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New Classification Method to Evaluate Pollution Levels of Sewage Contaminated Lakes

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Abstract: Monitoring water quality to minimize deterioration of a lake's functionality is important, as several Indian lakes are exposed to sewage contamination. Public health laboratories, citizen scientists, and volunteers in developing nations often find it difficult to perform elaborate tests to monitor the water quality of freshwater systems. Developing a classification method to evaluate the pollution status of sewage-contaminated lakes using limited tests will expand environmental monitoring of freshwater systems and contribute valuable data to the regional and global repository. Four classes of lake pollution ranging from unpolluted (class 1) to mixed wastewater (class 4) were identified based on the distribution of data points in the K^+ (potassium) versus COD (chemical oxygen demand) scatter chart. As pH, EC (electrical conductivity), turbidity, and DO (dissolved oxygen) are deteriorated by sewage contamination, these parameters were also incorporated in the proposed pollution classification table. Data of unpolluted and sewage polluted Indian lakes were employed to compile the limiting range of parameters in the proposed lake pollution classification. The five parameters (K^+, pH, EC, DO, turbidity) required to categorize lake pollution (class 1 to 4) can be measured with equipment costing 800–1000 USD, while COD can be measured at 5 USD/sample in laboratories.

Keywords: classification; lakes; pollution; sewage; water quality

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1. Introduction

Over the decades, improper management of urban wastewater, solid waste, industrial effluents, and destruction of natural flow channels have declined the extent and quality of Bengaluru lakes [1–3]. In addition, several Bengaluru lakes are replenished with treated water from sewage treatment plants and stormwater runoffs. Malfunctioning of sewage treatment plants that supply treated water to lakes, stormwater, and sewage overflow during a flood event, pollution from human settlements along lake periphery, cause an influx of partially treated or untreated sewage into the lakes [1,2,4–6].

Sewage influx pollutes the lakes with organic matter, micro-organisms, suspended solids, inorganics, nutrients, and toxicants. Often the self-cleansing ability of lakes to degrade organic matter, settle suspended solids, assimilate nutrients, and remove toxicants and inorganics using an ion-exchange/adsorption process cannot balance the sewage influx. This leads to nutrient/toxicant/inorganics enrichment, increased turbidity, eutrophication, algal bloom, alkaline pH, and water column anoxia [7–13]. Monitoring water quality to minimize deterioration of the lake's functionality is important for the urban lakes of India.

Monitoring water quality involves measurement [14,15] of physical (temperature, turbidity, and transparency), chemical (ion composition, organic carbon), and biological parameters (chlorophyll, coliforms, aquatic biota). Water quality indices (WQIs) grade lake water quality status from very poor to excellent state based on major water quality parameters [13]. The trophic status of freshwater resources evaluates the anthropogenic influence on the grading of the freshwater ecosystem [16,17]. Water quality parameters such as Secchi depth, nitrogen, phosphorous, and chlorophyll concentrations classify the trophic status of lakes from oligotrophic to hypereutrophic [18].

Existing water quality classifications rely on multiple parameters to classify freshwater quality for various functions. Central Pollution Control Board-India [19] categorizes freshwater resources for various uses based on BOD_5, pH, total coliform organisms, and dissolved oxygen (Class A to C). Class A pertains to drinking water sources without conventional treatment but with disinfection. Class B refers to outdoor bathing and Class C refers to a drinking water source with conventional treatment and disinfection. The use of the water resource for the propagation of wildlife and fisheries (Class D) additionally requires free ammonia (as N) concentration. Use of the water resource for irrigation, industrial cooling, and controlled waste disposal (Class E) use a different set of parameters; pH, EC (electrical conductivity), SAR (sodium adsorption ratio), and boron concentration. To meet the Class A to E criteria, the Malaysian water quality standard [20] recommends the evaluation of 17 parameters. Besides the 6 parameters recommended by the Central Pollution Control Board-India [19], the Malaysian surface water quality standard [20] recommends determination of COD, color, floatable, salinity, turbidity, taste, TSS (total suspended solids), temperature, and fecal coliforms.

Measurement of chemical and biological parameters to classify water quality according to existing norms (example, [19,20]) is resource-intensive. Public health laboratories and citizen scientists in developing nations are often resource-constrained and may therefore find it difficult to periodically monitor water quality using elaborate testing protocol [21]. Following the unprecedented death of fish during intense algal bloom in one of the Bengaluru lakes during March 2018, the authors were approached by the lake-volunteers for a simple method to monitor lake water quality to avoid such a catastrophe. The authors were also engaged with citizen scientists as an initiative of the Earthwatch Institute and Hongkong and Shanghai Banking Corporation (HSBC) freshwater watch program. As they had measured few parameters, the citizen scientists were unable to classify the lake pollution status using existing models. Citizen science is the generation of new information by the participation of members of the public in scientific projects. In environmental sciences, the contribution of citizen scientists ranges from web-based participation in processing and classifying images and data to full-scale fieldwork. Their involvement can lead to data collection at a scale not possible by professional scientists alone. The United Nations (UN) has recently recognized citizen science as a potential source of data that may contribute to the UN Sustainable Development Goals (SDGs) [22–24].

An alternate method of classification of water quality based on limited testing can allow public health laboratories, citizen scientists, and volunteers in developing nations to expand environmental monitoring of freshwater systems and contribute valuable data to the regional and global repository.

Citizen scientists/volunteers in developed nations have monitored water quality parameters such as Secchi depths, water turbidity, pH, total coliforms, dissolved oxygen, nitrate, and phosphate concentrations to address environmental issues of lakes and rivers at spatial and temporal scales. Collaborations among citizens, researchers, and government agencies have aided the development of a database to assess the impacts of sewer overflows, urbanization, modified agricultural practices, river restoration, extreme climate events, and alternative catchment management practices on freshwater ecosystems [6,22–29]. The involvement of citizen volunteers in lake water quality monitoring encourages communication between citizens and the scientific community. The citizen science projects provide valuable scientific tools for citizen volunteers to understand the impacts of water pollution at a local scale and develop consensus among various stakeholders of the society to seek sustainable solutions [22,30].

The proposed classification system is developed by characterizing the water quality data of Indian urban lakes. As the proposed classification system is developed as an indicator of the pollution status of freshwater systems, it does not provide recommendations for their suitability for various functions or trophic status/water quality index. The study also examines (a) water quality of Bengaluru lakes in relation to Most Common Natural Concentrations (MCNC) of world rivers [31], and (b) compares the quality of Bengaluru lakes with other urban lakes of India.

2. Experimental Program

2.1. Description of Lakes

Bengaluru is in the Southeastern part of Karnataka extending from north latitude 12°39′32″ to 13°14′13″ and East longitude 77°19′44″ to 77°50′13″ at an altitude of 920 m above mean sea level. Bengaluru is administratively divided into 8 zones covering 198 wards with a population of 12,326,532 in 2020 [32]. Bengaluru receives a total annual rainfall of 831 mm; the southwest monsoon contributes 54%, northeast monsoon 27%, and pre-monsoon showers contribute 19% to total annual rainfall. Puttenahalli, Sankey, Ulsoor, and Nagawara lakes examined in this study fall in the Ponniayar watershed in the eastern part of the city and the Arkavathi watershed in the southwestern part of the city. Maps of sampling points and inlet coordinates based on the recorded GPS data are available in earlier publications of the authors [12,33].

The vegetated buffer area of the lake is beneficial as biological filters of sediments and nutrient assimilation zone [6,34]. The urban vegetation cover of Bengaluru city corresponds to 30.1% in 2006 and 26.1% in 2019. Rapid urbanization has led to a 4% decline in the urban vegetation cover [35]. In the present study, Landsat satellite images for the chosen four lakes were downloaded for the years 2001 and 2020. Normalized Difference Vegetation Index (NDVI) index was applied to satellite images to analyze the change in vegetation cover of the lake (Figure 1). NDVI values ranges from −1.0 to +1.0 and values close to +1.0 represent healthy dense vegetation [36]. In general, the NDVI values for land covers such as water bodies, built-up area, bare soil, etc. range from a negative value to +0.2 and moderate to dense vegetation ranges from 0.4 to 1.0. The percent reduction in vegetation cover (NDVI > 0.4) for Sankey, Nagawara, Ulsoor, and Puttenahalli lakes correspond to 24.1%, 83.1%, 15.2%, and 31.1%, respectively. The reduction in vegetation cover of the buffer zone will increase the lake's vulnerability to non-point source pollution [6,34].

2.2. Field and Laboratory Tests

Nineteen grab samples (4 during non-algal bloom and 15 during algal bloom) were obtained from the four lakes from January to June 2018. Sampling was performed between 11 AM and 3 PM corresponding to an intense algal photosynthetic period at all lakes. Water samples representative of non-algal bloom conditions were obtained from Puttenahalli lake (PU1, PU2) and Sankey lake (SK1, SK2) on 4th and 11th January 2018 at depths of 95 and 190 cm, respectively.

Water samples after the onset of algal bloom were obtained from Nagawara lake (NG1a, NG2a) on 11th January 2018 (suffix *a* after sample number denotes algal bloom condition, while the absence of this suffix denotes non-bloom condition, Table 1) at a depth of 180 cm. Grab samples were obtained at shallow depths of 0 to 15 cm from Ulsoor lake (UL1a to UL6a) on two occasions: 4th January 2018 (UL1a and UL2a) and on 1st June 2018 (UL4a to UL6a) along with a sample from the stormwater runoff inlet. Fish kill due to influx of sewage was reported in Puttenahalli lake on 21st March 2018; grab samples (PU3a to PU10a) were obtained at shallow depths (≤15 cm) on 24th March 2018, along with a sample from the treated sewage inlet. Shallow depth sampling was necessitated in Puttenahalli lake (PU3a to PU10a) as the surface was covered with dead fish and accessibility to the lake was restricted. Shallow depth sampling was necessitated in Ulsoor lake owing to the non-availability of a boat for sampling from the deeper zone of the lake.

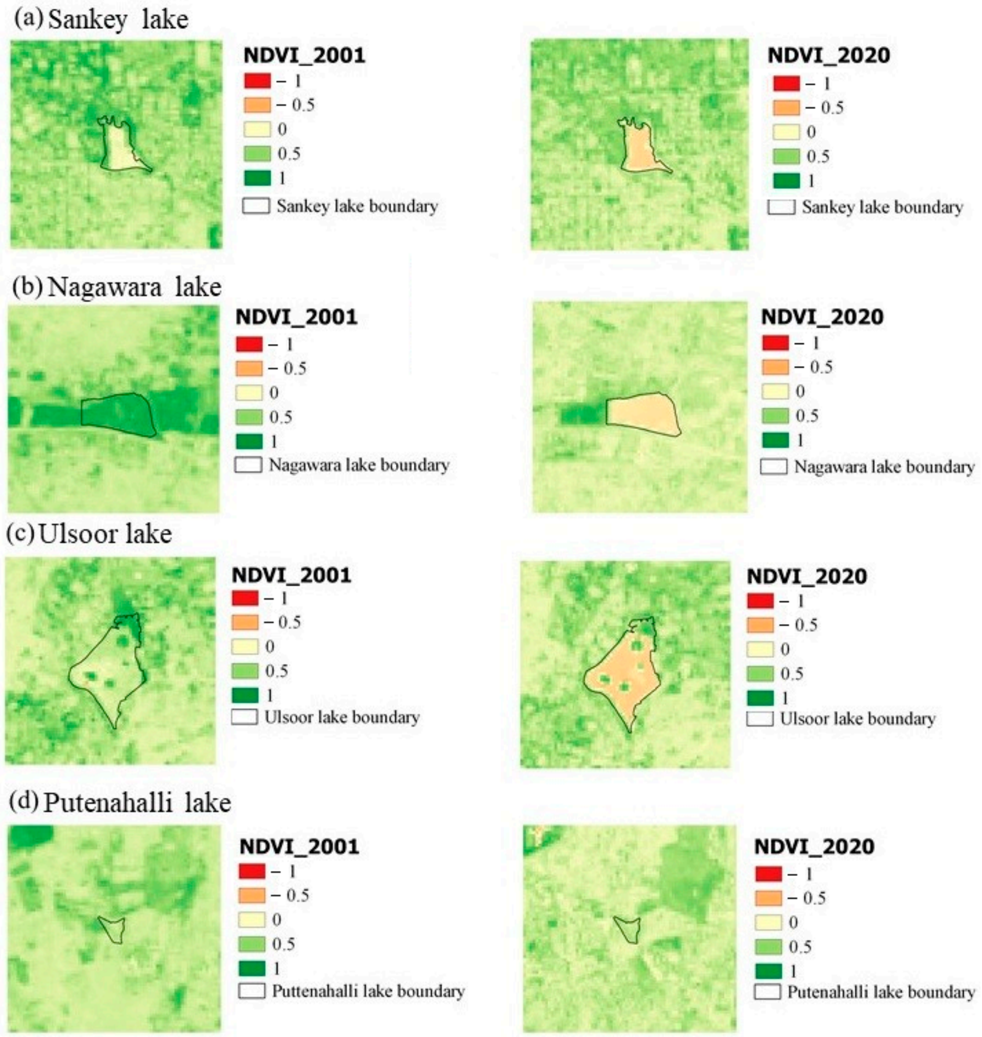

Figure 1. Variation in vegetation cover (NDVI) of the buffer zone of Bengaluru lakes.

Table 1. Biochemical characteristics of Bengaluru lakes (* suffix a indicates algal bloom).

Sample	EC (μS/cm)	pH	CO_3^{2-} (mg/L)	HCO_3^- (mg/L)	Cl^- (mg/L)	SO_4^{2-} (mg/L)	NO_3^-, mg/L	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na+ (mg/L)	K+ (mg/L)	DO, mg/L	COD, mg/L	N+P (mg/L)
PU1	533.0	6.2	0	236.7	66.0	236.0	4.0	57.0	29.0	29.0	13.0	4.8	20.0	4.2
PU2	813.0	6.5	0	344.0	97.0	319.0	9.0	90.0	40.0	92.0	16.0	4.2	20.0	3.3
PU3a *	603.0	9.9	17.0	104.0	81.7	7.0	0.22	41.2	16.8	76.5	15.3	13.0	51.0	1.0
PU4a	611.0	9.6	19.0	101.0	81.3	7.5	0.02	26.0	12.8	68.2	12.9	15.0	39.0	0.8
PU5a	616.0	10.2	21.0	92.0	84.5	7.5	0.02	24.7	13.9	73.9	14.4	13.2	46.0	0.9
PU6a	760.0	9.5	3.1	212.0	82.4	31.0	0.43	25.0	13.5	70.5	14.0	12.5	54.0	1.2
PU7a	622.0	9.0	18.0	109.0	101.8	18.0	0.43	17.0	13.5	68.1	13.3	12.5	45.1	1.0
PU8a	573.0	10.0	22.0	91.0	82.9	7.0	0.46	18.5	12.8	66.7	12.1	14.0	66.5	1.4
PU9a	545.0	10.1	24.0	80.0	86.2	7.0	0.02	24.5	12.9	66.6	13.1	14.0	42.0	0.8
PU10a	610.0	10.1	19.0	88.0	83.1	7.0	0	24.5	12.9	66.6	13.1	14.0	42.0	0.8
UL1a	269.0	8.9	2.0	114.7	36.0	116.0	4.0	18.0	14.0	28.0	10.0	5.9	26.0	1.7
UL2a	266.0	9.6	2.0	114.7	36.0	100.4	5.0	19.0	15.0	28.0	10.0	6.2	24.0	1.9
UL3a	446.0	7.0	0	169.0	24.0	61.0	27.0	36.0	7.7	39.3	7.2	0.4	96.0	14.7
UL4a	331.0	8.1	0	97.0	43.0	40.0	3.5	18.7	6.9	32.1	10.2	13.0	48.0	1.8
UL5a	331.0	8.4	3.0	95.0	43.0	23.0	3.8	17.4	6.9	33.2	10.4	13.0	52.0	1.9
UL6a	333.0	8.0	0	104.0	40.0	42.0	2.6	20.3	7.9	33.5	13.4	8.0	58.0	1.8
NG1a	1124.0	8.6	2.0	158.6	62.0	208.0	6.0	26.0	30.0	47.0	12.0	10.1	20.0	2.1
NG2a	1117.0	10.3	3.0	124.4	62.0	188.0	7.8	24.0	12.0	57.0	13.0	12.2	22.0	2.2
SK1	1100.0	7.8	0	219.6	50.0	51.0	7.0	44.0	30.0	20.0	8.0	5.8	16.0	2.0
SK2	1091.0	7.9	0	222.0	50.0	63.0	6.0	40.0	30.0	39.0	8.0	5.9	12.0	1.7

Besides sample collection from January 2018 to June 2018, additional sampling was performed by citizen scientists at SK, PU, and UL lakes, to monitor pH, DO (dissolved oxygen), and EC (electrical conductivity) parameters as an initiative of the Earthwatch

Institute and Hongkong and Shanghai Banking Corporation (HSBC) freshwater watch program. Samples were collected by citizen scientists from twenty-one additional locations at SK lake in July 2018, September 2018, February 2019, April 2019, and May 2019 respectively. Likewise, samples were collected from six additional locations at UL lake in July 2018 and February 2019. Samples were collected from seventeen additional locations at PU lake in September 2018, April 2019, and May 2019. The readings obtained by citizen scientists were nearly identical to those measured by the research staff of this study.

Electrical conductivity (EC), pH, and dissolved oxygen contents of lake water samples were measured in the field using portable pH, electrical conductivity, and DO meters. The turbidity of the lake water samples was determined in the laboratory using a nephelometer. Samples were analyzed for total COD using the silver sulfate-sulfuric acid digestion method [37].

Other parameters were measured with water samples filtered through a 0.45-µm filter prior to testing. The concentrations of magnesium, calcium, sodium, and potassium ions in the lake water samples were determined using an atomic absorption spectrometer (Thermo AAS, ICE 3000, Thermo Fisher Scientific, Waltham, MA, USA). Sulfate concentration was measured using the turbidimetric method [37]. Nitrate and ammonium ion concentrations were determined using an ion-chromatograph (Dionex ICS 2000, Thermo Fisher Scientific, Waltham, MA, USA), while chloride and bicarbonate/carbonate ion concentrations were determined using an automatic titrator (Metrohm, Titrino Plus 877, Metrohm AG, Herisau, Switzerland). Total dissolved P concentration in the lake water samples was determined using the sulfuric acid- nitric acid digestion method [37].

3. Discussion of Results

3.1. Water Quality of Bengaluru Lakes in Relation to Most Common Natural Concentrations (MCNC) of World Rivers

Treated sewage water inlets and stormwater drain inlets are examples of stream flow channels that discharge into the Bengaluru lakes. Samples obtained from a treated sewage water inlet and stormwater drain inlet (Table 2) exhibited COD concentrations of 54.4 to 99.2 mg/L (median = 83 mg/L), DO (dissolved oxygen) values of 0.10 to 0.48 mg/L (median = 0.42 mg/L), ammonium concentrations of 15.7 to 50.3 mg/L (median = 28.5 mg/L), nitrate concentration of 0.5 to 2.5 mg/L (median = 0.7 mg/L), sulfate concentrations of 6.3 to 20.2 mg/L (median = 10.0 mg/L), total P concentrations of 0.4 to 1.92 mg/L (median concentration = 0.8 mg/L), and potassium concentrations of 16.7 to 20.2 mg/L (median = 18.9 mg/L) (Table 2).

Table 2. Statistical distribution of measured parameters of mixed wastewater.

Parameter	Mixed Wastewater			
	Minimum	**Maximum**	**Median**	**Standard Deviation**
pH	7.1	7.9	7.2	0.42
HCO_3^- (mg/L)	108.6	551.0	305.0	221.6
Cl^- (mg/L)	95.4	101.6	99.8	3.2
SO_4^{2-} (mg/L)	6.3	20.2	10.0	7.2
NO_3^- (mg/L)	0.50	2.5	0.70	1.1
Ca^{2+} (mg/L)	46.0	78.3	52.6	17.1
Mg^{2+} (mg/L)	19.7	24.1	19.8	2.5
Na^+ (mg/L)	73.4	95.4	86.6	10.7
K^+ (mg/L)	16.7	20.2	18.9	1.8
NH_4^+ (mg/L)	15.7	50.3	28.5	17.5
TDS (mg/L)	590.9	811.0	682.5	110.6
COD (mg/L)	54.4	99.2	83.0	22.7
DO (mg/L)	0.10	0.48	0.42	0.20

Schouw et al. [38] had analyzed the chemical composition of excreta samples of 15 persons from Southern Thailand and observed that the concentration of macronutrients, such as N, K, and S correspond to 7.6–7.9 g N/person/day, 1.8–2.7 g K/person/day, and 1.0–1.1 g S/person/day. The macronutrients are present in the urine component of blackwater. Boutin and Eme [39] report that ammonium-N, nitrate-N, K, and S concentrations in Western Europe greywater samples range between 1–13 mg/L, 0–10 mg/L, 5–23 mg/L, and 18–72 mg/L. Kuradagi and Gadag [40] report that phosphate concentrations in raw sewage entering Bhisma lake in Gadag city, Karnataka range from 6.29 to 6.33 mg/L, which are much larger than the treated sewage water inlet and stormwater drain inlet values (0.4 to 1.92 mg/L). Contributions by blackwater and greywater are responsible for the macronutrient concentrations in the treated sewage water inlet and stormwater drain inlet samples (Table 2). Boutin and Eme [39] report that COD concentrations in greywater range from 25–1583 mg/L. Kuradagi and Gadag [40] report that the COD concentrations in raw sewage entering Bhisma lake in Gadag city, Karnataka range from 335 to 392 mg/L. The COD concentrations (Table 2) of treated sewage water inlet and stormwater drain inlet (54–99 mg/L) are much lower than the greywater and raw sewage concentrations. Consequently, the treated sewage water and stormwater runoffs feeding the Bengaluru lakes are termed mixed wastewater (MWW).

Table 3 presents the statistical distribution of chemical parameters of 63 lake water samples tested in the present study. Of the 63 samples, the bulk (45) of pH, TDS (total dissolved solids; obtained from EC measurement), and DO parameters were tested by citizen scientists as an initiative of the Earthwatch Institute and Hongkong and Shanghai Banking Corporation (HSBC) freshwater watch program. Data in Table 3 also includes the median ion compositions of world rivers, termed the most common natural concentrations (MCNC) [31]. The median ion concentrations of the lake samples exceeded the MCNC values of world rivers. The most common natural concentrations (MCNC) of sodium and chloride ions in world rivers correspond to 3.7 and 3.9 mg/L, while the corresponding values for Bengaluru lakes were 57 and 66 mg/L, respectively. The excess sodium and chloride concentrations in the lakes were attributed to contamination of lakes by the mixed wastewater. The MWW is characterized by median sodium and chloride concentrations of 86.6 mg/L and 99.8 mg/L respectively (Table 2).

Table 3. Statistical distribution of measured parameters of Bengaluru lakes (Present study).

Parameter (1)	Lake Samples				Median Composition of World Rivers [31] (6)	$\frac{Column\ 3}{Column\ 6}$
	Minimum (2)	Median (3)	Maximum (4)	Standard Deviation (5)		
pH	6.2	9.0	10.3	1.23	——	
HCO_3^- (mg/L)	80.0	109.0	344.0	71.1	31.0	3.5
Cl^- (mg/L)	36.0	66.0	101.8	21.6	3.9	16.9
$SO4_2^-$ (mg/L)	7.0	40.0	319.0	93.3	9.2	4.3
NO_3^- (mg/L)	0.0	3.5	9.0	3.0	0.44	8.0
Ca^{2+} (mg/L)	17.0	24.5	90.0	18.1	8.0	3.1
Mg^{2+} (mg/L)	6.9	13.5	40.0	9.4	2.4	5.6
Na^+ (mg/L)	20.0	57.0	92.0	21.3	3.7	15.4
K^+ (mg/L)	8.0	13.0	16.0	2.3	1.06	12.3
NH_4^+ (mg/L)	0.0	0.0	3.7	0.85	0.02	
TDS (mg/L)	172.7	396.1	729.9	188.2	——	
COD (mg/L)	12.0	42.0	66.6	16.3	——	
DO (mg/L)	4.2	12.5	18.8	3.8	——	

The median calcium, magnesium, bicarbonate, and sulfate ion concentrations in world rivers are 8.0, 2.4, 31.0, and 9.2 mg/L respectively. The median ion concentrations of Bengaluru lakes correspond to 24.5, 13.5, 109.0, and 40.0 mg/L, respectively (Table 3). Comparatively, the median Ca^{2+}, Mg^{2+}, HCO_3^- and SO_4^{2-} ion concentrations in the mixed wastewater were 52.6, 19.8, 305.0, and 10.0 mg/L respectively (Table 3). The Ca^{2+}, Mg^{2+}, and HCO_3^- ion concentrations of the lakes are lower than those of the mixed wastewater samples but are 3.06 to 5.63 times larger than the MCNC values of world rivers. The median SO_4^{2-} ion concentration of the lake samples was higher than the median MWW value. Removal of calcium, magnesium, and bicarbonate ions during mineral carbonate precipitation [12] along with bicarbonate consumption by algal photosynthesis led to lower Ca^{2+}, Mg^{2+}, and HCO_3^- ion concentrations in the lakes than in the MWW samples. Annual immersion of gypsum idols in lakes is a socio-religious practice in India [41]. Sulfate released from anthropogenic gypsum dissolution imposes higher sulfate concentration in the Bengaluru lakes [33].

The median potassium and nitrate ions concentrations in world rivers correspond to 1.06 and 0.44 mg/L, while the median values for Bengaluru lakes are 13 and 3.5 mg/L, respectively (Table 3). The median potassium concentration in the mixed wastewater was slightly larger (18.9), while the median nitrate concentration was much lower (0.68 mg/L) than the median values of lake samples (Table 3). The higher nitrate concentration of lake samples is attributed to the oxidation of ammonium ions to form nitrate ions.

3.2. Comparison of Quality of Bengaluru Lakes with Other Indian Lakes

A comparison of chemical molar ratios of major anions of Bengaluru lakes and lakes from other urban centers of India would detect if the ions had similar origin [42,43]. Statistical analysis of Cl/Na, NO_3/Na, HCO_3/Na molar ratios (ion concentrations are expressed in terms of millimoles/L) of four Bengaluru lakes and fifty-two lakes from other Indian towns/cities are given in Table 4. In addition to Bengaluru lakes (Table 1), molar ratios of 27 lakes from Raipur-Chhattisgarh State [44], 3 lakes (Ooty, Yercaud, and Kodai) from Tamil Nadu [45], and 22 lakes from Mysore district-Karnataka State [46] are considered for statistical analysis. The median Cl/Na molar ratio of 56 lakes varies between 0.7 to 1.2 with a standard deviation of 0.22. The median HCO_3/Na molar ratio varies between 0.8 and 1.55 with a standard deviation of 0.27. The median NO_3/Na ratios vary between 0.01 to 0.04 with a standard deviation of 0.012. The comparable chemical molar ratios point to a similar source of anion contamination in the Indian lakes. The urban lakes exhibit significant COD concentrations (average value = 72 mg/L, 216 data points). It is hence reasonable to infer that the inflow of untreated or partially treated sewage is a common feature in several urban lakes of India. The next section develops a method to evaluate the pollution status of lakes that are exposed to sewage contamination.

Table 4. Molar ratios of Indian lakes.

Lake	No. of Samples	Cl/Na			HCO_3/Na			SO_4/Na			NO_3/Na			COD (mg/L)		
		Min	Max	Median	Min	Max	Median	Min	Max	Median	Min	Max	Median	Min	Max	Median
Present study	19	0.68	1.62	0.81	0.45	4.14	1.13	0.02	2.03	0.31	0.00	0.13	0.04	12.0	66.6	42.0
Raipur [44]	27	0.50	1.09	0.76	0.42	1.79	0.80	0.00	0.28	0.05	0.00	0.09	0.01	8.0	118.0	39.0
Ooty [45]	4	0.83	1.29	1.18	1.29	1.83	1.55	0.04	0.12	0.08	0.00	0.15	0.01	46.0	70.4	60.8
Yercaud [45]	4	0.87	0.95	0.92	1.12	1.89	1.21	0.03	0.08	0.05	0.00	0.01	0.01	26.0	63.4	39.0
Kodai [45]	4	0.82	1.78	1.20	0.73	1.64	1.26	0.12	0.30	0.19	0.01	0.05	0.01	37.0	55.4	51.3
Mysore district [46]	22	0.21	23.6	0.70	0.42	7.54	0.90	0.00	0.24	0.04	0.01	0.19	0.01	12.0	248.0	28.0

3.3. Proposed Method to Evaluate Pollution Level of Sewage Contaminated Lakes

3.3.1. Data from Present Study

Sewage contaminated lakes are susceptible to algal bloom; during an algal bloom, the aqueous chemistry of lakes is altered by precipitation of mineral carbonates and nutrient consumption for algal growth [12]. Chemical indicators chosen to develop the classification system should be unaffected by algal bloom. The Puttenahalli lake data was chosen for identifying chemical indicators of sewage contamination as the lake quality was monitored during episodes of non-bloom (PU1 and PU2, January 2018) and bloom (PU3a-PU10a, March 2018) conditions (Table 1). Bicarbonate, calcium, and magnesium ion concentrations exhibit marked variation between the two periods (Table 1). This variation is ascribed to the precipitation of calcium and magnesium carbonates in the alkaline pH environment (pH: 9.02 to 10.2) during algal bloom [12]. The N+P concentrations vary between the two periods owing to nutrient consumption by algae in the bloom period (March 2018). Sodium and chloride ion concentrations vary between non-algal bloom and algal bloom periods from possible variations in the MWW concentrations. The K^+ ion concentrations were least affected during the two periods and similar concentration ranges are observed during January 2018 (13–16 mg/L) and March 2018 (12–15 mg/L). Further, as both K^+ and COD constituents originate from blackwater/greywater, a scatter chart is plotted between these sewage-derived parameters (Figure 2). The figure includes data of Puttenahailli, Sankey, Ulsoor, and Nagawara lakes (Table 1) and the MWW data (Table 2). The present study data is also used to construct pH versus COD and EC versus COD plots (Figures 3 and 4) and turbidity versus COD plots (Figure 5).

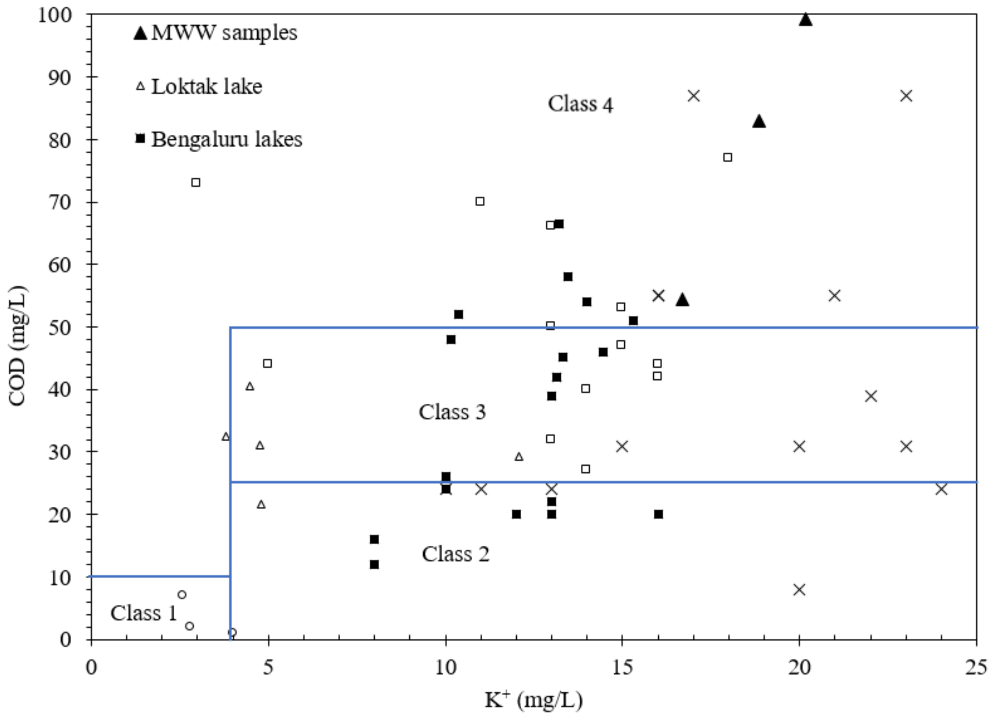

Figure 2. K^+ versus COD chart of lake samples.

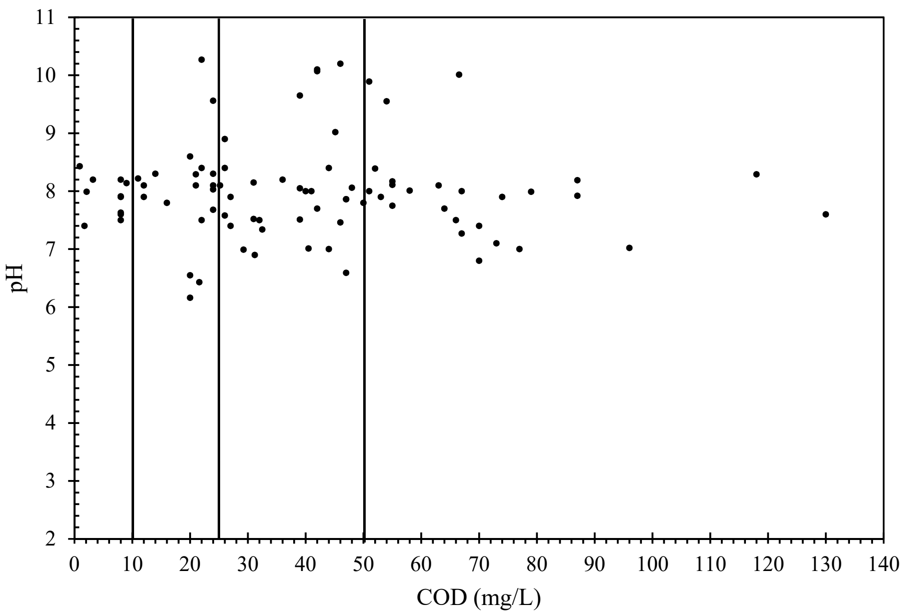

Figure 3. Distribution of pH of lake samples at various COD concentrations.

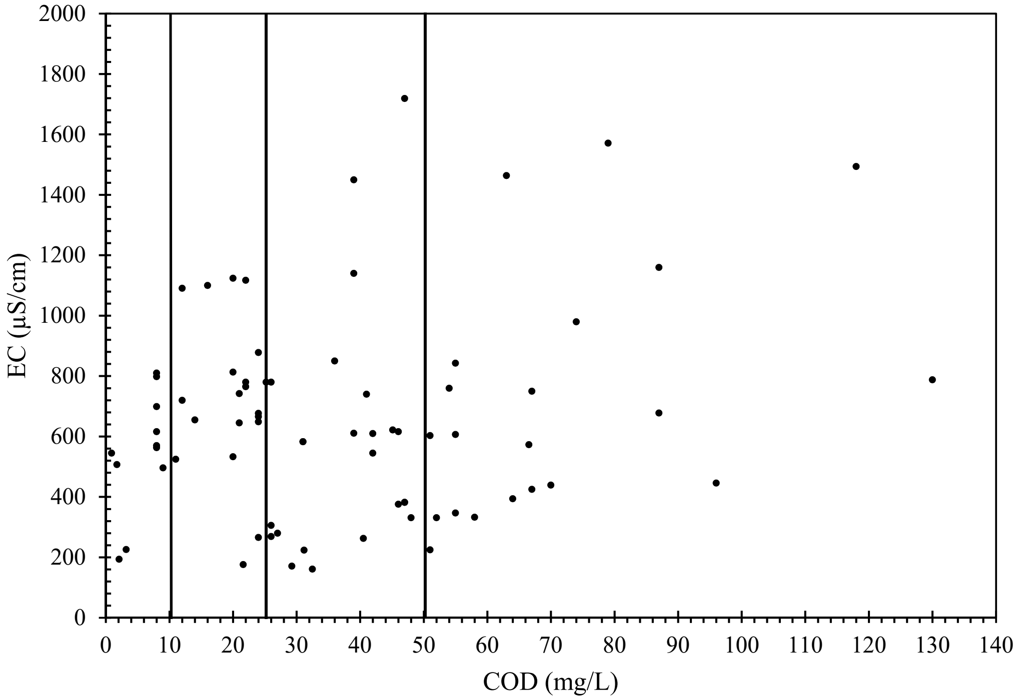

Figure 4. Distribution of EC of lake samples at various COD concentrations.

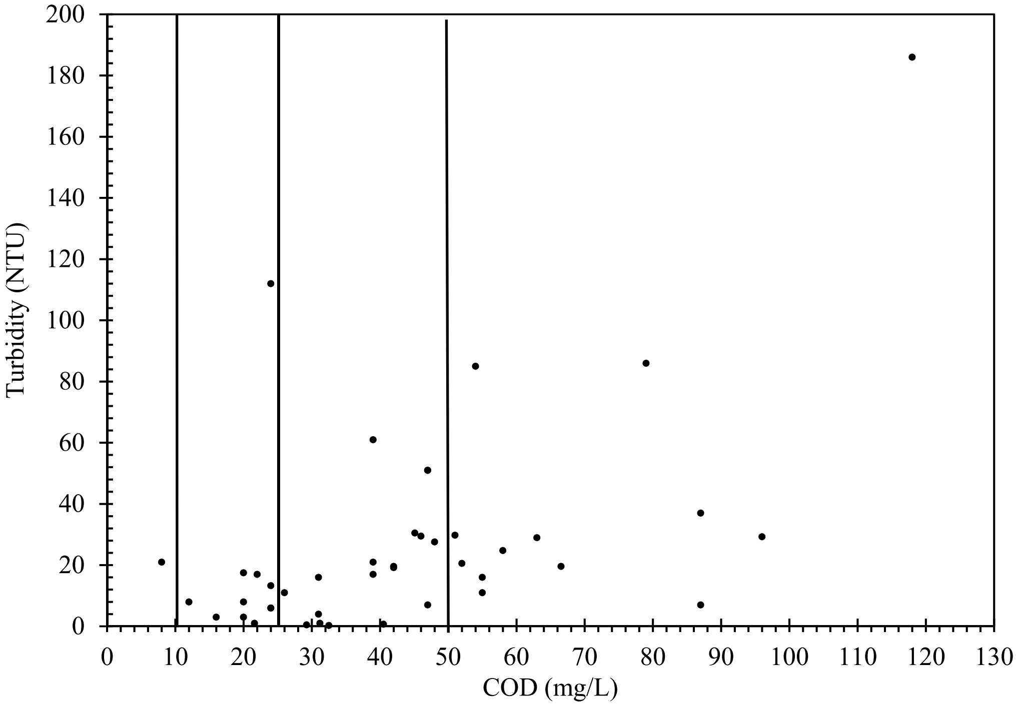

Figure 5. Distribution of turbidity of lake samples at various COD concentrations.

3.3.2. Data from Other Studies

Figure 2 includes the data from Hebbal lake-Bengaluru [2], Raipur city lakes-Chhattisgarh [44], Loktak lake-Manipur [47], and western Himalayan lakes Jammu and Kashmir, Himachal Pradesh [48].

The data points of the lakes fall into four broad classes:

Class 1: K^+ 0–4 mg/L and COD 0–10 mg/L (non-polluted).

Class 2: K^+ 4–25 mg/L and COD 10–25 mg/L (moderate pollution).

Class 3: K^+ 4–25 mg/L and COD 25–50 mg/L (severe pollution).

Class 4: K^+10–25 mg/L, COD > 50 mg/L (mixed wastewater).

Examination of Figure 2 indicates that the western Himalaya lakes are non-polluted. The bulk of the Bengaluru, Hebbal, Raipur, and Loktak lakes are severely polluted (class 3). The MWW samples classify as class 4. Few Bengaluru lakes and Raipur lakes also categorize as mixed wastewater (class 4).

Class 1 of the proposed system (COD < 10 mg/L) maps to class I of Malaysian standards [20], class 2 (COD 10–25 mg/L) maps with classes IIA and IIB, class 3 (COD 25–50 mg/L) fits class III and class 4 (COD > 50 mg/L) maps to classes IV and V of Malaysian standards [20]. It is emphasized that Malaysian standard [20] specifies limiting ranges for COD, turbidity, pH, EC, total coliform counts, and DO for utilization of the freshwater for various activities. If the parameters exceed the specified limits, the water body becomes unfit for the specific activity. In other words, standards such as, Central Pollution Control Board-India [19] and Malaysian standards [20] define safe limits of water quality parameters for utilization of freshwater for various activities. In comparison, the proposed classification system does not define safe limits but records a range of parameters, encountered in non-polluted to severely polluted freshwater systems from anthropogenic activities.

As pH, EC, turbidity, and DO are worsened by sewage contamination [12,33], the range of these parameters encountered in polluted lakes is incorporated in the proposed pollution classification system. The range of pH, EC, and turbidity parameters in non-polluted and polluted lakes is evaluated by typifying the pH, EC, and turbidity data of lake water samples at various COD concentrations (Figures 3–5). Data of Bengaluru lakes (present study), Hebbal lake-Bengaluru [2], Loktak lake-Manipur [47], Western Himalaya lakes-Jammu and Kashmir and Himachal Pradesh [48], Raipur lakes-Chhattisgarh [44], Tamil Nadu lakes [45], and Shahapura lake-Bhopal [49] are used to prepare the pH versus COD and EC versus COD plots (Figures 3 and 4). Data of Bengaluru lakes (present study) and Raipur lakes [44] are used to generate the turbidity versus COD plot (Figure 5). The COD boundaries in Figure 3 illustrate that pH of Class 1 to 4 lakes categorize as 7.0–8.5, 6.0–11.0, 6.0–11.0, and 6.0–11.0, respectively. The COD boundaries in Figure 4 illustrate that EC of Class 1, 2, 3, and 4 lakes categorize as 200–800, 200–1200, 200–2000, and 200–2000 µS/cm, respectively. The COD boundaries in Figure 5 illustrate that turbidity of Class 1, 2, 3, and 4 lakes categorize as ≤20 NTU, 1–120 NTU, 1–120, and 5–200 NTU, respectively.

The proposed system for classifying the pollution level of sewage-contaminated lakes is summarized in Table 5. Only six parameters are measured, making the system user-friendly for citizen scientists and laboratories with limited testing resources in developing nations. Of the six parameters, citizen scientists in Bengaluru (part of Earthwatch Institute and Hongkong and Shanghai Banking Corporation freshwater watch program) were trained to measure pH, TDS, and DO of four Bengaluru lakes from July 2018 to May 2019. Additional evaluation of K^+, COD, and turbidity would enable citizen scientists to flag the pollution status of freshwater systems using the proposed classification (Table 5). Mapping water quality data in a freshwater catchment can help identify the geographical locations where pollutants enter the system and eventually isolate them.

Table 5. Proposed pollution classification system for sewage contaminated lakes.

Class	Lake Pollution Status	K^+ (mg/L)	COD (mg/L)	EC (µS/cm)	pH	DO (mg/L)	Turbidity (NTU)
1	Non-polluted	0–4	0–10	200–800	7.0–8.5	7.5	≤20
2	Moderate pollution	4–25	10–25	200–1200	6.0–11.0	5.5–7.5	1–120
3	Severe pollution	4–25	25–50	200–2000	6.0–11.0	4.0–5.5	1–120
4	Mixed wastewater	10–25	>50	200–2000	6.0–11.0	0.9–4.0	5–200

The K^+ ion concentration can be measured using a relatively inexpensive, flame photometer (approximately 500–600 USD), while COD concentration can be measured using the silver sulfate-sulfuric acid digestion method [36] at local environment testing laboratories (approximately 5 USD/sample). The pH, EC, and DO of lake water samples can be measured using a portable water quality kit (200–250 USD), while turbidity can be measured with a turbidity meter (100–150 USD).

4. Conclusions

A mixture of treated and untreated sewage and a mixture of stormwater and raw sewage feed the examined Bengaluru lakes. The inflow of mixed wastewater and other anthropogenic activities caused the median sodium, calcium, magnesium, potassium, chloride, bicarbonate, sulfate, and nitrate concentrations of Bengaluru lakes to be 3.06 to 16.92 times larger than the most common natural concentration values of world rivers. The presence of significant COD concentrations suggested that the inflow of untreated or partially treated sewage is a common feature in the urban lakes of India.

The K^+ ion and COD concentrations were unaffected during non-bloom and algal bloom periods prompting their use for developing a categorization chart of lake pollution. The data points of the lakes are distributed into four classes: Class 1: K^+ 0–4 mg/L and COD 0–10 mg/L (non-polluted), Class 2: K^+ 4–25 mg/L and COD 10–25 mg/L (moderate pollution), Class 3: K^+ 4–25 mg/L and COD 25–50 mg/L (severe pollution) and Class 4: K^+ 10–25 mg/L, and COD > 50 mg/L (mixed wastewater).

Turbidity, pH, EC, and DO are included in the classification system as they are worsened by sewage contamination. The range of these parameters in Class 1 to 4 lakes is evaluated by characterizing the water quality data of Indian urban lakes. Equipment costing about 800–1000 USD can measure, pH, EC, DO, K^{+}, and turbidity of water samples, while COD can be measured at 5 USD/sample in laboratories. The proposed classification method will allow public health laboratories and citizen scientists in developing nations to expand environmental monitoring of freshwater systems and contribute valuable data to the regional and global repository.

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