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Fuzzy logic approach for the assessment of trophic state of water bodies

Sruthy G.S.[a], K.L. Priya[b,*], Athul M. Madhu[b], Suchith Chellappan[a], S. Adarsh[b], S. Haddout[c]

[a] *Department of Civil Engineering, UKF College of Engineering and Technology, Kollam, Kerala, India*
[b] *Department of Civil Engineering, TKM College of Engineering, Kollam, Kerala, India*
[c] *Department of Physics, Faculty of Science, Ibn Tofail University, B.P. 133 Kenitra, Morocco*

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ABSTRACT

Eutrophication has emerged as one of the main threats to surface water bodies. The parameters for assessing eutrophication are not generally measured regularly from the lakes of India as part of monitoring programmes and it is necessary to express the trophic status in terms of secondary indicator variables that are included in the routine analysis by the State/Central government. In this paper, the trophic status of Ashtamudi Lake has been studied, considering its international importance and socio-economic relevance. The cause and response variables such as total phosphorus, Secchi disc depth, chlorophyll-a and the secondary indicator variables such as pH, turbidity, DO, EC, Salinity, TDS and BOD were analysed during the pre-monsoon season. The lake was predominantly classified as eutrophic, with some areas coming under a hypereutrophic state. A comparison was made among the five methods of water quality index by the use of secondary indicator variables to identify the appropriate method for simulating trophic status and the WQI based on the logarithmic method considering pH, turbidity, DO and BOD was identified to predict the trophic state very well. Further, the application of numerical strategy such as fuzzy logic was used to determine water quality indexes and trophic status, which can define the quality of a water body as a consequence of the variation of environmental parameters. The developed approach was further validated by using historical data for the years 2013–2015, which were regularly monitored by the Kerala State Pollution Control Board. The trophic state predicted by the approach was found to be in agreement with that estimated using Carlson's method. Thus the developed model, based on secondary indicator parameters that are readily available from government agencies, can be used to assess the trophic state of lakes, thereby assisting policy makers to frame regulations to minimize eutrophication.

1. Introduction

Eutrophication is the enrichment of nutrients, mainly nitrogen and phosphorus, in water bodies. United Nations Environmental Protection (UNEP) reported that globally 30–40% of lakes and reservoirs show a tendency towards varying degrees of eutrophication (Farley, 2012). It is mainly caused due to human activities, increased land usage and the application of fertilizers, which is a major source of nutrients. Due to natural processes like flood, heavy runoff causes these nutrients to enter into the water bodies which may further result in eutrophication (Yang et al., 2008). It severely deteriorates water quality leading to increased turbidity, cyanobacterial blooms, loss of biodiversity, health hazards, diminishing aquatic growth caused by depletion of oxygen, and foul taste and odour (Havens, 2008). Increased phytoplankton biomass leading to algal blooms, venomous or poisonous plant species, raised macro algae biomass, reduced transparency of water, depletion of oxygen or hypoxia, slashed species diversity and also the changes of dominant biota are some of the major ecological impacts of eutrophication. This, in turn, creates socioeconomic challenges, such as increased water treatment costs, difficulties in fulfilling the criteria for disinfection by-products, and aesthetic damage (Chislock et al., 2013). Eutrophication management is, hence, the primary step towards the conservation of water bodies.

Eutrophication has been recognized as a challenge in freshwater systems for several years, but concern about the widespread occurrence of eutrophic conditions in estuarine systems has only been increasing in the last three decades. For a proper formative assessment of eutrophication, water resources must be categorized into various trophic states followed by quantitative analysis of all those states. Many researchers employed various criteria to measure the trophic status of lakes through the quantification of the trophic state index (El-Serehy et al., 2018).

Palmer (1969) developed two pollution indices on the basis of

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* Corresponding author.
E-mail address: klpriyaram@gmail.com (K.L. Priya).

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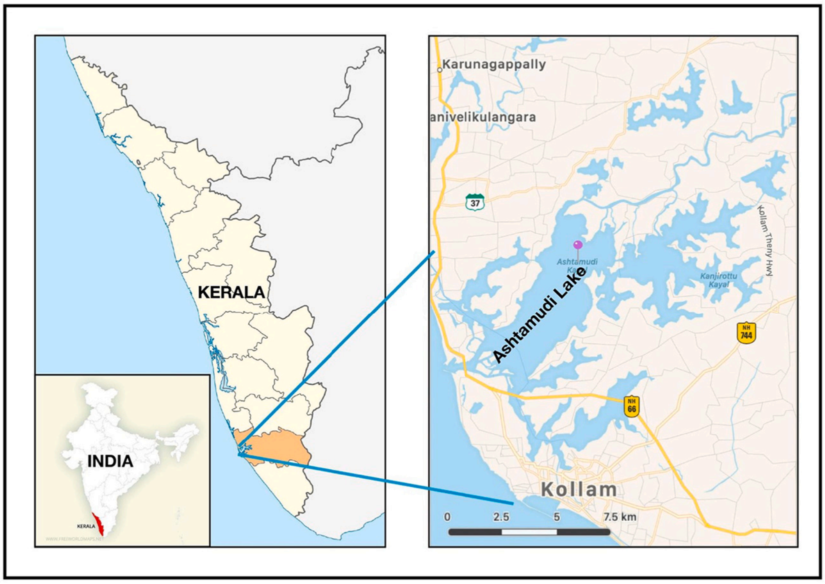

Fig. 1. Location map of the study area.

available knowledge and perspectives about organic pollution resistance, namely the Palmer algae genus organic pollution index and the Palmer algae species organic pollution index. Carlson's Trophic State Index (CTSI) is commonly accepted and applied to the lakes, where freshwater bodies have been categorized into four potential trophic states namely, oligotrophic, mesotrophic, eutrophic, and hyper-eutrophic based on chlorophyll-a (chl-a), total phosphorus (TP) and Secchi disc depth. Several criteria like nutrient concentration, species composition, transparency and various measures of biomass are analysed for determining trophic state of water bodies. Aizaki et al. (1981) evaluated the relationships between the index values and the parameters related to lake trophic status by examining the possibility of the application of Carlson's index on Japanese lakes. Even though Carlson's index is used widely, there arises a confusion among the assessment of three different values of trophic state index (TSI). Osgood (1982) strengthened this by using variations in the three indexes to help determine the lakes' water quality. Canfield and Hodgson (1983) used data from Florida lakes to develop models for prediction of chl-a concentrations and Secchi depth. The model provides unbiased estimates of chl-a and Secchi depth across a wide variety of lake types.

Vollenweider et al. (1998) proposed a new trophic index (TRIX) in order to categorise the trophic state of inland waters focusing chl-a, total nitrogen, pHosphorous, oxygen saturation and mineral, where the index is scaled from 0 to 10. Bricker et al. (2003) addressed management options in estuaries by the development of an index for the assessment trophic status of estuaries namely, ASSETS by ranking its eutrophication status. Further studies in Pernambuco, Brazil (Alves et al., 2013) and Guanabara Bay, Rio de Janeiro, Brazil (Santos, 2015) using TRIX indicated that the performance of TRIX is better than the TSI using pH and DO developed by O'Boyle et al. (2013) as these estuaries have good sea water exchange, but the application of TRIX is localized. Gupta (2014) further modified the index by adopting nitrite-nitrogen, chl-a and Secchi disc depth for Chilka Lagoon. In the Northern Beibu Gulf of China, Lai et al. (2014) conducted a comparative study between TRIX and ASSETS and concluded that TRIX was an indicator of organic process status for the assessment of eutrophication, while ASSETS demonstrated sensitive capacity in coastal areas.

An updated lake trophic classification model by Farnaz Nojavan et al. (2019) was presented recently that used a Bayesian method which constitutes a proportional odds logistic regression (POLR). This model operates on the current categorization of trophic status and reassesses the creation and classification methods for the TSI, thereby rethinking the classification and index for the lake trophic state.

Only a limited number of studies has been conducted on Kerala Lakes for assessing the trophic status and most of them followed the classical Carlson TSI (Carlson, 1977) approach. Sheela et al. (2011a) performed the estimation of the trophic state of Aakkulam-Veli Lake system using Carlson TSI. Sheela et al. (2011b) used Indian Remote Sensing imagery to analyse the trophic status profile based on Secchi depth and chlorophyll-a of the Akkulam-Veli Lake. Neena et al. (2019) determined the trophic status of Vellayani freshwater lake in Thiruvananthapuram district using Carlson TSI considering chlorophyll-a, total phosphorus and Secchi disk depth as parameters. Generally, the data collection of response variables such as chl-a and Secchi depth is challenging and not monitored regularly in the lake systems of Kerala, while water quality parameters are monitored regularly and readily available with Kerala State Pollution Control Board (KSPCB). Hence developing TSI based on the secondary indicator variables (water quality parameters) is highly essential for monitoring the trophic status of water bodies.

Water Quality Index (WQI) may be a valuable and distinctive rating employing a specific phrase that is valuable in choosing an appropriate recovery strategy to meet the problems involved. Horton (1965) was the first to propose the concept of indices to represent gradations in water quality in which he used the method of arithmetical aggregation to evaluate WQI. Unlike Horton (1965), Brown et al. (1970) also used simple arithmetic weight, but without the variables that multiply. The National Sanitation Foundation (NSF) sponsored this initiative by choosing the water quality parameters using the Delphi methodology (Dalkey, 1969). Dinius (1987) established an index with a diminishing range backed by multiplicative aggregation, including measures expressed in percentage of excellent quality of water that adore 100%. Extensive testing was also conducted by Helmer and Rescher (1959), Dalkey and Helmer (1963), making improvements to the Delphi system (Dalkey, 1969). McClelland (1974) introduced the geometric mean method of rating to WQI because he had been anxious about the process of eclipsing, a characteristic process in which the numerical mean lost tolerance to variables of low value. Later, Dojlido et al. (1994) used the harmonic mean to evaluate the WQI, in which there is no usage of weights for the individual indicators.

WQI applications for surface or groundwater are far more than that of coastal waters. In 2012, the USEPA evaluated the quality of coastal water using an index backed by the percentage of quality parameters

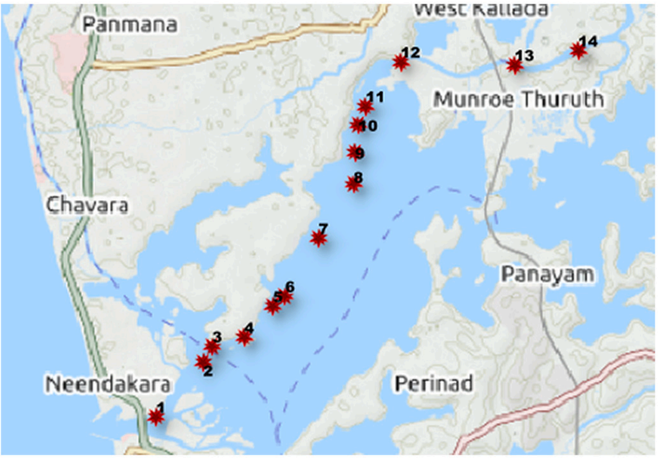

Fig. 2. Sampling stations adopted for the study.

ranging from excellent to poor (USEPA, 2012). Nguyen et al. (2013) suggested an updated mathematical WQI for Ha Long Bay, Vietnam, while Darko et al. (2013) used the Solway model for coastal waters in Ghana to measure WQI. Throughout modelling advanced environmental issues, there exists a tangle in making precise statements of inputs and outputs; at this time of view, fuzzy logic plays a major role in changing advanced input variables into easy output (McKone and Deshpande, 2005). Pereira et al. (2012) compared the WQI acquired through the application of the fuzzy sets with the strategy planned by the National Sanitation Foundation. By using fuzzy logic, de Oliveira et al. (2014) developed a study to assess the index of crude water quality. Gorai et al. (2016) used eleven physicochemical variables and developed a groundwater analysis study through the application of fuzzy logic. Li et al. (2016) explained the water quality of the Qu River in China using fuzzy logic which relied on Principal Component Analysis methodology to choose the most important parameters and stress how fuzzy set theory generates an additional correct result compared to various indices in the study. In general, the fuzzy logic provides several blessings in comparison to various strategies for evaluating water quality ratings, stressing the need for environmental variables not to validate weights. For this reason, formal reasoning was implemented for the production of this work, for each one of the WQI and as such the TSI, and a much stronger analysis of the large body of water was permitted in an extremely quick yet additional detailed approach.

The main objective of the study is to analyse the trophic state of Ashtamudi Lake using the readily available secondary indicator parameters. The trophic state of Ashtamudi Lake is estimated using Carlson TSI based on cause and response variables such as TP, Secchi disc depth and chlorophyll-a. An approach based on water quality index based on secondary indicator parameters such as pH, DO, turbidity and BOD is proposed for representing the trophic state of water bodies. An attempt has been made to develop a fuzzy inference system to determine WQI and TSI, which can define the trophic state of a water body as a consequence of the variation of environmental parameters. The proposed approach can be used to predict the TSI of a water body using secondary indicator variables that are regularly monitored by Government agencies. This will help in identifying the trophic state of the water body, thereby assisting policy makers to frame regulations to minimize eutrophication.

1.1. Study area

Ashtamudi Lake, Kerala's second largest and deepest estuarine ecosystem, is situated in the district of Kollam, Kerala (India), with an area of around 32 km^2. The lake lies between 8° 53′- 9° 2′N latitude and 76° 31′– 76° 41′E longitude. The location map of Ashtamudi Lake is shown in Fig. 1. Ashtamudi wetland is included in the list of wetlands of worldwide importance, which is defined by the Ramsar Convention on wetland protection which property use. Ashtamudi is recognized as a coastal estuarine lake of brackish water (MOEF Classification).

Data available on the ecological and hydrological parameters of Ashtamudi Lake showed the abundance of phytoplankton (Threasimma and Nair, 1980). Divakaran et al. (1982) reported the seasonal variations in the lake ecology. In addition to this study, the mode of distribution of major organic and inorganic nutrients in Ashtamudi backwater, its general ecology, ecology of grass beds, fishery resources, benthic macrofauna sediments, mineral metals, heavy metals and their seasonal variations were also reported (Nair et.al (1983a, b and c); Nair et al., 1984a, 1984b). Numerous studies are available regarding the features of Ashtamudi Lake. The effects of man-made changes in the mangrove ecosystem of Ashtamudi were reported by Mohandas et al. (1994). Biodiversity status and restoration measures of the Ashtamudi backwater systems (Bijoy and Abdul, 1996), nutrient dynamics of Ashtamudi Lake (Sujatha et al., 2009) and sedimentary characteristics along the Ashtamudi estuarine system (Soumya et al., 2011) and analysis of the effluents discharged to Ashtamudi Lake from China clay industry (Suma et al., 2012), were also well documented. From the above observations, it is presumed that the lake is now suffering from the deterioration of ecosystem and water quality, accumulation of sediments, waste disposal, eutrophication and above all a loss of the aesthetic value. Thus monitoring programs are necessitated so as to assess the trophic status and water quality of this lake system thereby imposing appropriate management measures for the conservation of the lake.

2. Materials and methods

2.1. Water sampling and analysis

Water samples were collected at regular intervals from fourteen locations in the Ashtamudi Lake, stretching from Neendakara harbour area to the Kallada river mouth (i.e. from saline zone to fresh water zone) during the pre-monsoon season (March 2020). Fig. 2 shows the location of sampling stations. The water samples were analysed for pH, turbidity, electrical conductivity (EC), salinity, total dissolved solids (TDS), total phosphorus (TP), dissolved oxygen (DO), biochemical oxygen demand (BOD), Secchi depth and chlorophyll-a (chl-a). The analyses of water samples for different physico-chemical parameters were followed from APHA (1999). A small controller-based instrument (Water Analyser-371, by Systronics) was used for the measurement of pH, salinity, turbidity, EC, temperature in water sample each one at a time. A standard 20 cm diameter Secchi disk with alternating black and white quarters in it was used to measure Secchi depth. Winkler's titrimetric analysis was used for analysing the values of DO and BOD (after 5 days), wherein titration with sodium thiosuphate was done (in the presence of starch as the indicator) to the sample to which manganeous sulphate and potassium iodide azide were added and subsequently concentrated sulphuric acid was added. Persulfate digestion process followed by the ascorbic acid method is used for the analysis of TP. Chl-a was calculated using the acetone extraction process, where different volumes of water samples were filtered through pre-washed Whatman GF / F 0.47 μm diameter filters using an electric filtration unit. Extraction was done using 90% acetone 5 mL, by measuring the absorption at 665 nm and 750 nm wavelength, chl-a absorption was then calculated using a UV / visible spectrophotometer (Type: AU 2701, by Systronics).

2.2. Estimation of trophic state index

The trophic status of Ashtamudi Lake was determined using the Carlson (1977) index. Carlson's TSI is a popular method of expressing the trophic condition of a lake and uses three variable estimates for protoctista biomass (Chlorophyll-a, Secchi Depth, and Total Phosphorous). Using the equations proposed by Carlson (1977), TSIs are

Table 1
Trophic classes adopted for the study.

Chl-a (μg/L)	TP (μg/L)	SD (m)	CTSI	Trophic Class
0–2.6	0–12	> 8–4	< 30–40	Oligotrophic
2.6–20	12–24	4–2	40–50	Mesotrophic
20–56	24–96	2–0.5	50–70	Eutrophic
56–155+	96–384+	0.5 < 0.25	70–100+	Hypereutrophic

Table 2
Standards for coastal water quality variables.

S. No.	Parameter	Standard Value
1	pH	6.5–8.5
2	Dissolved Oxygen (DO)	4.0 mg/L
3	Turbidity	5 NTU
4	Biochemical Oxygen Demand (BOD_5) (5 days at 20 °C)	< 3 mg/L
5	Electrical Conductivity (EC)	50 mS/cm
6	Salinity	35 ppt
7	Total Suspended Solids (TSS)	80 mg/L

Table 3
Statistical summary of parameters analysed.

Parameters	Min Value	Max Value	Mean	Median	Standard Deviation
Salinity (ppt)	6.35	28.70	16.57	14.90	7.82
pH	7	8.3	8.03	8.24	0.44
DO(ppm)	3.00	7.10	4.99	5.16	1.02
Conductivity (mS/cm)	10.34	44.44	33.15	36.44	11.92
Turbidity (NTU)	0.71	2.70	1.39	1.25	0.48
BOD (mg/L)	1.97	6.00	4.45	4.55	0.94
Chl-a (mg/m^3)	1.50	8.13	4.10	3.94	1.57
TP (mg/m^3)	95.00	376.54	214.66	192.08	87.61
Secchi Depth (m)	0.20	3.50	1.19	1.30	0.94

Table 4
Carlson TSI and trophic status of 14 sites at Ashtamudi Lake.

Sites	TSI (SD)	TSI (TP)	TSI (Chl-a)	TSI	Status
1	83.19	86.34	48.14	72.56	Hypereutrophic
2	69.99	80.83	42.31	64.38	Eutrophic
3	83.19	83.89	45.35	70.81	Hypereutrophic
4	73.20	81.83	44.44	66.49	Eutrophic
5	73.20	78.35	41.73	64.43	Eutrophic
6	55.15	76.39	43.64	58.39	Eutrophic
7	54.16	78.79	44.49	59.15	Eutrophic
8	54.16	79.06	43.64	58.95	Eutrophic
9	57.37	88.68	45.25	63.77	Eutrophic
10	75.13	89.68	51.16	71.99	Hypereutrophic
11	54.65	85.82	45.91	62.13	Eutrophic
12	51.53	74.77	41.79	56.03	Eutrophic
13	48.64	71.67	40.34	53.55	Eutrophic
14	41.95	69.82	34.58	48.78	Mesotrophic

Table 5
Parameter combinations for WQI calculation.

Water Quality Indices	Parameter Combinations
Arithmetic WQI	Salinity, pH, DO, BOD, EC
Multiplicative WQI	Salinity, pH, BOD, EC
Unweighted Arithmetic WQI	Salinity, pH, DO
Unweighted Multiplicative WQI	Salinity, pH, EC
Logarithmic WQI	pH, DO, BOD, EC
	pH, BOD, EC
	pH, DO, EC
	pH, DO, BOD, Turbidity
	pH, DO, Turbidity
	pH, BOD, Turbidity

Table 6
Comparison of CTSI and WQI.

Sites	TSI	Trophic Status	WQI	Water Quality
1	72.56	Hypereutrophic	120.82	Very poor
2	64.38	Eutrophic	85.21	Poor
3	70.81	Hypereutrophic	100.37	Very poor
4	66.49	Eutrophic	92.24	Poor
5	64.43	Eutrophic	80.24	Poor
6	58.39	Eutrophic	85.44	Poor
7	59.15	Eutrophic	82.90	Poor
8	58.95	Eutrophic	91.02	Poor
9	63.77	Eutrophic	86.34	Poor
10	71.99	Hypereutrophic	101.17	Very poor
11	62.13	Eutrophic	91.44	Poor
12	56.03	Eutrophic	76.71	Poor
13	53.55	Eutrophic	77.66	Poor
14	48.78	Mesotrophic	50.19	Moderate

measured in a water body as a whole, and are delineated as follows:

$$\mathrm{TSI} - \mathrm{TP} = 14.42\ ln\ (\mathrm{TP}) + 4.15 \tag{1}$$

$$\mathrm{TSI} - \mathrm{SD} = 60\text{–}14.41\ ln\ (\mathrm{SD}) \tag{2}$$

$$\mathrm{TSI} - \mathrm{Chl} - a = 9.81\ ln\ (\mathrm{Chl} - \mathrm{a}) + 30.6 \tag{3}$$

where, TSI-TP represents TSI referred to Total Phosphorus, TP is the Total phosphorus (μg/ L), TSI-SD represents TSI referred to Secchi Depth, SD is the Secchi Depth (m), TSI- Chl-a denominates TSI referred to chlorophyll-a and Chl-a is Chlorophyll-a (μg/ L). Table 1 demonstrates the classification of trophic state based on Carlson's TSI.

2.3. Water quality indices

WQI can become difficult to interpret if too many factors are considered. Therefore, a collection of parameters that, together, mirror the water quality are most appropriate. In this study seven parameters that are vital for marine and coastal waters were selected. The standard values of water quality parameters as per US EPA (1986a, 1986b) for aquatic and coastal water are given in Table 2.

For comparison of coastal water quality with the trophic condition of the lake, five entirely different water quality indices are thought-out. Those include arithmetic water quality index, multiplicative water quality index, unweighted arithmetic water quality index, unweighted multiplicative water quality index and logarithmic water quality index.

The arithmetic water quality index (WQI_A) was originally proposed by Horton and this can be primarily the weighted mean value within the following form:

$$WQI_A = \sum_{i=1}^{n} w_i q_i \tag{4}$$

where n is the number of variables, w_i is the relative weight of the ith parameter such that $\sum_{i=1}^{n} w_i = 1$and q_i is the quality rating of ith parameter. In this case, WQI value of up to 30 has an excellent water quality, 30–60 has a good quality, 60–90 has a poor quality and above 90, the lake will be of very poor water quality.

The multiplicative water quality index is a multiplicative form of index proposed by Brown et al. (1972). Later researchers have extensively utilized a weighted geometric mean value for aggregation. Here multiplicative water quality index (WQI_M) is outlined as follows:

$$WQI_M = \prod_{i=1}^{n} q_i^{w_i} \tag{5}$$

Here, WQI value of up to 40 has a very poor water quality, 40–60 has a poor quality, 60–80 has a good quality and between 80 and 100, the lake will be of excellent water quality.

The construction of the above two indices is based on the weight assigned as per the importance of water quality scenario. Such weights

Table 7
Validation of results from historical data.

Year	2013				2014				2015			
Months	WQI	Water Quality	TSI	Trophic State	WQI	Water Quality	TSI	Trophic State	WQI	Water Quality	TSI	Trophic State
January	–	–	–	–	81.08	Poor	58.01	Eutrophic	91.27	Poor	57.60	Eutrophic
February	84.49	Poor	50.42	Eutrophic	90.21	Poor	50.12	Eutrophic	89.45	Poor	50.63	Eutrophic
March	95.80	Poor	58.33	Eutrophic	64.97	Moderate	58.27	Eutrophic	81.93	Poor	57.16	Eutrophic
April	90.91	Poor	68.48	Eutrophic	87.52	Poor	58.14	Eutrophic	–	–	–	–
May	74.41	Poor	59.52	Eutrophic	97.39	Poor	55.98	Eutrophic	90.10	Poor	57.46	Eutrophic
June	79.15	Poor	59.92	Eutrophic	–	–	–	–	81.26	Poor	57.16	Eutrophic
July	96.15	Poor	57.46	Eutrophic	92.00	Poor	55.60	Eutrophic	82.33	Poor	57.01	Eutrophic
August	91.05	Poor	58.39	Eutrophic	92.65	Poor	54.50	Eutrophic	–	–	–	–
September	89.15	Poor	58.64	Eutrophic	83.41	Poor	55.40	Eutrophic	75.90	Poor	57.01	Eutrophic
October	76.98	Poor	56.52	Eutrophic	–	–	–	–	89.06	Poor	57.16	Eutrophic
November	85.30	Poor	57.01	Eutrophic	80.42	Poor	54.97	Eutrophic	85.02	Poor	55.48	Eutrophic
December	84.69	Poor	56.34	Eutrophic	93.92	Poor	55.40	Eutrophic	102.12	Very poor	55.98	Eutrophic

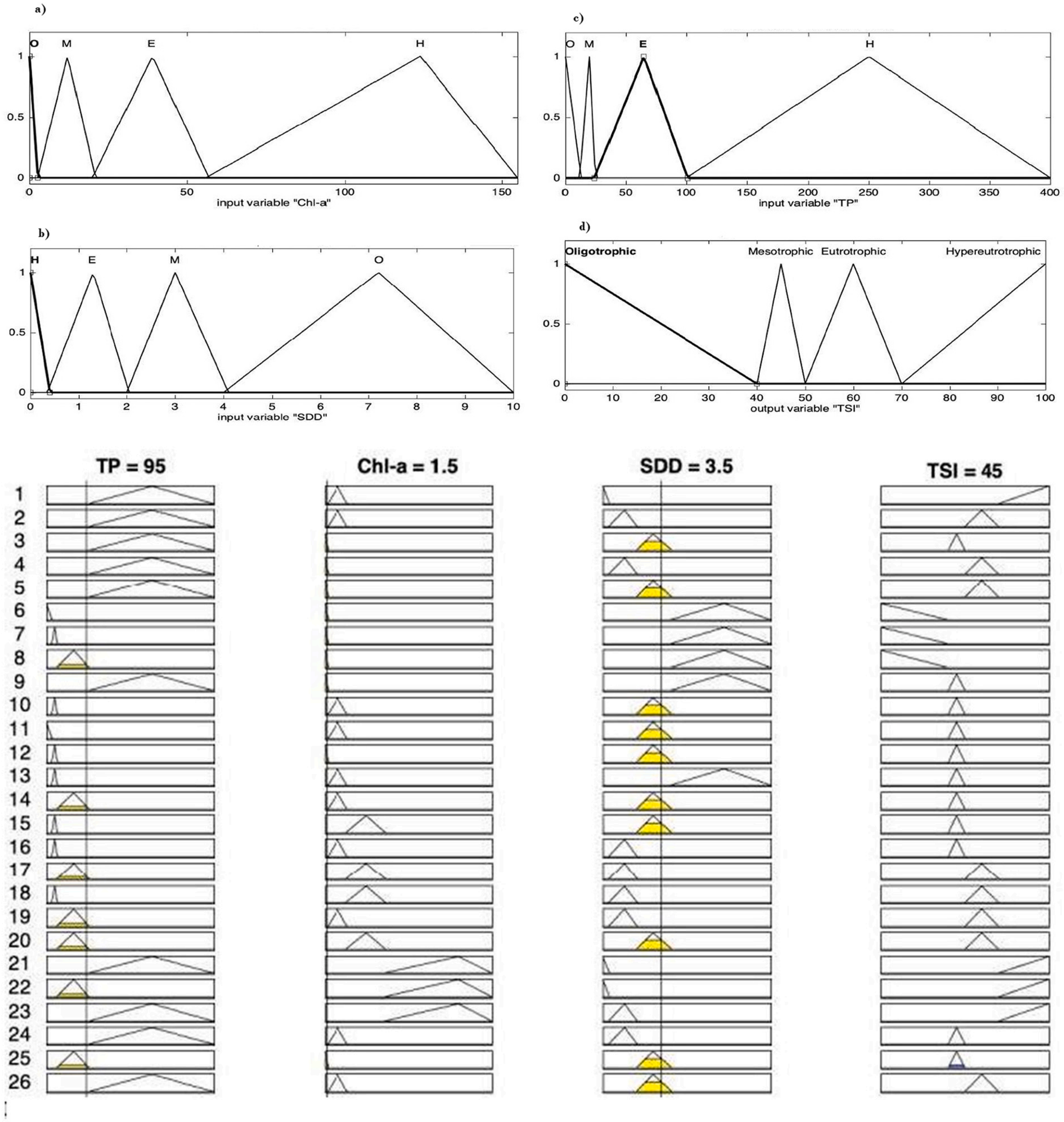

Fig. 3. A Membership functions of a) Chlorophyll-a; b) Secchi disc depth; c) Total Phosphorous; d) output variable, TSI. B Rules developed for FSI-TSI.

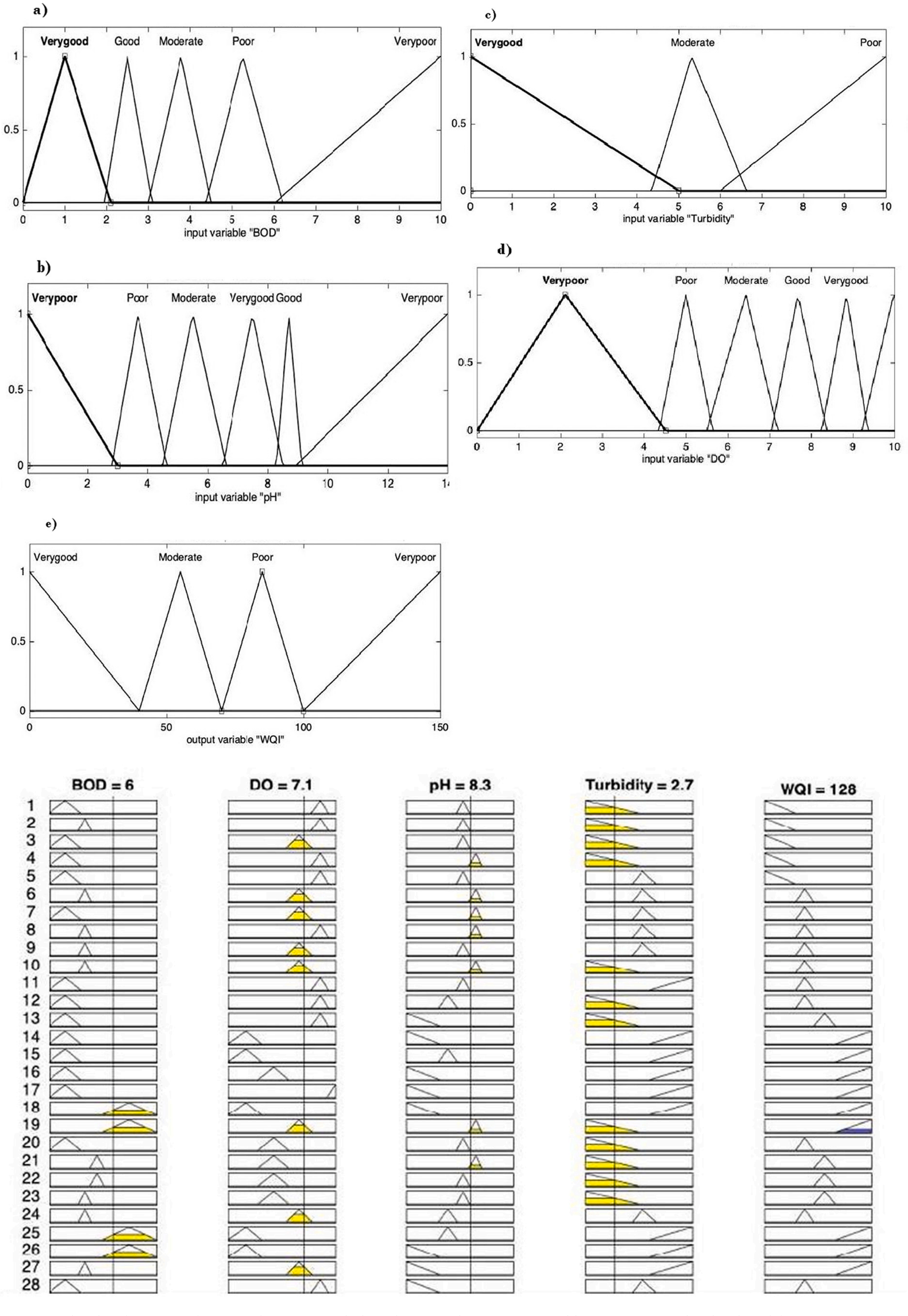

Fig. 4. Membership functions of a) BOD; b) pH; c) Turbidity; d) DO; and e) Output variable WQI (Top). Rules developed for FIS-WQI (Bottom).

Table 8

Comparison of FIS-TSI and FIS-WQI with observed Trophic Status.

Sites	FIS-TSI	Trophic status	FIS-WQI	Water quality	Observed trophic status
1	88	Hypereutrophic	128	Very poor	Hypereutrophic
2	65	Eutrophic	85	Poor	Eutrophic
3	87	Hypereutrophic	103	Very poor	Hypereutrophic
4	55	Eutrophic	85	Poor	Eutrophic
5	64	Eutrophic	85	Poor	Eutrophic
6	57	Eutrophic	85	Poor	Eutrophic
7	59	Eutrophic	85	Poor	Eutrophic
8	59	Eutrophic	84	Poor	Eutrophic
9	64	Eutrophic	85	Poor	Eutrophic
10	83	Hypereutrophic	126	Very poor	Hypereutrophic
11	72	Eutrophic	85	Poor	Eutrophic
12	59	Eutrophic	77	Poor	Eutrophic
13	61	Eutrophic	78	Poor	Eutrophic
14	45	Mesotrophic	55	Moderate	Mesotrophic

may be unnecessary in distinguishing between different quality situations in some cases. By the formulation of two extra indexes, this can be achieved. These indices are named as unweighted arithmetic water quality index ($\mathrm{WQI_{UA}}$) and unweighted multiplicative water quality index ($\mathrm{WQI_{UM}}$) and are formulated as given below:

$$WQI_{UA} = \left(\frac{1}{n}\right)\sum_{i=1}^{n} q_i \tag{6}$$

$$\mathrm{WQI}_{UM} = \left(\prod_{i=1}^{n} q_i\right)^{\frac{1}{n}} \tag{7}$$

The water quality rating of unweighted arithmetic WQI and unweighted multiplicative WQI method is same as that of weighted arithmetic WQI and multiplicative WQI, respectively.

Most recently used method for the analysis of WQI is the logarithmic method. The WQI strategy delineated by Tiwari and Mishra (1985) is comparable to the fundamental method of Horton. In this methodology, the power and numeral is employed, and is just for mathematical functions, so the power reduces the magnitude of the chemical variables and therefore the numeral is employed when, to broaden and create visible classification scale. The WQI using the standard and ideal absolute values for the coastal and marine waters is calculated by using the given formula:

$$MWQI = Antilog\sum_{i=1}^{n} w_i log_{10}(q_{ni}) \tag{8}$$

where w_i is the weightage factor of i^{th} parameter and is computed using the following equation:

$$w_i = \mathrm{K}/S_{ni} \tag{9}$$

Where K is the constant of proportionality which is derived from,

$$K = \frac{1}{\left(\sum_{i=1}^{n}\frac{1}{Sn_i}\right)} \tag{10}$$

Where Sn_i is the standard value of the i^{th} water quality parameter. The following formula can be used for calculating Quality rating (q_{ni}):

$$\mathrm{q_{ni}} = \{[(\mathrm{V_{actual}}-\mathrm{V_{ideal}})/(\mathrm{V_{standard}}-\mathrm{V_{ideal}})]*100\} \tag{11}$$

where q_{ni} represents the Quality rating of i^{th} parameter in n number of water quality parameters, V_{actual} is the observed concentration of water quality parameters from the field, V_{ideal} is the value of water quality parameter in ideal water, for example, the ideal value for all other parameters are zero except for pH and DO. Ideal value for pH is 7 and for DO is 8.24 mg/L at 25 °C and $V_{standard}$ represents the USEPA standard for the coastal water quality parameters.

2.4. Validation using historical data

The results are further validated with historical data of Ashtamudi Lake, collected from KSPCB. The water quality parameters monitored by KSPCB on a monthly basis include water temperature, dissolved oxygen (DO), pH, electrical conductivity, biochemical oxygen demand (BOD), nitrate, faecal coliform, total coliform, turbidity, phenolphthalein alkalinity, total alkalinity, chlorides, chemical oxygen demand (COD), total Kjeldahl nitrogen, ammonia nitrogen, hardness, calcium, magnesium, sulphate, sodium, total dissolved solids, total suspended solids, total fixed solids, phosphate, boron, potassium, fluoride. For calculating Carlson's TSI, Secchi depth and Chl-a are required, which were not monitored by KSPCB. Canfield (1983) and Canfield and Hodgson (1983) introduced models for the prediction of chlorophyll-a concentrations and Secchi depth using data of Florida lakes. Model yields unbiased estimates of chlorophyll-a concentrations and Secchi depth over a wide range of lake types. They developed a relationship between Secchi depth and nutrient loading and also between chlorophyll and nutrient loading and are given below:

$$ln\ \mathrm{Chl}-a\ \left(\mathrm{mg/m^3}\right) = -2.49 + 0.269{*}log_{10}(\mathrm{PO_4}) + 1.06{*}log_{10}(\mathrm{TN}) \tag{12}$$

$$ln\ \mathrm{SDD\ (m)} = 1.25\text{–}0.489{*}ln\ (\mathrm{Chl}-\mathrm{a}) \tag{13}$$

where Chl-a is the chlorophyll-a concentration ($\mathrm{mg/m^3}$), $\mathrm{PO_4}$ is the phosphate concentration ($\mathrm{mg/m^3}$), SDD is the Secchi disk depth (m) and TN is the total nitrogen concentration ($\mathrm{mg/m^3}$).

2.5. Fuzzy inference system

The modern water quality classification standards are based mainly either on compact sets of discrete limits or on continuous variables whose principles are strictly concrete to experts. Fuzzy sets make combining of these two methods possible (Silvert, 2000). Fuzzy logic typically includes fuzzification, implementation of the rule base to fuzzy knowledge, logical thought by presumption of fuzzy outcome and defuzzification of fuzzy output. Using ascertained values, the quality categories of the parameters are determined. To standardize the natural measuring scales of the standard parameter into a measurement of the standard degree (membership grade), the membership functions are used. Membership function matrices are developed and the rule bases are defined and the Mamdani approach is employed in defining fuzzy algorithmic rule. Using membership function grades, fuzzy community deductions are decided for the parameters. Finally, the fuzzy inferences of the groups are defuzzificated to obtain an index and in order to represent centre of gravity of the membership function, centroid strategies are used.

3. Results and discussion

3.1. General characteristics

The water samples were analysed for pH, turbidity, conductivity, salinity, total dissolved solids, total phosphorus, dissolved oxygen, BOD, Secchi depth and chlorophyll-a. The analyses of water samples for different physico-chemical parameters were followed from APHA (1999). A statistical summary of the parameters measured is given in Table 3.

Salinity varies from 28.7 ppt to 6.35 ppt, from the coastal region to the riverside. The variation of pH was between 8.3 and 7 and a lower pH was found near in the riverine region due to lower intrusion of saline water, accordingly the electrical conductivity has also varied proportionally with respect to salinity. Generally, sea water has a higher pH than a neutral condition. Similarly, a rise in turbidity and hence a decreased Secchi depth was observed at the upstream region as the influx of fresh water from the Kallada river causes resuspension of the bottom sediments. Also, a significant reduction in dissolved oxygen was observed near the riverine side due to the anthropogenic activities, retting of coconut fibres being predominant resulting in higher BOD values. Total phosphorus and Chl-a which are indicators of eutrophication in lakes and its concentration were higher near the fresh water side. But moving towards the ocean mouth, due to the dilution of saline water, the concentration of total phosphorus and chl-a shows a decrease in trend.

3.2. Trophic state index

The trophic state index of Ashtamudi Lake during the pre-monsoon season was estimated using Carlson's method. The average of respective TSI values corresponding to chl-a, Secchi depth and total phosphorus contribute to the overall trophic condition of the lake. Trophic state indices of different locations are shown in Table 4.

TSI based on Chl-a, SDD and TP estimated using Carlson's method ranged from 73 to 49 resulting in the categorization of Ashtamudi Lake into hypereutrophic to mesotrophic. Clarity of water gets reduced, as the concentration of TP content increases; this might ensue to the presence of considerable quantity of waste material, or because of the nutrients. However TSI values supported by Chl-a is incredibly low as compared to that of SDD and TP. Hyper eutrophication leads to the formation of dead zones below the surface, which further prevents life at lower depths and ends up in significant reduction of oxygen levels.

3.3. Water quality index

For comparison of coastal water quality with the trophic condition of the lake, five entirely different water quality indices were selected. Those include arithmetic index of water quality, multiplicative index of water quality, unweighted index of arithmetic water quality, unweighted index of multiplicative water quality and index of logarithmic water quality. In order to assess the water quality indices, different sets of parameter combinations were taken. The parameter combinations taken for calculating different water quality indices are given in Table 5.

Among the set of parameters, WQI using the combination of pH, DO, BOD and turbidity has shown some similarity to the measured TSI and hence these parameters were taken for calculating WQI. This combination of parameters was then used for analysing each of the five WQI stated earlier. The weighted arithmetic water quality index (WQI_A) indicates very poor quality for 12 sites and poor quality for 2 sites, unweighted arithmetic water quality index (WQI_{UA}) indicates very poor quality for 4 sites and poor quality for 10 sites. Whereas, the weighted multiplicative water quality index (WQI_M) and unweighted multiplicative water quality index (WQI_{UM}) shows very poor water quality for all the sites (which tends to 0 for all the sites), as the weighted arithmetic isn't ambiguous however extremely eclipsing and hence the weighted arithmetic index doesn't mirror the pollution levels in several cases. The disadvantage of multiplicative water quality indices is that the use of the geometric average is in comparison to the arithmetic average and even if the worth of any of the variables gets ready to null, regardless of the weight of the variables, the WQI would have been at zero. The logarithmic water quality index shows very poor water quality for 3 sites, poor water quality for 10 sites and a moderate water quality for one site. The results showed that by using the parameters pH, DO, BOD and turbidity, logarithmic WQI showed perfect correlation with Carlson's TSI in this study. Logarithmic WQI values based on pH, turbidity, BOD and DO enabled to classify waters at the lake into terribly poor quality to moderate quality, starting from 120 to 50 within the sites under investigation. Thus, it can be concluded that logarithmic WQI method is well correlated with CTSI and most suitable for predicting the trophic state of water bodies. The comparison of WQI computed using logarithmic method with CTSI is given in Table 6. It can be presumed that the classification of WQI represents the CTSI in the following manner:

WQI of Very Good corresponds to CTSI of Oligotrophic, WQI of Moderate to CTSI of Mesotrophic, WQI of Poor to CTSI of Eutrophic and WQI of Very Poor to CTSI of Hyper eutrophic.

3.4. Validation of historical data

The results were further validated with historical water quality data of Ashtamudi Lake which was monitored on a monthly basis by KSPCB. Even though the main parameters for the calculation of TSI were not monitored, an empirical relation has been used for calculating the Chl-a and SDD. By using the already monitored parameters pH, DO, BOD and Turbidity, the WQI has been calculated using logarithmic WQI method. The results are tabulated in Table 7. From the results, it is evident that the WQI estimated using logarithmic method suits well for predicting the trophic state of the lake for the historic data, thereby validating the proposed approach. Hence, by calculating WQI from the monitored secondary indicator parameters, the trophic state of the water body can be assessed even in the absence of Carlson TSI parameters.

3.5. Development of FIS for Carlson TSI and WQI

The input variables of FIS for assessing the trophic status of standing water consisted of three vital parameters namely, TP, Chlorophyll-a and Secchi depth. Three membership functions are defined for each of the parameters and four classes namely ‘Oligotrophic’, ‘Mesotrophic’, ‘Eutrophic’ and ‘Hypereutrophic’ were developed. The categories of membership functions for every parameter were selected as per Carlson's TSI. The three input membership functions and the output membership functions were connected with $4^3 = 64$ rules, victimising the fuzzy AND operator. The membership functions defined for each parameter and TSI are shown in Fig. 3A and the rules developed in Fig. 3B.

The input variables for the FIS consisted of four parameters, which are significant in assessing the water quality of the lake. As mentioned earlier, water quality variables were selected based on their relative importance to overall water quality. The input variables are the same as that taken for analysing WQI statistically, ie., pH, DO, BOD and Turbidity. For each of the parameters and for output membership functions, four classes such as ‘Very poor’, ‘Poor’, ‘Moderate’ and ‘Very good’ were developed. The four input membership functions were connected with the output membership function with $4^4 = 256$ rules using the fuzzy AND operator. The membership functions and rules defined for each parameter and WQI are shown in Fig. 4

The developed FIS has been applied for predicting the trophic state of Ashtamudi Lake using data measured during the pre-monsoon season. The two fuzzy models namely FIS-TSI for predicting the Carlson Trophic State Index and FIS-WQI for predicting the logarithmic Water Quality Index were used for the prediction. Table 8 gives the comparison of FIS developed for CTSI and WQI. The results indicate that the developed FIS for TSI and WQI can very well be used for identifying the trophic state of water bodies and act as a tool in acquiring knowledge on the eutrophication status with limited water quality parameters that are easily available and monitored with minimum efforts.

4. Conclusions

The study analysed the trophic status of Ashtamudi Lake using Carlson TSI and proposed a methodology to categorise the trophic state of a water body using readily available secondary indicator parameters. The lake was classified as predominantly eutrophic with a few locations coming under hypereutrophic category according to Carlson TSI. The water quality parameters such as pH, DO, BOD and turbidity can be used as indicator variables of eutrophication parameters namely, chlorophyll-a, total phosphorus and Secchi depth. Of the five methods for quantifying the WQI, the logarithmic method using the indicator variables such as pH, DO, BOD and turbidity proved to be useful for predicting the TSI. The proposed approach worked very well for the historical data for the years 2013–15, thereby indicating its applicability to different seasons. Further, the application of numerical method-fuzzy logic was accustomed to confirm WQI and trophic status, which as an outcome of variability of environmental factors, may outline the standard of a body of water with limited data and minimum efforts. Thus the developed model enables the assessment of TSI based on secondary indicator parameters that are readily available from the government agencies such as Kerala State Pollution Control Board (KSPCB). It is recommended to verify with other freshwater and brackish water bodies so that the method can be adopted universally for identifying the eutrophication status. This will help the policy makers to adopt appropriate management practices in order to mitigate the problems related with eutrophication.

Declaration of Competing Interest

There is no conflict of interest.

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