Assessment of water quality through indices around Kalpakkam, southeast coast of India

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Abstract

A Water Quality Index (*WQI*) is a numeric expression used to evaluate the quality of a given water body and to be easily understood by managers. The present study discusses and compares four different water quality indices, viz. arithmetic water quality index, multiplicative water quality index, unweighted arithmetic water quality index and unweighted multiplicative water quality index, which are considered for characterizing the coastal water quality along Kalpakkam, India. Dissolved oxygen (*DO*), pH, biochemical oxygen demand (*BOD*), temperature, suspended particulate matter (*SPM*), turbidity, nitrate and phosphate are used as the parameters for the development of water quality indices. The concordance correlation coefficients for various water quality indices were determined. It was found that the arithmetic water quality index was higher than unweighted arithmetic water quality index while the unweighted multiplicative water quality index was lower than multiplicative water quality index. Weighted arithmetic water quality index is almost perfectly correlated with unweighted arithmetic water quality index (Pearson $\rho = 0.98$) and also closely related with unweighted multiplicative water quality index (Pearson $\rho = 0.97$). All the indices were well correlated with each other except multiplicative water quality index. The comparison of different indices showed that the arithmetic water quality index is the most suitable for coastal waters and alternative index could be unweighted arithmetic water quality index.

Keywords: Coastal water quality, Kalpakkam, Water quality indices (*WQI*), Concordance correlation coefficient, Statistical data analysis

1. Introduction

Monitoring programs of aquatic systems play a significant role in water quality management. However, the water quality is difficult to be evaluated from a large number of samples, each containing concentrations of many water quality variables [1]. A water quality index (*WQI*) summarizes large amounts of water quality data into simple terms (e.g., excellent, good, bad, etc.) for reporting to managers and the public in a consistent manner [2]. *WQI* can be used as a tool in comparing the water quality of different sources and it gives the public a general idea of the possible problems with water in a particular region. The indices are among the most effective ways to communicate the information on water quality trends for the water quality management [3]. Available water quality indices have some limitations such as incorporating a limited number of water quality variables and providing deterministic outputs [4].

Water quality index is a performance measurement that aggregates information into a usable form, which reflects the composite influence of significant physical, chemical and biological parameters of water quality conditions [5]. Use of a *WQI* allows ‘good’ and ‘bad’ water quality to be quantified by reducing a large quantity of data on a range of physico-chemical and biological variables to be a single number in a simple, objective and reproducible manner [6]. The use of a numerical index as a management tool in water quality assessment is a rather recent innovation. An index is a number, usually dimensionless, which expresses the relative magnitude of some complex phenomenon or condition. [7] proposed the first water quality index (*WQI*), a great deal of consideration has been given to the development of index methods. Various types of arithmetical methods used, have included aggregation of quality-monitoring data to yield an overall quality index. The *WQI* system is a well-known method of expressing water quality that offers a simple, stable and reproducible unit of measure which responds to changes in the principal characteristics of water [8]. All indexing systems require measurements to be made for a selection of water quality determinants. From these measurements, a sub-index rating value is obtained for each determinant. These values are then aggregated in some way to produce the final index score [9].

Several researchers have assessed spatial and temporal changes in water quality [10-15]. Once the water quality monitoring data are collected, there is a further need to translate them into a form that is easily understood and effectively interpreted. Water quality index plays an important role in such translation process. It is a communication tool for transfer of water quality data [16]. The desirability of developing and using such indices has been described by [17]. These numbers allow meaningful spatial and temporal comparisons to be made and integrate the effects of the various pollutants present. *WQI* not only acts as indicator of water quality changes, but can also indicate the effects of these changes on potential water use. The objective of this article is to compare coastal water quality indices by considering the standards and aquatic life.

The concordance correlation coefficient, which evaluates the agreement of paired samples, can be used to validate the reproducibility of an assay, instrument, or method. It is meaningful and easy to perform. The proposed guidelines for such validation require the specification of allowable losses in precision and accuracy. The sample size requirement for effective validation can be computed based on the same principle. The concordance correlation coefficient can potentially be an excellent tool in many types of goodness-of-fit evaluation by simply examining how well the observed outcomes concord with the hypothesized values [18].

Suggested Rating Function Values for Various Variables

To describe the water quality, it is useful to employ a sub-index of quality variable to indicate the quality of the water on a zero (worst quality) to unity (best quality) scale. In this context, a variety of sub-indices have been proposed over the last two decades. These sub-indices can be classified as absolute sub-indices, which are independent of the water quality standards, and relative sub-indices, which depend on the water quality standards. The sub-index rating function of a quality variable is not unique but depends on the intended water use. To yield an overall water quality index, the sub-indices are aggregated. The sub-indices consist of nonlinear and segmented nonlinear explicit functions, except two unimodal variables, pH and temperature.

The coefficients and factors in the sub-index equations were developed based on coastal water quality standards, aquatic life, and the review of literature. The eight parameters included for the development of water quality indices are dissolved oxygen (*DO*), pH, biochemical oxygen demand (*BOD*), temperature, suspended particulate matter (*SPM*), turbidity, nitrate and phosphate. The rating function values of 1.0, 0.9, 0.8, 0.5, and 0.01, represent respective water quality index values of 100, 90, 80, 50, and 1. For each sub-index, the values of the pollutant variable were identified, which correspond to ‘‘intolerable’’ (I = 0.01), “poor” (I = 0.1), “good” (I = 0.9), and “perfect” (I = 1) water quality. In Table 1, the values of water quality parameters that correspond to 0.9, 0.5, and 0.1 values of rating functions are given [19]. The value function graphs for the various parameters are shown in Figs 1-8.

Table 1. Values of water quality parameters corresponding to 0.9, 0.5, and 0.1 values of sensitivity functions

Parameter	0.9	0.5	0.1
Dissolved oxygen (mg/L)	6	4.5	2.5
pH	5.5, 8.0	3.5, 10	2.3, 11.5
Biochemical oxygen demand (mg/L)	1.5	3	4.5
Temperature (°C)	14, 26	6, 32	2, 35
Suspended particulate matter (mg/L)	60	150	200
Turbidity (NTU)	40	100	200
Nitrate (µmol)	5	12	41
Phosphate (µmol)	0.7	1.11	3.67

Figure 1. Sensitivity function for dissolved oxygen.

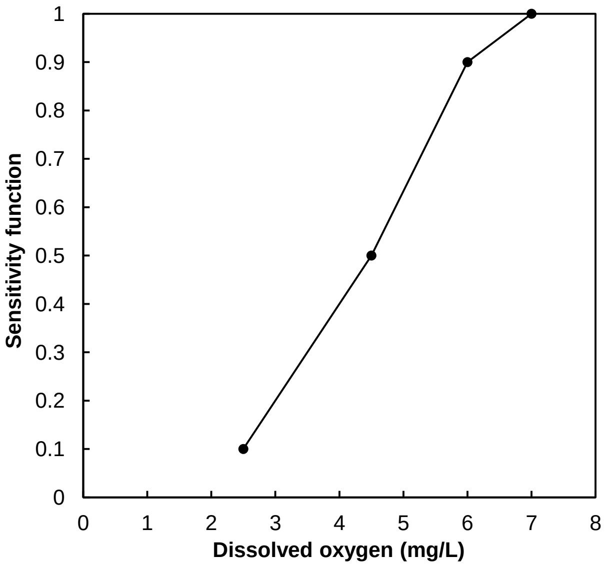


Figure 2. Sensitivity function for pH.

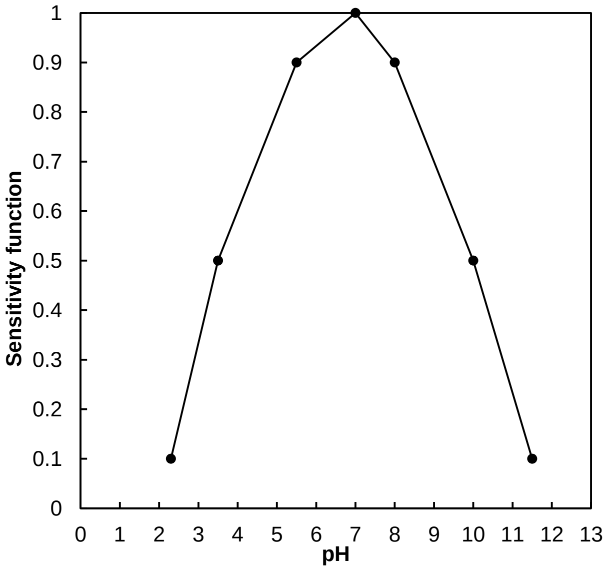


Figure 3. Sensitivity function for BOD.

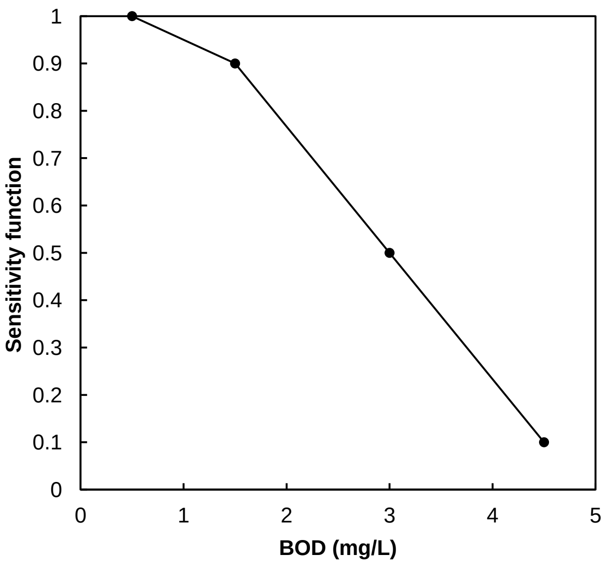


Figure 4. Sensitivity function for temperature.

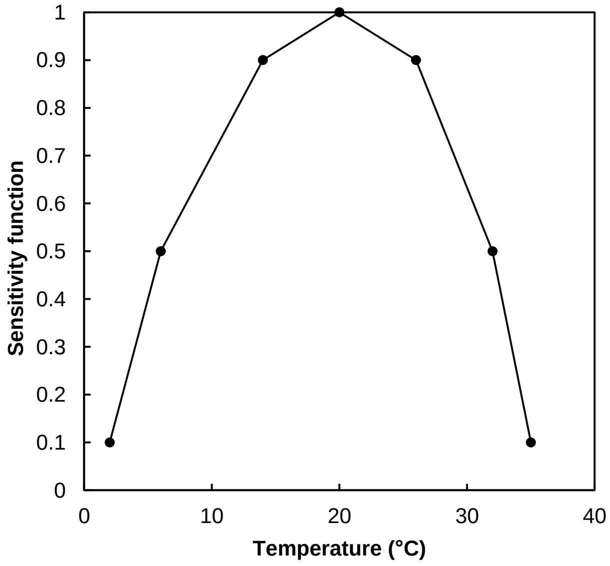


Figure 5. Sensitivity function for SPM.

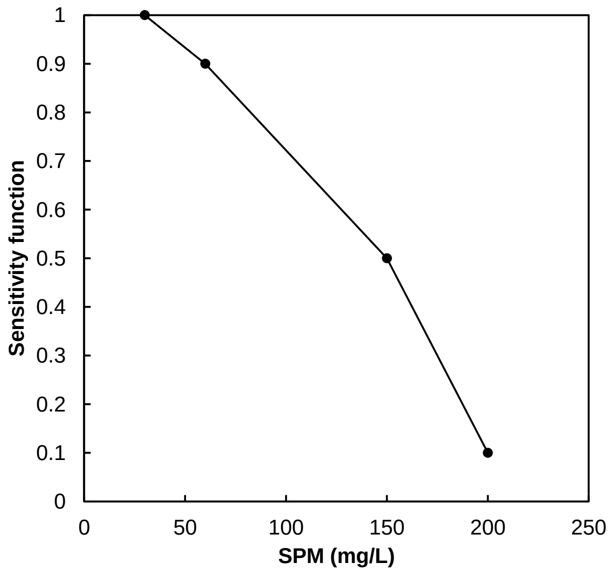


Figure 6. Sensitivity function for Turbidity.

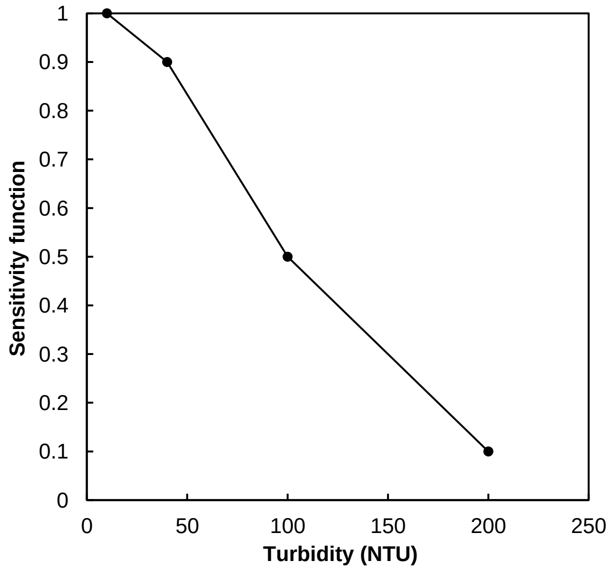


Figure 7. Sensitivity function for Nitrate.

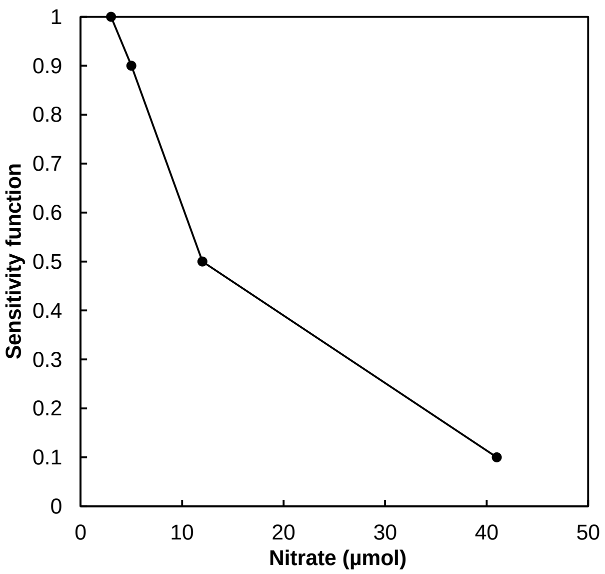


Figure 8. Sensitivity function for Phosphate.

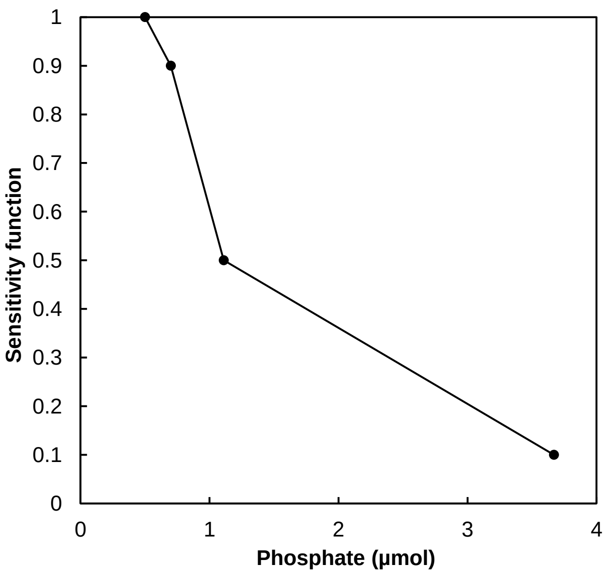


Table 2. Weights for six water quality variables (Gupta et al., 2003)

Variable	Temporary weight	Final weight (w_i)
Dissolved oxygen (mg/L)	1.0	0.18
pH	0.9	0.16
Biochemical oxygen demand (mg/L)	0.8	0.14
Temperature (°C)	0.7	0.13
Suspended particulate matter (mg/L)	0.6	0.11
Turbidity (NTU)	0.6	0.11
Nitrate (μmol)	0.5	0.09
Phosphate (μmol)	0.5	0.09

The assigning of weightage to each parameter depends on the relative importance of the parameter. Then temporary weight is assigned to each parameter. The final weightage can be determined by dividing the individual temporary weight of each parameter by the total temporary weight and the final weights are given in Table 2. The basis of water quality categories is given in Table 3 [19].

Table 3. Descriptor categories for WQI

WQI	Category
0-25	Very bad
26-50	Bad
51-70	Medium
71-90	Good
91-100	Excellent

Structure of Various Water Quality Indices

The four different water quality indices have been considered for comparison of coastal water quality of Kalpakkam coastal area. Individual index (q_i) and weighing factors (W_i) for six parameters (*DO*, pH, *BOD*, temperature, *SPM*, turbidity, nitrate and phosphate) were fitted into the following formulas.

The first, water quality index is an index originally proposed by [7], also called as the arithmetic water quality index (WQI_A). Many researchers [20-22] have used this index in their research work, which is basically the weighted arithmetic mean in the following form:

$$WQI_A = \sum_{i=1}^{n} w_i q_i \tag{1}$$

where n is the number of variables, w_i is the relative weight of the i^{th} parameter such that $\sum_{i=1}^{n} w_i = 1$ and q_i is the quality rating of i^{th} parameter.

Second water quality index is a multiplicative form of index proposed by [8]. Later researchers [23-26] have also employed a weighted geometric mean for aggregation. The multiplicative water quality index (WQI_M) is defined as follows:

$$WQI_M = \sum_{i=1}^{n} q_i w_i \tag{2}$$

The construction of the above two indices suggests that each parameter may be of different weight based on the importance of water quality situation.

Third and fourth water quality indices are as follows:

The unweighted arithmetic water quality index (WQI_{UA}) is defined as given in the following equation.

$$WQI_{UA} = \frac{1}{n}\sum_{i=1}^{n} q_i \qquad (3)$$

Unweighted multiplicative water quality index (WQI_{UM}) is defined as:

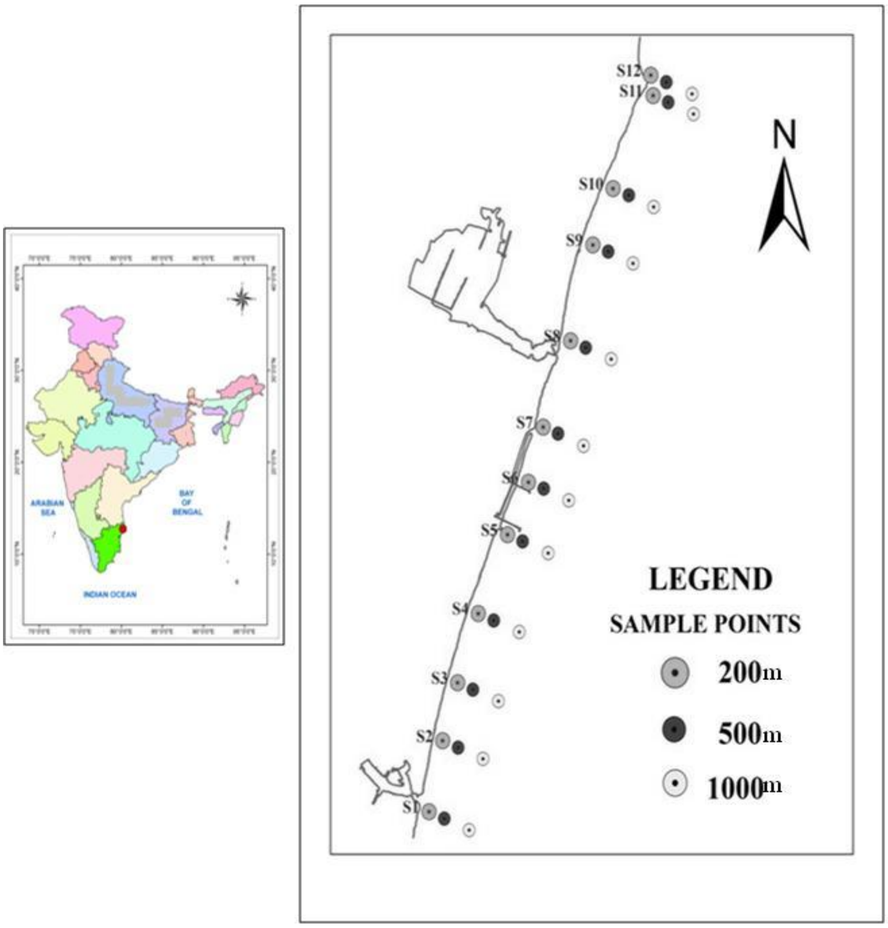
$$WQI_{UM} = \sum_{i=1}^{n} q_i \qquad (4)$$

2. Study Site and Method

Study Area

The study was carried out in the vicinity of Madras atomic power station (MAPS) located at Kalpakkam, East Coast of India (12°33'N and 80°11'E) at about 70 km south of Chennai (Fig. 9). At present a nuclear power plant (*MAPS*) and a desalination plant are operating near the coast. *MAPS* use seawater at a rate of 35 m^3/s for condenser cooling purpose. The seawater is drawn through an intake structure located inside the sea at about 500 m away from the shore. After extracting the heat, the heated seawater is released into the sea. Two backwaters namely the Edaiyur and the Sadras located in this coast, are connected to the Buckingham canal, which runs parallel to the coast. Buckingham Canal carries urban runoff from Chennai and adjacent coastal inhabitants. The Sadras backwater receives the domestic discharge from the Kalpakkam Township, which has a population of about 50,000. Two villages inhabited by fishermen are located adjoining both sides of the township having sizable population. The Edaiyur backwaters mouth remained open throughout the study period due to dredging activities.

Figure 9. Locations of water quality monitoring stations.



Station Code	Description
S1	South of Sadras
S2	North of Sadras
S3	North of Sadras
S4	Periya Odai
S5	Near PFBR jetty
S6	Near MAPS jetty
S7	Engineering canal
S8	Edaiyur
S9	Kokilamedu
S10	North of Kokilamedu
S11	South of shore temple
S12	North of shore temple

Sample Collection and Analysis

Surface water samples were collected every month from the stations S1 to S12 for a period from January to December 2010, for the estimation of various physico-chemical parameters. Each station has a transect with sampling stations at 200 m, 500 m and 1 km into the sea (Fig. 9). Sampling stations were fixed with the help of a Global Positioning System. A total of 36 water samples were collected from all transects in acid cleaned polythene bottles. In the present study, for comparison of coastal water quality indices, different physico-chemical parameters and nutrients such as dissolved oxygen, pH, biochemical oxygen demand, temperature, suspended particulate matter, turbidity, nitrate and phosphate were analyzed. Systronics pH meter with accuracy of ± 0.002 was used to estimate pH. Temperature was measured using standard thermometer. Winkler's titrimetric method [27] was followed for the estimation of DO. Biochemical oxygen demand was determined by the dilution and incubation method [27]. Nitrate and phosphate were estimated by colorimetry following standard methods [27]. Concordance correlation coefficient was computed for different water quality indices [28,29].

3. Results and Discussion

Water quality indices are established from important physico-chemical parameters for different months to understand the coastal water quality better for the general public. A higher value would indicate a better quality of water. Various parameters selected for the estimation of different water quality indices are dissolved oxygen, pH, biochemical oxygen demand, temperature, suspended particulate matter, turbidity, nitrate and phosphate. Statistics description values of the parameters considered are given in Table 4. Using these rating curves and equations, the *WQI* obtained for various points in Kalpakkam coastal water is given in Figs. 1 to 8. Values of the *WQI* can be used not only to indicate the spatial variation of coastal water but also as a good indicator of behaviour of water along environmental gradients.

Comparison of Water Quality Indices

The station variations of sub-index values for above mentioned parameters are given in Table 5. The comparison of different water quality indices is shown in Table 6. The results of arithmetic water quality index (WQI_A) show no expected development except that lower value of water quality index has been observed in station S7 to S10. At S11 and S12, the water quality appears to have recovered slightly. Above 80 occurs for stations S1, S2, S5, S6, S11 and S12 and station S7 has the lowest value (74). The unweighted arithmetic water quality index (WQI_{UA}) is lower than weighted arithmetic water quality index (WQI_A). The highest value is observed in S10 and S11 (84) and lowest value in S7 (74). These two indices are substantially correlated with a concordance correlation coefficient of 0.97. But it is observed that WQI_A values are higher than WQI_{UA}, WQI_M and WQI_{UM}. WQI_{UA} has the problem of ambiguity, while WQI_A has the problem of eclipsing. The problem of eclipsing is the underestimation rather than exaggeration of pollution. Eclipsing is said to occur when extremely poor environmental quality exists for at least one pollutant variable, but the overall index does not reflect this fact [19].

Table 6. Comparison of various water quality indices

Stations	WQI_A	WQI_{UA}	WQI_M	WQI_{UM}
S1	85	83	82	80
S2	82	81	78	72
S3	78	78	75	70
S4	79	79	74	67
S5	81	80	77	76
S6	81	80	77	69
S7	74	74	69	60
S8	77	82	77	75
S9	76	76	72	66
S10	80	84	78	76
S11	82	84	79	69
S12	81	77	72	67

The third index for comparison is the multiplicative water quality index. The multiplicative index (WQI_M) is higher than unweighted multiplicative index (WQI_{UM}). WQI_M value is also lower than the earlier indices. The highest and lowest values are observed to be 82 (at S1) and 69 (for S7). These two indices are moderately correlated having a correlation coefficient of 0.92 (Table 7).

Table 7. Concordance correlation coefficient (Pearson ρ) among four indices

	WQI_A	WQI_{UA}	WQI_M	WQI_{UM}
WQI_A	1.00			
WQI_{UA}	0.98	1.00		
WQI_M	0.91	0.96	1.00	
WQI_{UM}	0.97	0.96	0.92	1.00

Table 4. Statistics description of various parameters for different stations.

Parameters	Statistics	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
DO (mg/L)	Minimum	4.29	4.24	4.03	4.19	4.63	4.52	4.34	4.36	4.48	4.35	4.66	4.59
	Maximum	4.68	4.61	4.22	4.39	4.83	4.86	4.83	4.63	4.59	4.68	4.87	4.78
	Mean	4.49	4.43	4.13	4.29	4.73	4.69	4.58	4.49	4.53	4.52	4.77	4.68
	Std. Deviation	± 0.20	± 0.20	± 0.10	± 0.10	± 0.09	± 0.17	± 0.25	± 0.13	± 0.06	± 0.17	± 0.11	± 0.09
pH	Minimum	7.28	7.36	7.24	7.27	7.36	7.40	7.24	7.30	7.35	7.30	7.22	7.37
	Maximum	7.42	7.38	7.42	7.39	7.43	7.45	7.46	7.50	7.43	7.46	7.47	7.48
	Mean	7.36	7.37	7.36	7.34	7.39	7.43	7.32	7.43	7.40	7.36	7.35	7.43
	Std. Deviation	± 0.06	± 0.01	± 0.10	± 0.05	± 0.03	± 0.02	± 0.12	± 0.11	± 0.04	± 0.08	± 0.12	± 0.05
BOD (mg/L)	Minimum	1.29	1.09	1.28	1.06	1.55	1.58	2.38	2.52	2.40	2.40	2.34	2.52
	Maximum	2.16	1.81	1.61	1.87	1.85	1.98	2.83	2.74	2.82	2.85	2.92	2.93
	Mean	1.72	1.40	1.43	1.44	1.72	1.83	2.62	2.60	2.57	2.55	2.70	2.69
	Std. Deviation	± 0.43	± 0.37	± 0.16	± 0.40	± 0.15	± 0.21	± 0.22	± 0.12	± 0.21	± 0.25	± 0.31	± 0.21
Temperature (℃)	Minimum	28.22	27.96	28.20	28.05	27.98	28.25	28.58	28.72	28.70	28.83	28.75	28.73
	Maximum	28.40	27.97	28.41	28.41	28.52	28.54	29.88	29.13	29.06	29.16	29.18	29.08
	Mean	28.29	27.96	28.29	28.27	28.27	28.41	29.18	28.95	28.83	28.98	28.93	28.92
	Std. Deviation	± 0.09	± 0.00	± 0.10	± 0.19	± 0.27	± 0.14	± 0.65	± 0.21	± 0.19	± 0.16	± 0.21	± 0.17
SPM (mg/L)	Minimum	43.00	44.50	46.17	41.40	43.30	42.40	46.93	47.70	44.03	45.70	46.10	48.47
	Maximum	48.87	50.03	48.10	52.10	44.37	44.53	51.77	53.20	50.77	48.70	49.53	50.24
	Mean	46.08	47.38	47.17	46.07	43.81	43.13	48.89	50.26	47.88	47.61	47.80	49.45
	Std. Deviation	± 2.94	± 2.7	± 0.96	± 5.47	± 0.53	± 1.21	± 2.54	± 2.77	± 3.46	± 1.66	± 1.71	± 0.89
Turbidity (NTU)	Minimum	2.84	2.82	3.01	2.84	2.71	3.23	2.33	4.41	3.19	2.54	2.82	2.91
	Maximum	4.43	4.11	3.86	4.45	5.09	4.53	7.10	7.91	5.70	4.42	3.87	4.54
	Mean	3.65	3.32	3.31	3.50	3.69	3.94	4.67	6.52	4.62	3.39	3.20	3.67
	Std. Deviation	± 0.79	± 0.69	± 0.47	± 0.84	± 1.24	± 0.65	± 2.38	± 1.85	± 1.28	± 0.95	± 0.58	± 0.82
Nitrate (µmol)	Minimum	6.92	7.00	7.13	15.17	14.17	10.83	11.5	8.67	11.33	7.67	12.5	13.33
	Maximum	9.55	9.50	8.00	17.00	15.50	14.50	13.50	10.00	16.50	10.50	15.50	14.50
	Mean	5.00	5.00	5.90	13.0	13.00	6.00	7.50	7.00	4.50	3.50	9.00	11.50
	Std. Deviation	± 2.35	± 2.29	± 1.09	± 2.02	± 1.25	± 4.36	± 3.46	± 1.52	± 6.17	± 3.68	± 3.27	± 1.60

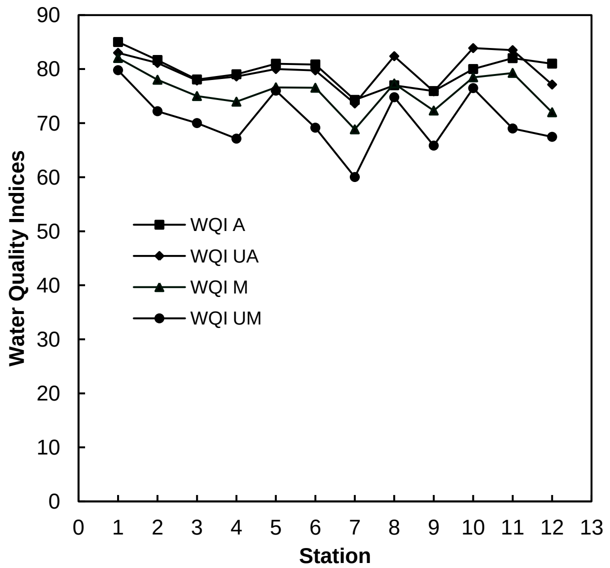
Phosphate (µmol)	Minimum	1.44	2.45	2.51	2.41	2.78	2.44	3.00	1.01	1.89	0.89	2.11	2.11
	Maximum	2.00	3.33	3.33	3.22	3.67	3.00	3.33	2.00	2.33	1.67	3.67	3.33
	Mean	0.67	1.33	2.00	2.00	2.00	2.00	2.67	0.33	1.33	0.33	0.67	1.33
	Std. Deviation	± 0.69	± 1.01	± 0.71	± 0.70	± 0.84	± 0.50	± 0.33	± 0.87	± 0.50	± 0.69	± 1.50	± 1.07

Table 5. Sensitivity function values for different physico-chemical parameters around Kalpakkam coast

Stations	DO (mg/L)	pH	BOD (mg/L)	Temperature (°C)	SPM (mg/L)	Turbidity (NTU)	Nitrate (µmol)	Phosphate (µmol)
S1	0.54	0.98	0.88	0.76	0.96	0.94	0.90	0.90
S2	0.54	0.98	0.90	0.80	0.94	0.98	0.90	0.45
S3	0.42	0.98	0.90	0.76	0.93	0.98	0.92	0.34
S4	0.48	0.96	0.90	0.76	0.96	0.96	0.93	0.34
S5	0.58	0.98	0.88	0.76	0.99	0.94	0.93	0.34
S6	0.58	0.98	0.89	0.77	0.99	0.92	0.91	0.34
S7	0.54	0.96	0.62	0.72	0.94	0.92	0.94	0.25
S8	0.53	0.98	0.62	0.70	0.92	0.90	0.95	0.99
S9	0.54	0.98	0.61	0.70	0.94	0.92	0.93	0.45
S10	0.54	0.97	0.61	0.71	0.93	0.98	0.98	0.99
S11	0.59	0.97	0.63	0.70	0.94	0.98	0.97	0.90
S12	0.58	0.98	0.63	0.70	0.92	0.94	0.97	0.45

The graphs plotted for water quality indices versus stations for Kalpakkam coastal water (Fig. 10), show an increasing trend where higher *WQI* on stations give higher WQI. This means that there is positive correlation between water quality indices and stations. The results from WQI_A, S1 to S6 and S10 to S12 show good water quality and stations S7, S8 and S9 are slightly polluted compared with remaining stations. This is because S7 is affected with the heated water discharges from *MAPS* outfall, S8 is polluted due to the dredging activities which allows inflow of fresh water into the sea and S9 is contaminated either through fisher man activities or heated water from outfall. On the whole, water quality at all stations appears to be good except S7 to S9. The stations S10 to S12 are slightly polluted compared with S7 to S9.

Figure 10. Comparison of various water quality indices values for different stations.



The mathematical analysis had been carried out to determine the correlation among the indices. The MedCalc software package [28,29] was used to calculate the concordance correlation coefficients (Table 7). Based on the earliest developed method (WQI_A) as reference method, the comparison were done with other newer methods developed later (WQI_{UA}, WQI_M and WQI_{UM}). It can be seen that all four indices are meaningfully correlated with each other. Unweighted multiplicative water quality index is almost perfectly correlated with arithmetic water quality index (Pearson $\rho = 0.99$) and also closely related with unweighted arithmetic water quality index (Pearson $\rho = 0.98$).

4. Conclusion

The study investigates how index methods are effective in deriving the information from complex water quality data sets. The water quality index gives a relative indication of the quality of the water along the coastal water. Coastal water with a WQI value in the ranges 0-25, 26-50, 51-70, 71-90, and 91-100 would be considered very bad, bad, medium, good and excellent respectively. Using this classification, it can be stated that stations S1 to S6 are unpolluted, S7 to S9 are polluted whereas S10 to S12 are slightly polluted. However, these are only rough indications and the divisions are rather subjective. The weighted arithmetic water quality index (WQI_A) is higher than unweighted arithmetic water quality index (WQI_{UA}). These two indices are almost perfectly correlated having a concordance correlation coefficient of 0.98. Weighted multiplicative index (WQI_M) is higher than unweighted multiplicative index (WQI_{UM}). The weighted multiplicative index value is also lower than the earlier indices. Although all the indices showed significant correlation with each other, the best choice would be the arithmetic water quality index (WQI_A) and the better alternative would be unweighted arithmetic water quality index for characterizing the coastal waters.

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