Assessment of river water quality indices based on various fuzzy models and arithmetic indexing method

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Abstract. River water is a major source of natural freshwater for both rural and urban areas. The severe threat in the form of pollutants is the major cause of deterioration of surface water quality. Water Quality Index (WQI) is a single measure of overall water quality in a specific location with a special emphasis on the time-based readings of water quality parameters. WQI can be used as a good tool to assess the intensity of water pollution. In this study, two water quality index models using fuzzy logic in MATLAB R2015a by trapezoidal and sigmoid membership functions are proposed. Fuzzy water quality index models were developed for various seasons, using eight experimentally estimated water quality parameters, such as Temperature (T), Chlorides (Ca$^+$), Nitrates (NO$_3^-$), Sulphates (SO$_4^{2-}$), Total Coli forms (TC), Total Dissolved Solids(TDS), Electrical conductivity (EC) and Total Hardness (TH) of the water samples at 8 locations stretching 55 km of Chalakudy River from January 2018 to December 2018. The models are validated by comparing with the WQI values obtained by the application of arithmetic index method (AIM) based on Indian Standards, by finding the absolute average relative error (AARE) and root mean square error (RMSE). The fuzzy logic model using trapezoidal membership function (FTWQI) was found to be more reliable with the least error (AARE 0.0214 and RMSE 0.318) compared with the fuzzy sigmoid water quality index (FSWQI) (AARE 0.573 and RMSE 0.86). The models enable the easy prediction of the risk of water consumption.

1. Introduction

Water pollution is a major environmental problem and unless due attention is given to this area and proper measures are undertaken, the situation would be worse in the future. In recent years, due to tremendous development in the field of agriculture and industry, and also an increase in population, water ecosystems have become perceptibly altered in several aspects. Consequently, the rivers are exposed to all local disturbances regardless of their source of occurrence [1]. Significantly, improper water management and conservation of water bodies lead to the inevitable water crisis in the entire world. Therefore, the health of the rivers and their biological diversity will be directly related to the health of almost every component of the ecosystem [2]. Surface water pollution with chemical, physical and biological contaminants due to anthropogenic activities pose a high risk and demands environmental attention [3]. Moreover, constant discharges of domestic and industrial wastewater and seasonal changes like climate, surface runoff also have an important role in the river water quality [4]. Chalakudy River is the fourth-longest river in Kerala and the longest river in Thrissur district having a length 144 km with a total drainage area is 1704 sq km. Out of which 1404 sq km is in Kerala and the rest 300 sq km in Coimbatore district of Tamil Nadu. It originates from the Anamalai hills, Nelliampathy ranges of the Western Ghats. In Kerala it flows westward...
through the Palakkad, Thrissur, and Ernakulam districts. A major portion lies in the Thrissur district. The community living near the river basin mainly depends on this river for satisfying its basic requirements. Chalakudy and Kodungallur municipalities utilize this river water as their major drinking water source. Also, water in this river is mainly used for domestic, agricultural, and industrial uses for Thrissur and in Palakkad Districts. The drinking water scenario in the basin displays that this basin is getting into a serious drinking water crisis. Study areas facing serious drinking water scarcity.

The main reasons for drinking water scarcity are the misuse of water, excess use of water, improper water management, and difficulties faced in water supply and pumping of water from the river during summer. Thirty-one irrigation projects and more than ten water-pumping stations are situated in this river along the study area. A water treatment plant has a capacity of 26.1 million m$^3$ is situated at Vynthala. This drinking water supply scheme supplies water to all the panchayaths and the Chalakudy municipalities along the basin. Some coastal panchayaths such as Eriyad, Methala, Puthenvelikkara, and the Kodungallur municipality depends on this scheme for drinking purpose.

Water quality index (WQI) can be used as a good tool to convert complex data into a simple and understandable tool making it feasible for the public to rely upon. Similar types of studies related to WQI have been conducted in India [5,6,7]. Viewed from this perspective, water quality monitoring and analysis of water quality index are remarkable steps in the process of managing and conserving the entire ecosystem[8,9]. In the present study, fuzzy water quality index model (FTWQI and FSWQI) models were developed using fuzzy logic in R MATLAB 2015a and models were validated using the WQI values derived by arithmetic index method (AIM). Fuzzy logic has shown a good promise in modelling new water quality models [10]. Prediction modelling involves various environmental control parameters [11].

2. Materials and Methods

2.1. Study Area

Chalakudy sub-basin is located between the 76°20’0” and 77°0’0” E and 10°10’0” and 10°30’0” N. The present study area starts from Vazhachal10°17’18.34N and 76°31’42.18E (400m above sea level) to Vynthala10°11’33.75N and 76°20’07.24E (Sea level). The length of the river studied is 55km i.e. 38% of the total river length (145.5 km). Upstream from the study area is the dense forest area around the Vazhachal region. The sampling stations along the study areas are shown in Table 1.

2.2. Sample Collection

Samples were collected in 1000 ml HDPE bottles for determination of all the parameters except Total Coliform (TC). The plastic bottles were rinsed with 1M HCl and then with distilled water. The bottles were also rinsed thrice with water sample before collection. The collected samples were capped tightly and placed in a cooler box with ice for transportation to the laboratory [12]. Sterilized glass bottles were used for collecting water samples of TC.

| Site | Place | Activity | longitude and latitude |
|------|-------|----------|------------------------|
| I    | Vazhachal | Tourist spot, Forest division | 10°17’18.34N-76°31’42.18E |
| II   | Vettilappara | Water theme park, Agricultural area | 10°17’33.86N-76°28’39.32E |
| III  | Kanjirappilly | Paper mill (Presently not working) | 10°18’14.59N-76°23’48.29E |
| IV   | Pariyaram | Bathing, Skol breweries | 10°17’31.65N-76°21’26.06E |
| V    | Chalakudy | Major town, KWA pumping station, cattle farms | 10°17’41.04N-76°20’11.06E |
| VI   | Vynthala | KWA drinking water pumping station | 10°11’33.75N-76°20’07.24E |
| VII  | Pulikkakadavu | DCP plant, agriculture area | 10°14’01.75N-76°19’53.29E |
| VIII | Palapuzhakadavu | Bathing, residential area, Agriculture area | 10°14’01.75N-76°20’10.96E |
All the samples were labelled by site name and date to avoid any error between sample collection and analysis. The samples were stored in a refrigerator at 4°C immediately upon arrival at the laboratory.

2.3. Analytical Methods

All the eight water quality parameters such as Total dissolved solids (TDS), Temperature (T), Electrical conductivity (EC), Nitrates (NO$_3^-$), Sulphates (SO$_4^{2-}$), Total Coliforms (TC), Total Hardness (TH), and Chlorides (Cl$^-$), shown in Table 2, were analyzed in the laboratory using American Public Health Association’s (APHA) standard methods [21,22]. All the values except EC and TC are expressed in mg/l. EC expressed in the unit μmhos/cm and TC in MPN/100ml. WQI is a dimensionless index. The analyzed values were compared with Indian water quality standards (IS.10500; 2012).

Table 2. Standard methods of analysis as per APHA

| SI.No. | Parameter      | Method of analysis              |
|-------|----------------|---------------------------------|
| 1     | EC             | Conductivity meter in water Analyser |
| 2     | Temperature    | Hg Thermometer                  |
| 3     | TDS            | Electronic Water Analyser       |
| 4     | Chloride       | Argentometry                    |
| 5     | Total Hardness | Titrimetric (EDTA)              |
| 6     | Sulphate       | Spectrophotometer               |
| 7     | Total Coliform | Membrane filtration method      |
| 8     | Nitrates       | Cadmium reduction Method        |

2.4 Model Development Using Fuzzy logic in MATLAB

Determination and prediction of water quality index models of river water using eight input parameters T, EC, TDS, Cl$^-$, TH, NO$_3^-$, TC and SO$_4^{2-}$ was developed using fuzzy inference system. Mamdani model using trapezoidal membership functions and sigmoid membership functions were applied to develop fuzzy WQI prediction models. The steps comprises in fuzzy model development is shown in the Figure 1. By finding WQI based on AIM, it was found that there is a strong relationship between all the input parameters with the output parameter WQI [13]. In order to increase system accuracy, a large number of membership functions overlapping are required. Sigmoid membership functions were found to increase the model accuracy of environmental problems. The fuzzyfier takes input values and determines the degree to which they belong to each of the fuzzy set through these membership functions [14]. For any given indicators, the rules are derived automatically based on the number of variables as well as the membership functions.

The rules were developed for each factor by MATLAB programming which can execute a series of statements [15]. Further values corresponding to the input variables generated were subdivided and recorded into groups with specific ranges and symbols such as E, G, P, VP, Desirable, Acceptable, and Not acceptable. This helped in creating the membership functions for fuzzy modelling within the permitted range. Trapezoidal and Sigmoid membership functions of each parameter were generated for developing water quality index.
2.4.1. Fuzzification. Fuzzification is the process of transforming the input data with the rule conditions to determine how the conditions of each rule will match that particular instance. The first step of the modelling is to define the inputs and determine the degree to which each linguistic term belongs to each of the appropriate fuzzy sets and that too through membership functions [16]. In this work, the fuzzy sets were quantitatively defined by trapezoidal membership functions [17] and by sigmoid membership functions. These membership functions were determined by the expert’s knowledge and Indian drinking water quality standard IS: 2012. The steps involved in the model development process are described below as diagrammatically in the Figure1. Fuzzy trapezoidal water quality index (FTWQI) and Fuzzy Sigmoid Water Quality Index (FSWQI) are developed with overlapping for all eight input parameters and WQI (output) in the fuzzy system. The fuzzyfier develops the rules to map an input space to output space ‘if-then’ statements called rules. Aggregation is the process by which the fuzzy steps are combined into a single fuzzy set [18] which are FTWQI and FSWQI. For the aggregation process’ maximum method was used in fuzzy logic [16].

2.4.2. Defuzzification. The last step for fuzzy model development is defuzzification [19]. Related to this, the defuzzification fuzzy set assigned to a control output variable at first, and then they get to transform into crisp values by comparing all the inputs within the range by centroid method of calculation, which returns the centre of the area under the membership functions. Predicted WQI will be obtained as an output crisp value from the defuzzifier [20]. All the fuzzy operations were carried out using MATLAB R2015a software [Mathworks, 2015].

2.5. Validation of the Models

Fuzzy based water quality index was depended on the linguistic terminology in the form of fuzzy rules. Hence, the models can be extended to any combinations of input parameters, which are influencing the level of output parameter directly or indirectly. Ten sets of values of WQI were taken for the validation of the model as shown in Table 3. The WQI values obtained from these two fuzzy models were compared with calculated values of WQI based on AIM using the given equations 1 to 4 [12].

\[
WQI = \sum Qn Wn
\]  \hspace{1cm} (1)

Water quality rating (Qn) of each parameter is calculated using the relationship

\[
Q_n = \frac{100 \times (V_n - V)}{(V_{\text{ideal}} - V)}
\]  \hspace{1cm} (2)

Here V_n is the observed value of n^{th} parameter, V is the standard value of each parameter and V_is the ideal value of the n^{th} parameter in pure water. [19,13]

\[
Wn = \frac{k}{V_n}
\]  \hspace{1cm} (3)

Where Wn is unit weight, n is the number of standard values.
Predicted values of FTWQI and FSWQI were tabulated to evaluate their performance. Interestingly, the models were checked to be agreeing with the experimental findings statistically with average absolute relative error (AARE) and root mean square error RMSE values using (eqn.5) and (eqn.6).

\[
AARE\% = \frac{1}{n} \sum_{i=0}^{n} \frac{(E_i - P_i)}{E_i} \times 100
\]

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=0}^{n} \frac{(E_i - P_i)^2}{E_i}}
\]

Where \(E_i\) is calculated value of WQI using AIM, \(P_i\) is the predicted value obtained from the FTWQI and FSWQI models.

3. Results and discussions

3.1. AIM based WQI

The concentrations of all the eight water quality parameters measured experimentally in the laboratory and calculated the values of WQI using AIM were consolidated in a single pivot table. Then all the parameters were analysed statistically based on the season. The statistically analyzed values of all the input parameters and their permissible limits as per Indian standard are shown in Table 3. Most of the parameters analyzed in the river water samples were found to be within the permissible limits according to the drinking water standards. The bacteriological contamination (TC) is significantly high along the area of study in Chalakudy River. So, by keeping the standard value for TC as 50 CFU/100ml (in the absence of alternate sources), Water quality indices of Chalakudy River were developed by AIM. The seasonal comparison was performed using the average values of WQI calculated using AIM as shown in the Figure 2.

### Table 3. Statistics of experimentally analyzed parameters used for the development of WQI

| Parameter  | Permissible limit | Summer season | Monsoon Season | Winter Season |
|------------|-------------------|---------------|----------------|---------------|
|            | Max | Mini | Mean | SD | Max | Mini | Mean | SD | Max | Mini | Mean | SD |
| Cl⁻, mg/l  | 250  | 125.6 | 1.43 | 27.79 | 25 | 178.6 | 58 | 100.37 | 38 | 42.25 | 3.55 | 24.41 | 14.81 |
| EC μmhos/cm| 300  | 287  | 41.33 | 94.24 | 57 | 390.4 | 87 | 242.36 | 82 | 78.67 | 6.3  | 52.41 | 22.93 |
| NO₃⁻, mg/l | 45   | 7.89 | 0.003 | 1.25 | 1.7 | 3.67 | 0.66 | 1.84 | 1   | 1.7  | 0.21 | 0.99  | 0.51  |
| SO₄²⁻, mg/l| 250  | 2.43 | 0.067 | 1.14 | 0.8 | 5.4  | 0.45 | 2.18 | 1.5 | 1.7   | 0.07 | 0.79  | 0.53  |
| T, °C      | -    | 32.8 | 29.6 | 31.18 | 1 | 30.5 | 28 | 29.46 | 0.8 | 31   | 28.9 | 30.4  | 0.89  |
| TC, MPN/100 ml | 50 | 2900 | 210 | 876.9 | 572 | 3800 | 1200 | 2415 | 839 | 1780 | 560 | 1071  | 511.82 |
| TDS, mg/l  | 500  | 360 | 43   | 109.4 | 72 | 350  | 83.7 | 223.23 | 78 | 172.84 | 62.66 | 99.18 | 39.12 |
| TH, mg/l   | 150  | 183.55 | 0.02 | 67.13 | 47 | 218.6 | 68.9 | 141.78 | 47 | 142.6 | 6.9  | 69.69 | 43.21 |

During the period of study, WQI of Chalakudy River was found to be between 163 to 867 considering TC standard values as 50 CFU/100 respectively. Classification of water quality based on WQI is shown in Table 4. Based on the classification [19], most of the samples lies within the class ‘not acceptable’ for drinking purpose especially during monsoon season. This is mostly due to the
presence of high values of TC. During the period of study, variations in all other parameters had not affected WQI much. Vazhachal, Vettilappara and Pariyaram sites had less TC values as compared to Chalakudy, Vythala, Pulikkakadavu and Palapuzhakadavu sites and their mean values of WQI were in turn low. Remarkably all other values used for computing WQI except TC, at all the sites, was found to be within the permitted standards meant for human consumption. But TC is an essential and important parameter for the drinking water quality assessment of human concern because this parameter is an indication of disease-causing pathogens. And it was identified that total coliform is the major pollutant which worsens river water quality.

![Seasonal variations of WQI](image)

**Figure 2.** Seasonal variations of WQI

| Table 4. Classification of water quality according to WQI value |
|-----------------------------|------------------|
| WQI Value                  | Water quality    |
| WQI < 50                   | Excellent        |
| 50 < WQI < 100             | Good             |
| 100 < WQI < 200            | Poor             |
| 200 < WQI < 300            | Very Poor        |
| WQI > 300                  | Not Acceptable   |

3.2. Comparison of FTWQI and FSWQI

Fuzzy logic was used to develop FTWQI model and FSWQI model. Steps involved in Mamdanifuzzy modeling for water quality using trapizoidal and sigmoid membership functions are shown in Figures 3(a-i) and Figures 4(a-h). The performance of these two models in predicting water quality indices of Chalakudy river water during various seasons, the values obtained from FTWQI are closer to the WQI values obtained from AIM than the values FSWQI. Only difference in the type of membership functions were selected for the construction of these two fuzzy models. But as per the errors (AARE and RMSE) obtained during the validation process shown in Table 5. FSWQI showed an AARE and RMSE as 0.57 and 0.86 respectively. The predicted WQI value by FTWQI was found very much closer to the actual calculated values with AARE 0.0214 and RMSE 0.318 than FSWQI.
Figure 3. Fuzzy trapezoidal membership functions of (a) NO$_3^-$ (b) Cl$^-$ (c) TDS (d) EC (e) TC (f) SO$_4^{2-}$ (g) T (h) TH and (i) WQI.
Figure 4. Fuzzy Sigmoid membership functions of (a) NO$_3^-$ (b) Cl$^-$ (c) TDS (d) EC (e) TC (f) SO$_4^{2-}$ (g) T (h) TH and (i) WQI
Table 5. Validation of FTWQI and FSWQI

| SI NO | AIM WQI | FSWQI | AARE | RMSE | FTWQI | AARE | RMS |
|-------|---------|-------|------|------|-------|------|-----|
| 1     | 197     | 190   | 3.55 | 0.248 | 195   | 0.01 | 0.0203 |
| 2     | 60      | 55    | 8.33 | 0.416 | 58    | 0.033 | 0.0666 |
| 3     | 59      | 53    | 10.16| 0.61  | 55    | 0.067 | 0.0276 |
| 4     | 157     | 147   | 6.36 | 0.636 | 155   | 0.0127 | 0.025 |
| 5     | 139     | 128   | 7.91 | 0.87  | 135   | 0.0028 | 0.115 |
| 6     | 111     | 105   | 5.4  | 0.324 | 112   | 0.009 | 0.009 |
| 7     | 469     | 430   | 8.31 | 3.243 | 456   | 0.0277 | 0.3603 |
| 8     | 537     | 521   | 2.97 | 0.476 | 535   | 0.0037 | 0.0074 |
| 9     | 510     | 500   | 1.96 | 0.196 | 504   | 0.0117 | 0.0705 |
| 10    | 729     | 712   | 2.33 | 0.396 | 722   | 0.0096 | 0.067 |

0.573 0.86 0.0214 0.318

4. Conclusions

In this study, two reliable fuzzy logic models were proposed to predict the water quality index of surface water. These models are named as Fuzzy Trapezoidal Water Quality Index (FTWQI) and Fuzzy Sigmoid Water Quality Index (FSWQI). The mamdani models with trapezoidal and Sigmoid membership functions using MATLABR2015a is found to be an efficient numerical models to predict the WQI level of the surface water. Fuzzy logic was used to solve the nonlinearity and uncertainty in the environmental problems. Hence, the models can be extended to any combinations of input parameters, which influence the level of WQI directly or indirectly followed by drinking water standards. FTWQI model was found to be agreeing with the experimental findings (AIM) statistically with an AARE and RMSE values 0.0214 and 0.318 respectively. FSWQI is also statistically agreeing with an AARE and RMSE values as 0.573 and 0.86 respectively. The classification of river water based on the values of WQI, most of the samples in the river lies within the class ‘not acceptable for drinking purpose’ without any treatment. This is mainly due to the presence of high values of Total Coliform. The water can be used for domestic purposes only after a proper disinfection processes. Significant decrease in the overall water quality of river water was observed during the period of study. After the flood in August 2018, trend of water quality of the river water was found drastically changed as compared with that of previous years. This had resulted in serious drinking water scarcity. It is high time for the formation of proper water management systems and rules to conserve river water.

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