAPD = 0.52%), WPM WQI (MAPD = 0.62%) and GRA WQI (MAPD = 0.83%) (Table 7). All the WQI showed similar patterns of distribution over the study area (Fig. 1(b)), which confirms the parity of the MCDM WQI with NSF WQI.

The low standard deviation of 7 for all the MCDM WQI indicates that little difference existed among the water qualities of different sampling locations (Table 7). This is also supported by low kurtosis values of the WQI, which suggests that the distribution of the WQI values is rather flat (Table 7). The lower skewness depicts that the distribution of the WQI is rather symmetrical. The high 85th percentile value (70)

Table 6
Sensitivity analysis of the WQP

Parameters	WSM		WPM		GRA		Combined	
	PV	Sensitivity	PV	Sensitivity	PV	Sensitivity	PV	Sensitivity
DO	0.20	0.37	0.19	0.37	0.21	0.40	0.20	0.38
BOD	0.14	0.18	0.14	0.17	0.13	0.17	0.14	0.18
pH	0.12	0.35	0.12	0.35	0.12	0.32	0.12	0.35
Total phosphate	0.12	0.04	0.13	0.04	0.12	0.05	0.12	0.04
Temperature	0.11	0.05	0.11	0.05	0.11	0.05	0.11	0.05
Nitrates	0.12	0.01	0.13	0.01	0.11	0.01	0.12	0.01
Turbidity	0.11	0.00	0.10	0.00	0.11	0.00	0.10	0.00
Total solids	0.08	0.00	0.08	0.00	0.10	0.00	0.10	0.00

Table 7
Statistical analysis of different WQI

Methods	WSM WQI	WPM WQI	GRA WQI	Combined WQI
MAPD from NSF WQI	0.42	0.62	0.83	0.52
Standard deviation	7.16	7.16	7.22	7.18
Skewness	–0.40	–0.38	–0.48	–0.42
Kurtosis	0.34	0.23	0.47	0.35
85th percentile	70	70	70	70

indicates that most of the samples were of medium or bad quality, only 15% of the total samples are good (Table 7). Thus, the overall quality of surface water in the study area is found to be poor.

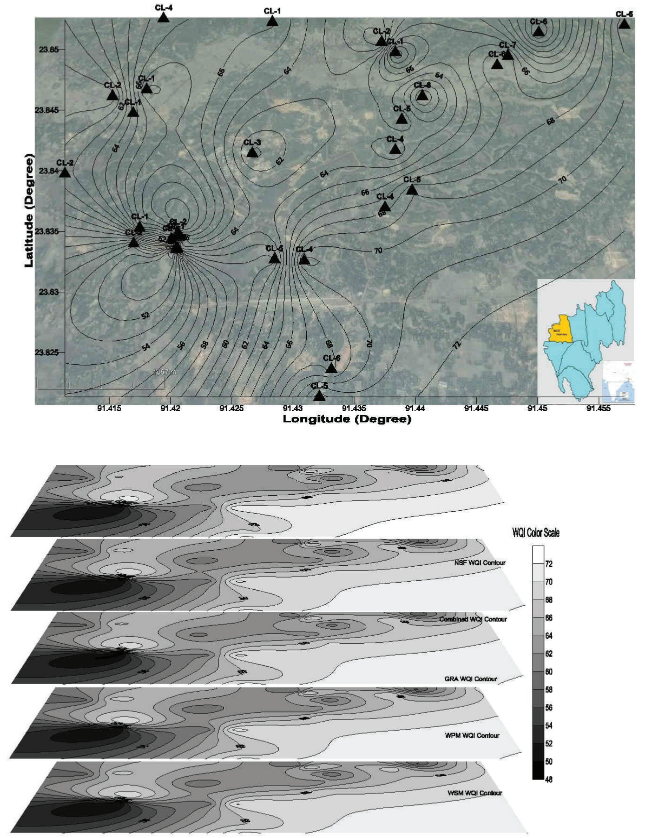

Fig. 1. Distribution of WQI of the samples over study area. (a) Sampling points (black triangles) with water quality indices. (b) Distribution of different MCDM WQI over the study area. The colour scale for WQI is also given.

Table 8
Suitability ranking of different methods for determining PV of WQP

WQI	Sensitivity	Accuracy	Descriptive statistics	Overall
WSM WQI	3	1	2	1
WPM WQI	4	3	1	3
GRA WQI	1	4	4	4
Combined WQI	2	2	3	2

The standard deviation (7.22), skewness (–0.48) and kurtosis (0.47) of GRA WQI of the samples were found to be higher than those of WSM WQI, WPM WQI and combined WQI (Table 7) of the samples. This implies that GRA method is not much suitable for the determination of PV of the WQP. WPM WQI, on the other hand, has the minimum standard deviation (7.16), skewness (–-0.38) and kurtosis (0.23) among all the MCDM WQI (Table 7). Therefore, in terms of reliability, WPM is the most suitable of the MCDM methods used in this study, followed by WSM WQI. Combined method remained in the third position.

3.6. Selection of the suitable WQI

GRA WQI was found to be most sensitive one (Table 6), while WPM WQI shows most data reliability (Table 7). WSM WQI was found to be closest to the reference WQI. Considering all the matrices together, WSM WQI was found to have the best overall matrix (Table 8).

Thus, WSM WQI is the most suitable MCDM method to determine the PV of WQP among all the MCDM methods used in this study.

3.7. Comparison between WQI and land use

Samples were collected from 36 different locations of south and west of Tripura, a state located in the north eastern region of India. The water quality was assessed in the field with sensor-based Water Quality Monitoring device (Horiba U50 and YSI 6600). Biochemical oxygen demand (BOD), total suspended solids (TSS) and TS were measured in laboratory. The sampling locations have different settlement type, density, degree of cultivation, vegetation type and vegetation density. Fig. 1(a) shows different sampling locations with water quality indices and Fig. 1(b) shows the contour of WQI for the MDCM WQI, developed in this study.

Results suggest that good quality of water was found in areas with mostly dense settlement, moderate to low vegetation and dense cultivation (Table 9). Areas with moderate settlement, low vegetation and dense cultivation, on the other hand, generally maintain medium quality of water (Table 9). However, moderate to low settlement, dense vegetation and moderate cultivation may lead to bad water quality (Table 9). Vegetation and cultivation seems to have greater impact on water quality than settlement (Table 9).

Thus, the results indicate, dense settlement, moderate to low vegetation and dense cultivation is good for water, whereas low settlement, dense vegetation and moderate cultivation is bad for water. The results of this study is, however, in contrary with the general notion that dense vegetation is good

Table 9
Percentage of water quality of samples against different land use

Water quality	Settlement density			Vegetation density			Cultivation density		
	Dense	Moderate	Low	Dense	Moderate	Low	Dense	Moderate	Low
Good	2	1	1	1	3	3	5	1	0
Medium	6	8	6	5	4	11	13	4	3
Bad	1	4	4	4	2	1	3	4	0

for maintaining water quality [38], settlement [39] and cultivation [40] impose negative impact on water quality. These findings may be useful for effective planning and management of land use to maintain optimum surface water quality.

The present study, however, has the limitation of small study area and small sample volume, also there is a scope to use finer land use classification. Also, inclusion of land parameters like soil texture, amount of pesticide and fertilizer deposition, etc., may give a better insight [41,42]. A larger study area with greater sample volume, along with more extensive land use classification may lead to more useful findings. Also, an index of land use can be developed for each class of use on the basis of its impact on water quality. Such an index, when compared with WQI, can produce a convenient, dependable numerical expression for land use as the predictor of water quality.

4. Conclusion

As important criteria like hazard potential, utilization potential, cost of treatment and popularity among researchers were included and MCDM methods were used to develop the WQI for this study, the WQI was more holistic and reliable in nature.

The overall quality of surface water in the study area was found to be unsatisfactory with a flat distribution over different locations.

On comparison of different land use patterns with the respective WQI, dense settlement, moderate to low vegetation and dense cultivation was found good for surface water. The results also indicate low settlement, dense vegetation and moderate cultivation are bad for the quality of surface water. Moderate settlement, low vegetation and dense cultivation, however, lead to medium quality of water.

The findings of this study may be useful for the policy makers to manage optimally the land use and water quality of a location.

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