



Assessment of pollution state of Beira Lake in Sri Lanka using water quality index, trophic status, and principal component analysis

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Abstract Beira Lake, in the heart of Colombo City in Sri Lanka, is a prominent landmark, serving a variety of important services such as flood control, and providing habitat and nesting grounds for the city's wildlife. During the past decades, Beira Lake has become highly polluted due to anthropogenic activities. The majority of the past restoration attempts failed, revealing a lack of understanding of the pollutant intricacies. The objective of this study is to investigate the trophic status of all four basins of the lake to investigate the pollution status. Thirty-nine sampling locations were randomly selected based on a 100×100 m grid covering the entire lake for water quality sampling. Water quality index (WQI) and trophic level index (TLI) were calculated to further investigate the pollution scenarios. WQI, total nitrogen, total phosphorous, Secchi depth, and Chlorophyll-a were considered to calculate the TLI of the lake. As per the WQI, more than 93% of the lake's

surface area is in poor condition. The TLI reveals the hypereutrophic status of the lake water. According to principal component analysis, eutrophication and algal bloom index observed can be due to the heavy anthropogenic activities and land use patterns around the catchment indicating a high possibility of untreated effluent entering the lake through the active inlets. The effluent entering the lake should be managed immediately to prevent further deterioration of the entire lake. Immediate restoration of the lake is recommended, as the hypereutrophic state may lead to irreversible an imbalance in the lake ecosystem.

Keywords Anthropogenic activities · Geographic information system · Lake deterioration · Monitoring · Pollution scenarios · Restoration

Abbreviations

BOD ₅	Biochemical oxygen demand
CEA	Central Environmental Authority
Chl-a	Chlorophyll-a
COD	Chemical oxygen demand
DO	Dissolved oxygen
EC	Electrical conductivity
PC	Principal component
PCA	Principal component analysis
TDS	Total dissolved solids
TLI	Trophic level index
TSI	Trophic state index
WQI	Water quality index

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Introduction

In 1551, the Portuguese established Beira Lake, a man-made water body for defensive purposes (Kamaladasa and Jayatunga 2007). Apart from serving as a significant landmark in the heart of Colombo, Beira Lake performs a variety of crucial ecosystem functions such as the regulation of floods, and the provision of habitat and nesting grounds for urban wildlife (MCUDP 2016). It helps the process of recharging groundwater, providing a rich and invaluable ecosystem for biodiversity to thrive (Sivakumar et al. 2014; Ratnayake et al. 2018). The decline of the water quality of Beira Lake began at the end of the nineteenth century. Rapid urbanization has had a drastic and adverse impact on Beira Lake due to factors such as its size, stagnancy of the water, and relatively shallow depth, polluting its water. The highly urbanized and tightly populated catchment has contributed indirectly and directly to the degradation of the lake's water quality with an influx of urban stormwater and untreated wastewater (Weerasingha and Handapangoda 2019), leading to high levels of eutrophication, and loss of biodiversity (Bronmark and Hanson 2001).

In the past 45 years, many restoration attempts have been implemented for Beira Lake by different government authorities. Although the failure of restoration attempts is partially due to the implementation of inadequate pollution mitigation strategies without a detailed investigation of its catchment and inlets, the inadequacy of detailed and long-term studies, understanding and evaluating water as well as sediment quality, seems to play a major role. It is, therefore, necessary to understand the existing pollution scenarios across all four Beira Lake basins before any long-term monitoring mechanisms and pollution mitigation plans are implemented.

Much research (Weerasinghe et al. 2019; Dissanayake and Pereira 1996; Wetland Management Strategy MCUDP 2016) has been conducted regarding Beira Lake and its water quality in different basins at different times in the past. Weerasinghe et al. (2019) focused on the selected physiochemical parameters of the surface water of East Beira Lake for 6 months to investigate the suitability for fish and aquatic life. Meanwhile, the Beira Lake Restoration Study in 2017 focused on the internal and external nutrient loadings to the lake. Kamaladasa et al. (2007) studied

the restored part of Southwest and non-restored East Beira Lakes, with the objectives of determining their current trophic status and investigating the effects of restoration in the Southwest Lake on selected water quality parameters. Though the water quality of Beira Lake has been studied previously, they had limitations in establishing the causes of the present pollution status. Past similar studies indicated that although the water quality of Beira Lake has been investigated several times, all four basins of the lake were not investigated at once, hindering problem identification.

Development of water quality index (WQI) models has proved to be an effective tool to comparatively understand the effect of multiple water quality variables by utilizing aggregation functions (Egbe et al. 2023, Menberu et al. 2021, Uddin et al. 2021, Hamed et al. 2018, Wan Abdul Ghani et al. 2018). The primary concept of WQI was first introduced by Horton (1965), which has been accepted worldwide and modified over time to suit the application. More and more recent studies have used WQI as a key factor for water resource management (Parparov and Hambright 2007) as it differentiates and elaborates on forcing factors such as external nutrient loading with the considered lake ecosystem. The trophic state index (TSI), a numerical classification of the trophic status based on relationships between Chl-a and other water quality parameters such as total Phosphorus and transparency, was developed by Carlson (1977). Burns et al. (1999) modified the TSI into trophic level index (TLI) to include total nitrogen in the equation.

TLI is a tool used to assess the trophic state of water bodies, which is an indicator of the nutrient loading status of a water body (Trifonova et al. 2021). TLI also is a measure of the biological productivity of a water body and is determined by the composition of nutrients, such as nitrogen and phosphorus, present in the water (Liu et al. 2022). The Carlson trophic state index (CTSI) is also a commonly used TLI that classifies water bodies into different categories, including oligotrophic, mesotrophic, and eutrophic, based on their nutrient concentrations and other water quality parameters (Trifonova et al. 2021).

Many studies were able to use the water quality indices to make informed decisions about different lake ecosystems. The studies on Lake Timsah and Lake Taihu Basin in China by Serehy et al. (2018) and Wu et al. (2017), respectively, provide good examples of the use of indices such as TSI, TLI, and WQI. Both

the TSI and the TLI indices were used to show the eutrophic condition of the lake waters and confirmed that eutrophication is a major threat in Lake Timsah. Further, a study conducted on Saraydüzü Dam Lake by Kükrer and Mutlu (2019) also provided evidence of the effective use of water quality indices. The study was able to assess the suitability of the water for irrigation purposes. All these studies provided evidence for the effective use of water quality indices for water quality management in lake ecosystems and as a rapid and low-cost water quality evaluation method.

Thus, the present study focused on the quantitative assessment of the water quality and health of the entire Beira Lake covering the East, West, South-West Beira, and the Galle Face Lake basins utilizing numerical indices such as WQI and TLI. Furthermore, a detailed study and analysis of the Beira Lake catchment were carried out to methodically infer areas of the Beira Lake catchment requiring further investigation as well as the areas that need immediate attention concerning pollution mitigation.

Materials and methods

Study area and selection of sample stations

The Beira Lake consists of four main basins covering 0.66 km². The area distribution and boundary coordinates of each catchment of four basins are given in Table 1. Thirty-nine sample stations, covering all four lake basins, were randomly selected by using a 100 m × 100 m grid overlay method. The positioning of sampling locations within the four basins of Beira Lake is shown in Fig. 1.

A sample station was placed in every other square, within the chosen area of the lake. In addition to locating the sampling points within the grid, further considerations were given for the ability to study and

assess the pollutant contribution from the surrounding catchment activities and the effectiveness of the rehabilitation methods implemented.

Therefore, the sampling stations of the lake boundary were placed targeting the inlets such as active stormwater pipes, active wastewater pipes and drains, canals, seasonal stormwater outlets, and inactive wastewater pipes. All the selected sampling stations as in Table 2 were verified through a detailed field survey for validity. Factors such as flow of the water, depth of the water mass, adjacent land use (as shown in Fig. 2), risk of pollution from the surrounding catchment area, and accessibility of the area were considered when confirming the sampling points.

Sample collection and experimental analysis of water quality parameters

Surface water samples were collected at a depth of 1–10 cm in June 2022 and transported to the laboratory following standard methods before testing as per ISO 5667-1:2020. Sample collection times varied from 7.00 a.m. to 12.00 noon. During the sampling, the ambient temperature varied from 29 to 34 °C. Table 3 shows the analytical methods followed for measuring each water quality parameter.

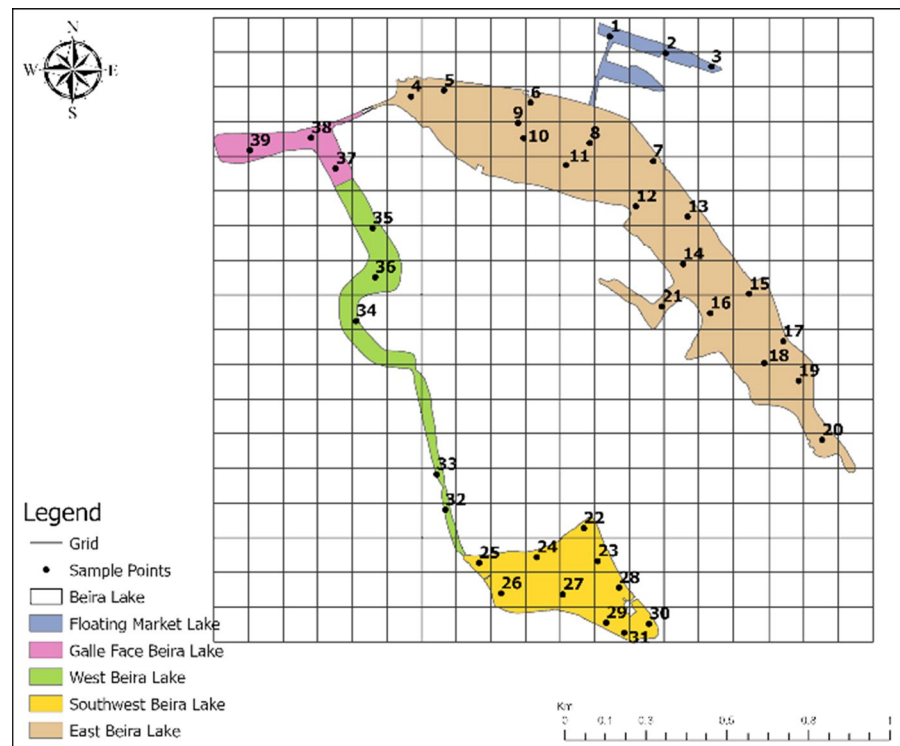
Assessment of water quality indices

Protocol adopted in the water quality analysis to understand interactions and possible pollution scenarios is shown in Fig. 3. Analytical results were compared with the Sri Lankan ambient water quality standards stipulated by the Central Environmental Authority (CEA) in 2019 to understand the current nature of the lake, while extreme conditions were omitted with the help of box plots for obtaining the uniform distribution of the results.

Table 1 Boundary coordinates of the two waterbodies covering 39 sampling points of four basins of Beira Lake

Waterbody	Basin	Area (km ²)	Boundary coordinates	Sample points
1	East Beira Lake (including floating market)	0.437	(79.853803 N, 6.931759 E) to (79.861083 N, 6.920822 E)	21
2	Southwest Beira Lake	0.113	(79.845795 N, 6.930410 E)	10
	West Beira Lake	0.071	to	5
	Galle Face Beira Lake	0.039	(79.855453 N, 6.916004 E)	3

Fig. 1 Positioning of sampling locations within the four basins of the Beira Lake using 100 m × 100 m grids



Estimation of WQI

The WQI was calculated to express the overall state of Beira Lake in the form of a single dimensionless number (Sutadian et al. 2018). A WQI model was developed to estimate the surface water quality of the 39 sample stations spread over different basins of Beira Lake: East, West, Southwest, and Galle Face Lake. The development of the WQI index followed the method proposed by Uddin et al. (2021).

Choosing WQI model parameters

The parameters of the WQI model were chosen based on factors such as data availability, experts' opinions, and the environmental significance of a specific water quality parameter. Temperature is a crucial factor for all biological and chemical reactions. pH affects the solubility and toxicity of many pollutants as well as the growth and reproduction of aquatic organisms. High TDS levels can cause problems for aquatic life. EC is a good indicator of salinity, which can affect the survival of aquatic organisms. Salinity can also increase corrosion rates, leading to the release of metals into the water. Nitrate and nitrite levels are

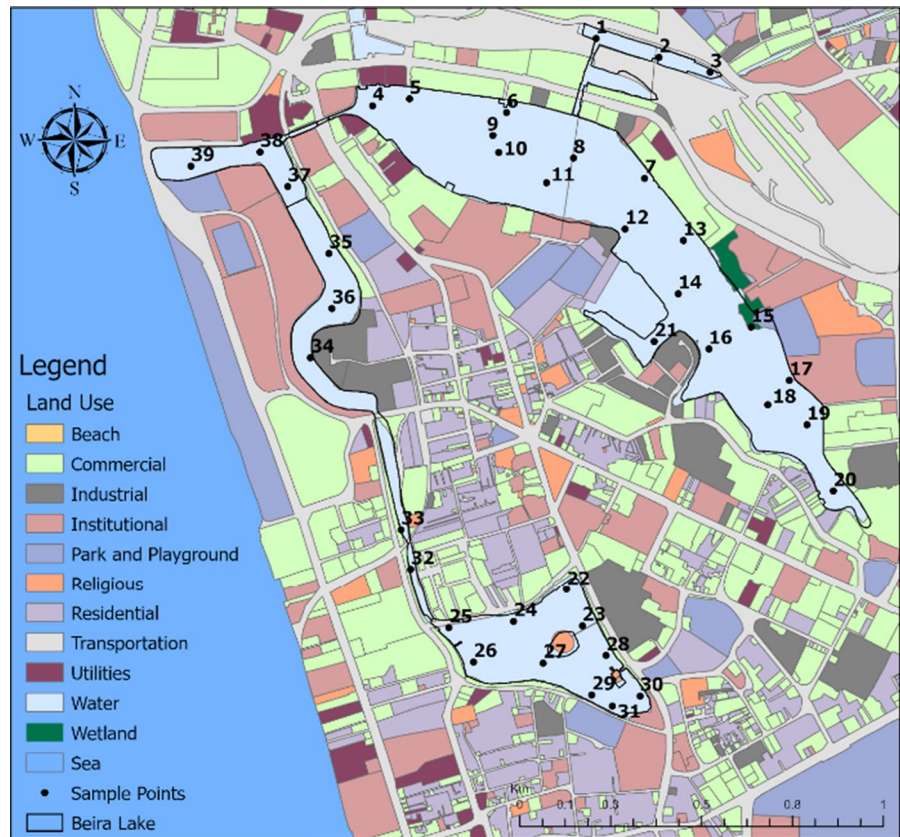
important indicators of nutrient pollution, which can lead to algal blooms and hypoxia in water bodies. Phosphorus is a nutrient that can cause eutrophication, leading to algal blooms and hypoxia. Ammonia can be toxic to aquatic organisms and can also contribute to eutrophication. High levels of BOD₅ can lead to oxygen depletion and harm aquatic life. High levels of COD can indicate high levels of organic matter and can lead to oxygen depletion (Uddin et al. 2021). Therefore, temperature, pH, TDS, EC, salinity, TDS, nitrate, nitrite, reactive phosphorus, nitrogen-ammonia, BOD₅, and COD were selected during the study based on the high levels of organic and industrial pollution of Beira Lake.

The main objective of defining a WQI is to convert the parameter concentrations into unitless values which are denoted as parameter subindices and the method proposed by Abbasi and Abbasi (2012) was followed in this study. The standard water quality guidelines published by the CEA in Sri Lanka were used to determine the subindices. The measured parameter concentrations were directly used as sub-index values, and no conversion process was carried out. Quality rating for the n th parameter is given in Eqs. 1 and 2.

Table 2 Coordinates and details of sampling stations in the four basins of Beira Lake

Station number	Location (basin)	Detail of sampling location	Coordinates		
			X	Y	
1	Floating market (East Beira Lake)	Close to water inlets of the lake from the surrounding catchment	79.854078	6.933241	
2	Floating market (East Beira Lake)		79.855685	6.932758	
3	Floating market (East Beira Lake)		79.857012	6.932371	
4	East Beira Lake	Close to the water inlets of the lake	79.84834	6.93151	
5	East Beira Lake		79.84929	6.931687	
6	East Beira Lake		79.85178	6.931333	
7	East Beira Lake		79.85533	6.929647	
8	East Beira Lake		Close to the middle of the lake	79.8535	6.930164
9	East Beira Lake			79.85143	6.930745
10	East Beira Lake		Within the lake	79.85158	6.930315
11	East Beira Lake	79.85281		6.92953	
12	East Beira Lake	79.85483		6.928345	
13	East Beira Lake	Close to water inlets into the lake	79.85632	6.928046	
14	East Beira Lake	Within the lake	79.85623	6.926681	
15	East Beira Lake	Close to water inlets into the lake	79.85806	6.925819	
16	East Beira Lake	Within the lake	79.85698	6.925261	
17	East Beira Lake	Close to water inlets into the lake	79.85905	6.924455	
18	East Beira Lake	Within the lake	79.85853	6.923829	
19	East Beira Lake	Close to water inlets into the lake	79.85952	6.923313	
20	East Beira Lake	Within the lake	79.86017	6.921609	
21	East Beira Lake	Close to water inlets into the lake	79.85558	6.925451	
22	Southwest Beira Lake	Near an active wastewater drain	79.853321	6.9190636	
23	Southwest Beira Lake	Within the lake	79.8537263	6.9181154	
24	Southwest Beira Lake	Near to active wastewater and drain/pipes	79.8519645	6.9182259	
25	Southwest Beira Lake	Close to an active wastewater drain/pipe and an inactive wastewater pipe	79.850298	6.918063	
26	Southwest Beira Lake	Near active wastewater pipe and inactive wastewater pipe	79.8509335	6.9171818	
27	Southwest Beira Lake	Within the lake	79.85272	6.917157	
28	Southwest Beira Lake	Near Seema malakaya-temple	79.8543382	6.9173475	
29	Southwest Beira Lake	Inside the lake, an active stormwater pipe	79.8539701	6.9163367	
30	Southwest Beira Lake	Within the lake	79.8552113	6.9163084	
31	Southwest Beira Lake	Near a construction site	79.8544961	6.9160481	
32	West Beira Lake	Near active wastewater pipe	79.84932	6.919593	
33	West Beira Lake	Near active wastewater drains	79.8490724	6.9206159	
34	West Beira Lake	Inside the lake near inactive stormwater pipes	79.8467459	6.925037	
35	West Beira Lake	Inside the lake near an active stormwater pipe	79.84722	6.9277152	
36	West Beira Lake	Inside the lake neat inactive stormwater pipes	79.847294	6.926299	
37	Galle Face Lake	Within the lake	79.8461581	6.9294379	
38	Galle Face Lake		79.8454447	6.9303239	
39	Galle Face Lake	Inside the lake near an inactive wastewater pipe	79.8436751	6.9299585	

Fig. 2 Land use pattern around the Beira Lake catchments



$$Q_n = \left\{ \frac{V_n - V_{i0}}{S_n - V_{i0}} \right\} \quad (1)$$

where, Q_n is the quality rating for n th parameter, V_n is the estimated value of the n th parameter of the considered sampling station, V_{i0} is the ideal value of n th parameter in pure water, and S_n is the standard

permissible value for n th parameter specified by CEA.

$$K = \frac{1}{\left(\frac{1}{\sum_{i=1}^n S_n} \right)} \quad (2)$$

Table 3 Analytical methods used for water quality and physiochemical parameters

Parameter	Analytical method
Nitrate	Cadmium reduction method (Hach method 8039)
Nitrite	USEPA diazotization method
Reactive phosphorus	USEPA PhosVer 3 [®] (Ascorbic acid method)
Ammonium nitrogen	Salicylate method, Hach method 10,205
BOD ₅	ASTM standard
COD	USEPA reactor digestion method using DRB200 Reactor (HACH)
Chlorophyll-a (Chl-a)	Spectrophotometric methods as per standard methods for the examination of water and wastewater—20th edition
pH, salinity, temperature	HANNA combined pH/Temp/MV meter (Model—HI991001Ph/temp)
Total dissolved solids (TDS), electrical conductivity (EC), and Secchi disc depth	In situ measurement

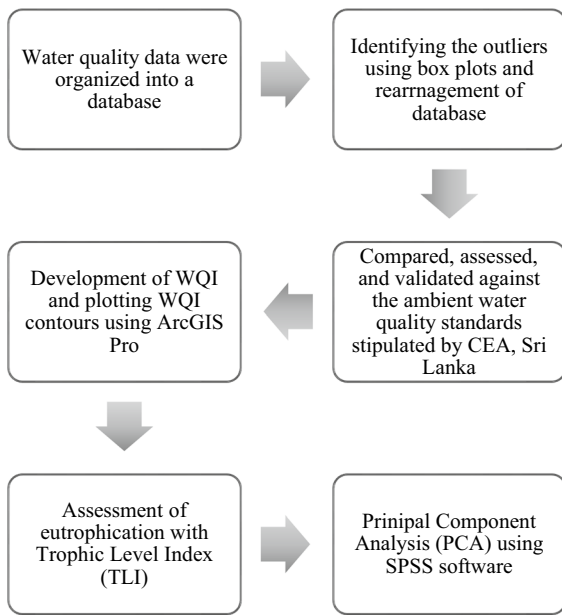


Fig. 3 Process flow diagram of assessing data for water quality indices and statistical analysis of Beira Lake

where K is the proportionality constant, S_n is the standard permissible value for the n th parameter specified by CEA.

Parameter weighting

As per Sarkar and Abbasi (2006), the parameter weight value is assigned based on the relative significance of the considered water quality parameter. This WQI model applied an unequal weighting technique where the addition of all the parameter weights was equal to one. The next step of the WQI model development is the aggregation function, the parameter weight values have a strong and significant influence on the final index value. Therefore, to improve the developed robustness of the WQI model, the unequal weighting technique was used to assign the appropriate weighting values to each parameter considered (Eq. 3). This further reduces any uncertainty and enhances the model’s integrity.

$$W_n = \frac{K}{S_n} \tag{3}$$

where, W_n is the unit weight for n th parameter, K is the proportionality constant, and S_n is the standard

Table 4 Categorization of WQI classes

WQI	Water quality status	Class
0–25	Excellent	A
26–50	Good	B
51–75	Poor	C
76–100	Very poor	D
> 100	Unfit for consumption	E

permissible value for n th parameter specified by CEA.

Aggregation of the subindices to obtain the overall WQI value

This process is applied to aggregate the parameter sub-indices into a single WQI score. In this WQI model, the additive function was utilized as given in Eq. 4.

$$WQI = \frac{\sum W_n \cdot Q_n}{\sum W_n} \tag{4}$$

where, WQI is the water quality index value for the sampling station, W_n is the unit weight for n th parameter, and Q_n is the quality rating for n th parameter.

WQI evaluation

The WQI values obtained at each sampling station were evaluated and categorized according to the classes as shown in Table 4.

Graphical representation of WQI using ArcGIS Pro

The main objective of this step was to graphically represent the WQI values to further support the discussion and justification of how the water quality of Beira Lake is affected by the surrounding catchment properties, land use, and anthropogenic activities. A single map was drawn using ArcGIS Pro software to indicate the WQI values at each sample station and contour lines were mapped at 10 m unit intervals.

TLI evaluation

Given that Beira Lake is well known for its green color waters and algal growth, it is crucial to examine

the eutrophication status at each sampling station. This was accomplished by determining TLI values at each sampling station. Chl-a concentration, Secchi disc depth, total phosphorus, and total nitrogen are the water quality parameters used for the TLI (Abell et al. 2019) (Eqs. 5, 6, 7, 8, and 9).

$$TLI = \frac{1}{4} \{ TL(\text{Chl-a}) + TL(\text{SD}) + TL(\text{TP}) + TL(\text{TN}) \} \quad (5)$$

where, Chl-a, SD, TP, and TN are Chl-a concentration in $\mu\text{g/L}$, Secchi disc depth in meters (m), total phosphorus in $\mu\text{g/L}$, and total nitrogen in $\mu\text{g/L}$ at the considered sampling station.

$$TL(\text{Chl-a}) = 2.22 + 2.54 \log(\text{Chl-a}) \quad (6)$$

$$TL(\text{SD}) = 5.10 + 2.60 \log\left(\frac{1}{\text{SD}} - \frac{1}{40}\right) \quad (7)$$

$$TL(\text{TP}) = 0.218 + 2.92 \log(\text{TP}) \quad (8)$$

$$TL(N) = -3.61 + 3.01 \log(\text{TN}) \quad (9)$$

Data analysis

The multimodal structure of water quality data makes it a challenging process to identify anomalous observations, which is a major concern in water quality monitoring (Blasi et al. 2013). The overall values recorded for each water quality parameter were graphically represented by using box plots through XLStat software to remove the outliers from the water quality parameters such as temperature, pH, TDS, EC, salinity, DO, Secchi disc depth, nitrate, nitrite, reactive phosphorus, ammonium-nitrogen, BOD5, COD, and Chl-a from all basins Southwest, East, West, Galle Face Beira Lake including Floating market segment.. This eliminated the abnormal variation in the WQI, TLI, and TSI as well.

The scatter plots were drawn for all samples collectively to investigate the special scattering patterns of the water quality of the sampling stations prior subsequent analysis. Software for canonical community ordination (CANOCO version 4.5) was used (Ter Braak and Smilauer 2002). The scatter plot analysis revealed that the sampling stations were broadly scattered into two distinct regions.

Hence, considering the scattering pattern, sampling stations were grouped into two main waterbodies, such as waterbody 1 (Southwest, West, Galle Face Beira Lake) and 2 (East Beira Lake including Floating market segments of Beira Lake) as shown in Fig. 4. Hence, it was decided to conduct a principal component analysis (PCA) separately on waterbody 1 and waterbody 2 to classify and recognize the key factors (principal components) that have caused the eutrophication and algae growth in present study. Past research has successfully used PCA to identify the key contributing water quality parameters for Lake Eutrophication status (Acharya et al 2012).

Varimax rotation was utilized in PCA as this was the most accepted method of orthogonal rotation (Abdi et al. 2010). Further, it could also be considered advantageous given that it amplifies the variances of the weighing within the factors while consequently maximizing the disparity between high and low loadings of a considered factor. In this test, the water quality parameters that obtained a coefficient value greater than 0.6 were considered significant.

Pearson's correlation was conducted to check the linearity of the two variables. Kaiser–Meyer–Olkin (KMO) test was done to measure the sampling adequacy of the data set and Bartlett's test of sphericity was conducted to check whether the data set is suitable for the reduction.

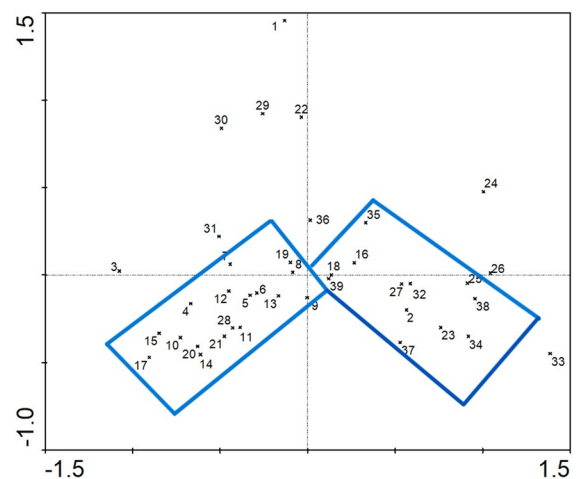


Fig. 4 Scatter plot of the sampling points covering the entire Beira Lake

Results and discussion

Elimination of outliers in water quality data of the Beira Lake

Figure 5 shows Box and whisker plots used to identify and eliminate outliers in the water quality data. Stations 28 and 31 have recorded an extremely higher concentration of $\text{NH}_4\text{-N}$, meanwhile, station 28 recorded an extremely higher concentration of Chl-a and was considered as outliers.

Water quality index (WQI) and trophic level index (TLI) of Beira Lake

WQI combines intricate analytical raw data and produces a single number (much like a letter grade, e.g., A, B, C, D, E) that expresses the water quality subjectively as shown in Fig. 6. Such a scoring system enabled simplicity and clear understanding of water quality parameters measured. In this study, the WQI was used to determine the suitability of the Lake water for

different applications such as swimming, bathing, or other recreational activities.

The WQI shown in Fig. 6 provided an overall analysis of the water quality of Beira Lake coupled with the land use pattern around the lake and the water outlet network. Most of the sample stations indicated that the water quality was unfit for consumption; however, only three sample stations (8, 9 and 13) indicated ‘good’ quality water which is located on East Beira Lake which is surrounded by less number of active and few inactive stormwater inlet pipes.

‘Poor’ WQI was mainly found at Southwest Lake where the lake is surrounded by several active wastewater inlet pipes bringing effluent from multiple residential buildings and a few industries around the Southwest Lake. Meanwhile, in East Beira Lake, the area around sampling stations 15, 17 and 20 displayed the ‘poorest’ water quality according to the WQI. The stations are surrounded by institutional and residential buildings where there is a possibility of sewage entering the lake and direct waste dumping illegally. Accordingly, the Floating Market area of Lake is completely unfit for any water related activity. This

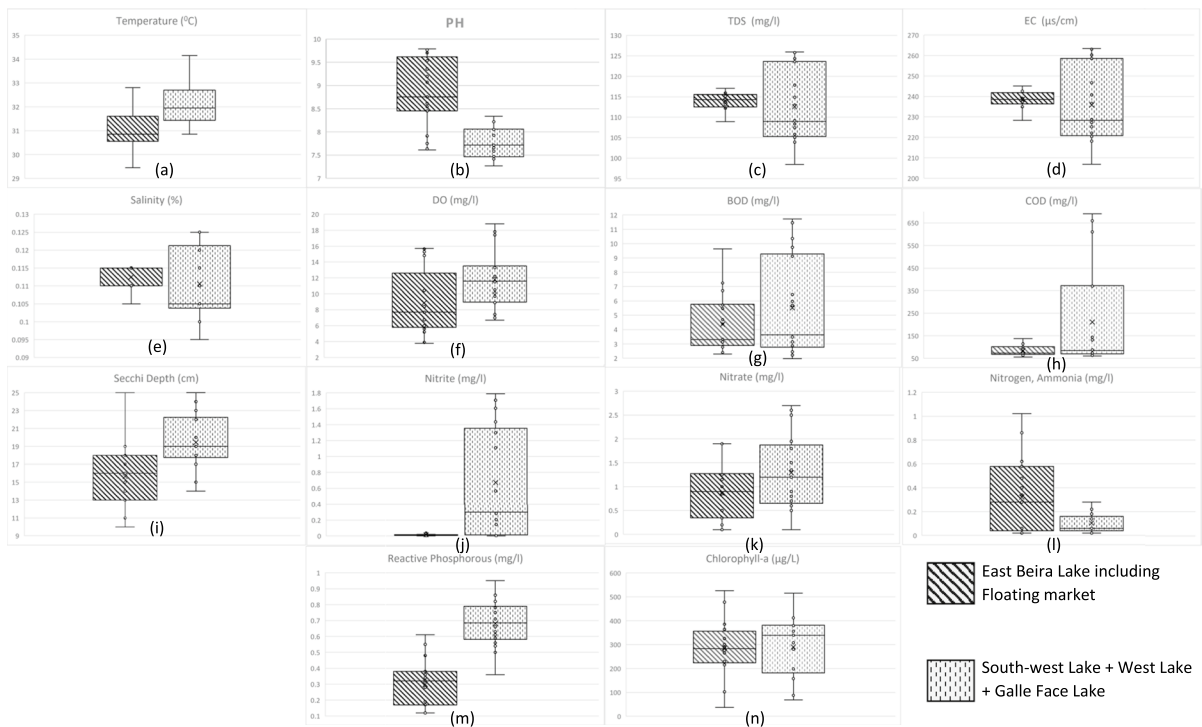


Fig. 5 Box and whisker plots of the water quality parameters of catchments in Beira Lake

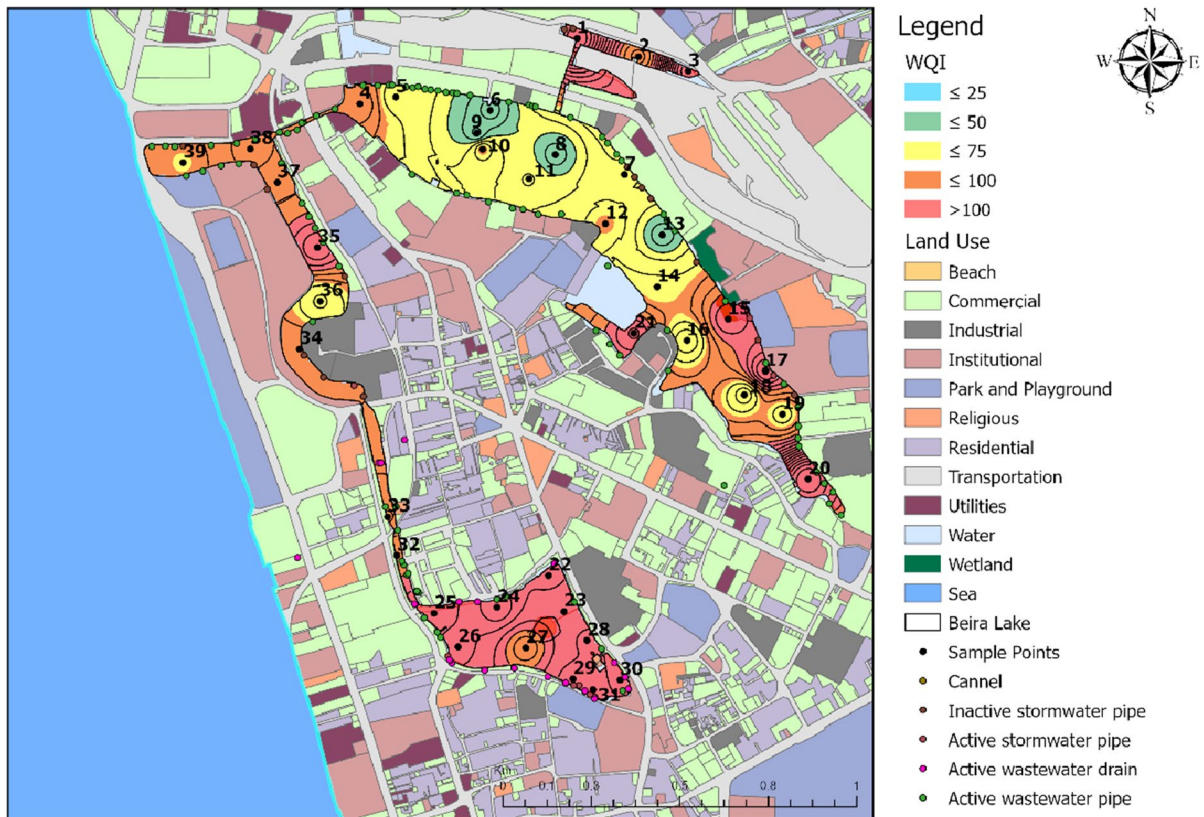


Fig. 6 Distribution and contour map of WQI related to land use pattern in the catchment covering four basins of Beira Lake

area is enclosed by the central bus depot of Colombo city, an open market where the stormwater and sewage from the public facilities could end up in the lake.

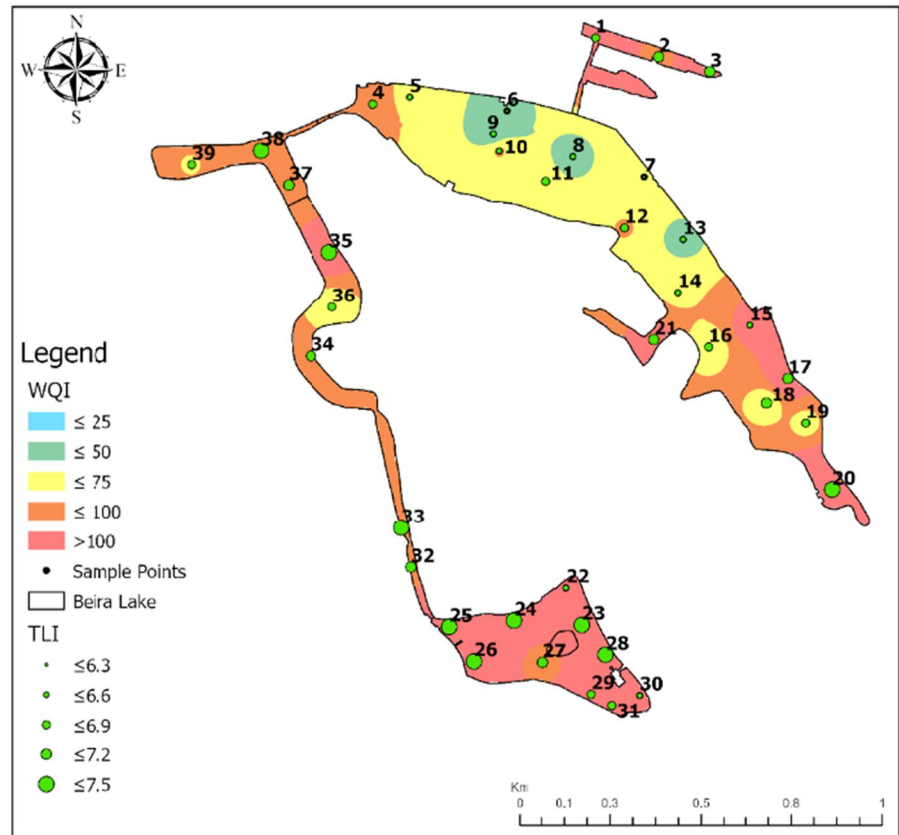
The variation of TLI fits and confirms the variation of the WQI in the lake where the higher the WQI, the higher the TLI. TLI indicates that all sample stations within Beira Lake were hyper-eutrophic thus classifying the whole of Beira Lake as “hypereutrophic” as shown in Fig. 7. The sampling locations 6, 8, 9, and 13 have best WQIs among the sampling locations, where the TLI was observed to be the least.

The measured data were evaluated in comparison with the ambient water quality standards published by the CEA of Sri Lanka (National Environmental (Ambient Water Quality) Regulations, No. 01 of 2019 on November 5, 2019) to obtain a qualitative evaluation of the pollution status of East Beira Lake. The study of Weerasingha and Handapangoda (2019) showed a similar variation in temperature and was under 40 °C being within the tolerance limits. Although the tolerance limits for pH ranged from 6.5

to 8.5, 71% of the sample stations exceeded these levels being on par with the studies conducted in 2017 by the Ministry of Megapolis and Western Development. The ambient water quality standards did not provide the appropriate threshold values for parameters such as salinity, TDS, and conductivity. Except for two sample stations (1—Floating Market and 10—East Lake), the rest of the sample stations indicated acceptable levels (as per National Environmental (ambient water quality) Regulations, No. 01 of 2019 on November 5, 2019) of DO values (≥ 5 mg/l) for the existence of aquatic fish and plants, this may probably be due to the photosynthesis activities of the algal blooms during the daytime.

Nitrate, reactive phosphorus, and ammonium nitrogen in sample station 1 showed a deviation from the given threshold values. A similar deviation could be observed for the COD of the same station as well as all the other stations which may be due to anthropogenic activities such as unauthorized release of the stormwater runoff, domestic wastewater, and

Fig. 7 Magnitude of TLI with the variation of WQI in the catchment covering four basins in the Beira Lake



industrial wastewater discharges. It is evident that the industries operating in the surrounding catchment area that release their sewage into the waters of East Beira Lake are responsible. Furthermore, 48% of the sample stations indicated that BOD₅ levels exceeded the provided threshold value (National Environmental (Ambient Water Quality) Regulations, No. 01 of 2019 on November 5, 2019) of 4 mg/l which indicated high levels of pollution within the basins.

Key factors affecting eutrophication of Beira Lake

PCA was utilized to identify the most prominent factors contributing to eutrophication. All values below 0.1 were omitted, while all values above 0.6 were regarded as correlated factors. A novel set of factors each consisting of a key subdivision of the original variables with minor overlays due to the rotation of the axis was conducted by the factor analysis.

The Pearson correlation coefficient between the variables showed that a linear relationship exists (Sharma and Vardhan 2018). Kaiser–Meyer–Olkin’s

measure of sampling adequacy was 0.683, which is greater than 0.65 with an approximate chi-square of 287.798, indicating sufficient variables within the data set to conduct the PCA. Bartlett’s test of sphericity showed a significant value of 0.0001 which is less than 0.05 confirming that there is a significant difference between the correlation matrix and the identity matrix, where correlations among the variables are close to zero. All the extracted communalities were greater than 0.5 which is at the acceptable limits.

The significance level of the factor analysis was assessed by the Eigenvalue. The eigenvalue showed how the variance was distributed among the factors. Eigenvalues greater than 1 were considered. An eigenvalue less than 1 described fewer facts than a single item would have explained IBM-SPSS (Vadde et al. 2018; Razmkhah et al. 2010; Badaii et al. 2013; Ustaoglu et al. 2019). Therefore, the eigenvalues less than 1 were omitted and five principal component factors were considered in the analysis of this study. A rotated factor matrix was considered due to rotation occupies several underlying factors that

predict distinct items. Varimax rotation with Kaiser Normalization maximized the variances of the loadings on a given factor while it increases the difference between high and low loadings on the factor considered. Hence, 15 experimental variables on the varimax rotated PCs on five significant variables for Beira Lake were analyzed. Values greater than 0.6 were considered highly loaded in the rotated component matrix and values less than 0.1 of absolute values were omitted. The generated, rotated component matrix of water quality parameters with the PCs is shown in Table 5.

Thus, taking into consideration the loadings on each of the considered PCs derived, they can be named as follows.

PC1—Nutrient index (Anthropogenic activities)

PC2—Eutrophication and algal bloom index

PC3—TDS and water temperature index

PC4—Water clarity index

PC5—Water alkalinity/acidity index

The first five PCs accounted for 84.288% of the total variance for East Beira Lake as shown in Table 5. Therefore, abiding by Ruggieri et al. (2011), five PCs were obtained, which consisted of Eigenvalues greater than one where the first PC explained 29.403% of the total given variance. Similarly, the

first five PCs of waterbody 2 combined to form a total variance of more than 82%.

PC1—Nutrient index (Anthropogenic activities)

PC1, the nutrient index of 29.403%, was intensely positively loaded with the variables: ammonium nitrogen, reactive phosphorus, nitrite, nitrate, and BOD₅ of waterbody 1, while PC1 accounts for 28.794% of the total variance of the waterbody 2. Moreover, a prominent negative loading was contributed by pH in waterbody 1, while pH and TDS negatively contributed to waterbody 2. PC1 recognizes the significance of the contributions made to East Beira Lake including Floating market by the surrounding anthropogenic activities. The Beira Lake catchment is highly urbanized and densely populated with industries, commercial establishments, institutions, hotels, religious places of worship, human settlements, and colonies that are responsible for the indirect and direct influx of wastewater to the Beira Lake. It is also noticeable that the Beira Lake bank coverage comprises a very scarce amount of vegetation (Weerasingha and Handapangoda 2019). Therefore, it is evident that the negative impact of industrial and anthropogenic activities surrounding Beira Lake severely

Table 5 Rotated component matrix of water quality parameters of PCA for the waterbodies of the Beira Lake

Variables	Water body 1					Water body 2				
	PC1	PC2	PC3	PC4	PC5	PC1	PC2	PC3	PC4	PC5
Salinity	0.462			0.734		0.231	0.103	0.106	0.213	
TDS	0.588			0.752		0.512	−0.254	0.115	0.228	0.763
EC	0.286					0.148		0.114	0.130	
pH	−0.365				−0.777	−0.638		−0.793		
Nitrite	0.759	0.624				0.611	0.506	0.147		0.190
COD		−0.324	−0.185			0.125	−0.412	0.273		
Reactive phosphorous	0.764	0.677	0.315			0.816	0.623		−0.259	
Temperature		0.260	0.836	−0.425		−0.155	−0.401	−0.228	0.789	−0.124
DO		−0.532	−0.764			−0.625	0.242		−0.652	
Secchi disc depth		−0.638	0.231					−0.255		−0.682
BOD ₅	0.744					0.753		0.767	0.338	0.134
Nitrate	0.758	0.146	−0.234			0.643	0.602	0.179	−0.541	0.162
Ammonium nitrogen	0.774	0.132		−0.382		0.871	0.611	−0.457		−0.408
Chl-a	0.324	0.782				0.203	0.814	0.250		
Eigenvalues	4.116	2.561	2.182	1.571	1.370	4.031	2.558	1.789	1.711	1.395
PV (%)	29.403	18.294	15.586	11.221	9.784	28.794	18.272	12.781	12.220	9.967
CPV (%)	29.403	47.697	63.283	74.504	84.288	28.794	47.066	59.848	72.067	82.034

affects its water quality. Therefore, this interprets the anthropogenic input to the lake.

PC2—Eutrophication and algal bloom index

The PC2 accounts for 18.294% of the total variance in waterbody 1, while 18.272% accounts for waterbody 2. This component indicates maintaining the strongest positive correlation with the Chl-a variable that explains the eutrophication status of East Beira Lake. Other prominent positive loadings for this PC can be identified as reactive phosphorus and nitrite, while Secchi disc depth indicates a powerful negative association. PC2 in waterbody 2 is highly positively loaded with Chl-a, reactive phosphorus, ammonium nitrogen, and nitrate, where the ammonium nitrogen indicates the direct influence of the sewage. The high levels of eutrophication caused by these nutrients and algae are an indication of the hypertrophic state of Beira Lake. This factor can be categorized to provide the eutrophication status within Beira Lake.

PC3—TDS and water temperature index

PC3, which represents 15.586% of the total given variance, was strongly positively loaded with temperature and prominently negatively loaded with DO. Therefore, this component can be identified to reflect the physical characteristics of the East Beira Lake environment in waterbody 1. The PC3 contributes to 12.781% of the total variance in waterbody 2. This includes highly positive loaded BOD₅, with extremely negative loaded pH. PC3 gives an alkalinity index with degrading BOD₅ variation of the Beira Lake.

PC4—Water clarity index

PC4 contributing 11.221% of the total variance was strongly positively correlated by salinity and TDS in waterbody 1 while in waterbody 2 PC4 accounts for 12.220% of the total variance where highly positively loaded with temperatures while negatively correlated with TDS where this component shows the physical environment in the lake. The increasing levels of TDS within the water body contribute to the lowered turbidity thus reducing water transparency. The high levels of Chl-a values recorded at each of the sample stations indicate the increased unfavorable water quality. Chl-a values ranged from 68 to 693 µg/l in

the waterbody 2 which were recorded in sample stations 30 and 28, respectively.

PC5—Water alkalinity/acidity index

PC5 contributed 9.784% of the total variance where independently negatively loaded by pH while PC5 accounts for 9.967% of the total variance in waterbody 2, which is highly positively correlated with TDS and highly negatively loaded with Secchi disc depth indicating the deprived water transparency of Beira Lake. East Beira Lake is highly polluted with large amounts of algae blooms in all sampling stations. According to Fig. 4b, the pH of Beira Lake was greater than 7 where the lake status is alkaline. The Secchi disc depth (Fig. 4i) varied from 27 to 10 cm, which indicated that the water clarity of the whole Beira Lake system is considerably poor.

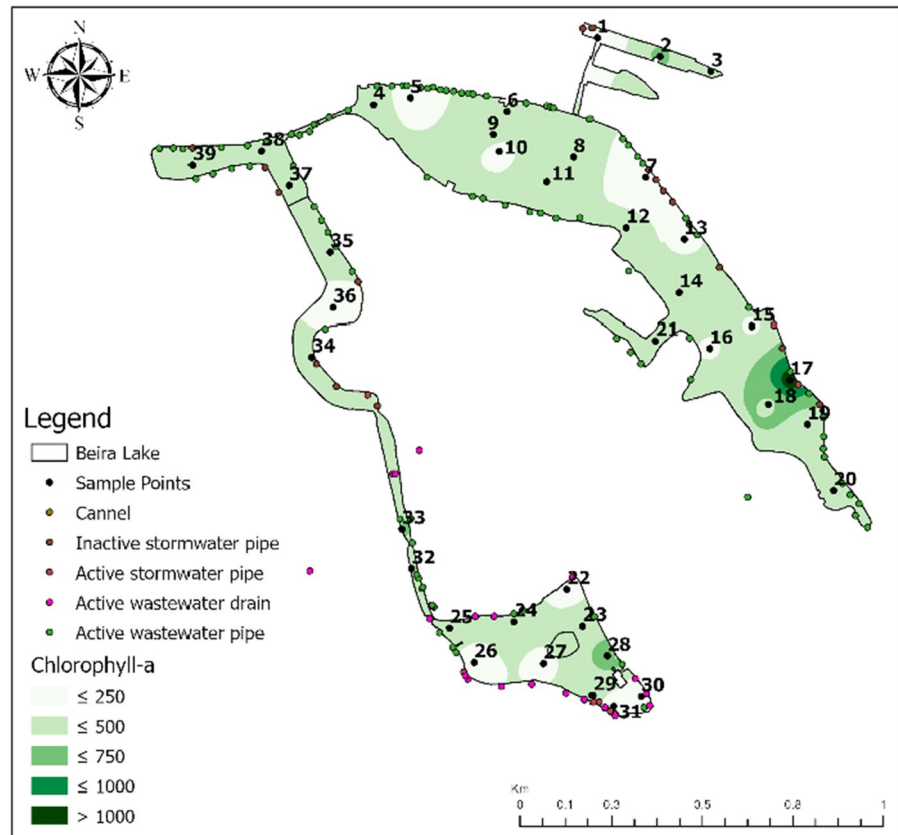
Influence of the anthropogenic activities on the algal blooms of Beira Lake

Chl-a is a direct indication of the concentrations of algal blooms in terms of the algal distribution throughout the lake that can be quantified. Algal blooms were severely concentrated in locations where the sewage outfalls as shown in Fig. 8. This was indicated through the PC1 and PC2. In addition, the WQI is in category E (Unfit for Consumption) and the trophic status indices reflect the stations to be “hypereutrophic”.

The highest Chl-a concentration of 1108 µg/l was recorded in the Southern part of the East Beira Lake (stations 17 and 18) which was surrounded by several active wastewater outlets which bring nutrients with high concentrations where the algal bloom has grown rapidly. These observations are in par with similar studies from other countries (French and Petticrew 2007). These stations were situated near active wastewater pipes which release diverse types of waste with the water which contains high nutrient concentrations such as nitrate and phosphorus that accelerate the growth of the algal, dense accumulation of algal can be observed in these areas.

Furthermore, the next highest distribution of Chl-a can be identified in Galle Face Lake and the upper area of the West Lake which contain discharges from active wastewater pipes, inactive wastewater, and stormwater pipes. This has a relatively low

Fig. 8 Stormwater, wastewater inlets and the distribution of Chl-a ($\mu\text{g/l}$) concentration in the entire Beira Lake



concentration distribution; however, these values are well above the allowed value of $10 \mu\text{g/l NO}_3\text{-N}$ indicating the hypertrophic status of Beira Lake.

Suggestions for lake restoration

More extensive and comprehensive solutions are urgently needed to eliminate nutrient pollution caused by anthropogenic activities. The initial step would be to reduce the pollution loads from the surrounding catchment by encouraging the industries and homeowners to reduce the unauthorized discharges, which are major contributors to nutrient pollution in the lake. Further, government interventions are necessary to upgrade the sewage treatment facilities in the area to ensure that all wastewater is properly treated before being discharged into the lake. Erosion is another significant contributor to nutrient pollution in the lake. Implementing measures such as soil conservation practices, terracing, and erosion control structures to minimize soil erosion and prevent sediment from entering the lake would be appropriate. Stormwater runoff can carry pollutants

such as sediment, nutrients, and other contaminants into the lake. Implementing measures such as rain gardens, green roofs, and permeable pavement to reduce the amount of stormwater runoff entering the lake could have major impacts to reduce the pollution. Educate the local community about the importance of the lake and the need to reduce pollution. This can be done through community outreach programs, public service announcements, and other educational initiatives. Most importantly, establishment of a water quality monitoring program would be required to track the progress of the restoration efforts and identify any emerging issues that need to be addressed. By implementing a combination of these measures, it would be possible to restore the health of Beira Lake and prevent further degradation in the future.

Conclusion

The study assessed the extent of eutrophication based on the indices represented by TLI and the WQI. TLI

showed that all four lake basins were hypereutrophic, while the WQI reconfirmed the deteriorated status of the water quality. The observed variation in nutrient concentrations across sampling locations supported the hypothesis that nutrient enrichment plays a significant role in the lake's water quality and trophic status. These findings affirm the previously suggested notion that nutrient enrichment is a critical factor influencing water quality and trophic level.

Direct and indirect evidence could be established (highest Chl-a concentration) in the Southern part of the East Beira Lake to conclude the high possibility of several active wastewater outlets bringing nutrient loads into the Beira Lake leading to high algal blooms. WQI calculations indicated that more than 93% of the lake is in poor water quality condition. The TLI revealed that the lake water is completely unfit for any type of human activities, indicating a hypereutrophic state. According to the findings, Nutrient index (Anthropogenic activities) is the most prominent factor contributing to the lake's deterioration, followed by Eutrophication and algal bloom index. According to PCA analysis confirmed anthropogenic input to the lake due to land use pattern around the catchment indicating a high possibility of untreated effluent entering the lake through active inlets. The effluent entering the lake should be addressed immediately to prevent the further deterioration of the entire lake.

More extensive and comprehensive solutions are urgently needed to eliminate nutrient pollution caused by anthropogenic activities. By implementing a combination of these measures such as completely eliminating the unauthorized pollution loads entering the lake by improving the sewage treatment facilities in the catchment, providing buffer strips with deep-rooted vegetation along the lake to reduce the sedimentation due to stormwater runoff, increasing public awareness, implementing a continuous water quality monitoring program are some of the possible to restore the health of Beira Lake and prevent further degradation in the future.

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Declarations

Conflict of interest There are no competing interests to declare.

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