Assessment of Pollution State of Beire 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 sampling locations were selected based on a 100×100 m grid to cover the entire lake. 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 (Chl-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 principle 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.

Introduction

In 1551, the Portuguese established Beira Lake, a man-made water body for defensive purposes (Kamaladasa & 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 (Metro Colombo Urban Development Project, 2016). It helps the process of recharging groundwater, providing a rich and invaluable ecosystem for biodiversity to thrive (Anand, 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 & Handapangoda, 2019), leading to high levels of eutrophication, and loss of biodiversity (Bronmark & 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; Restoring Beira Lake, 1996; Beira Lake Restoration Study, 2017; Wetland Management Strategy (MCUDP), 2016) has been conducted regarding Beira Lake and its water quality in different basins of the Beira Lake 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 06 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 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, it had its 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). 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 & 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 in 1977. In 2005, Burns et al. modified the TSI into Trophic Level Index (TLI) to include Total Nitrogen in the equation.

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 Sarayduzu 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 that cover 0.66 km\(^2\). 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 100m × 100m grid overlay method. The positioning of sampling locations within the four basins of Beira Lake is shown in Fig. 1.
Table 1
- Boundary coordinates of the two waterbodies covering 39 sampling points of four basins of Beira Lake

<table>
<thead>
<tr>
<th>Waterbody</th>
<th>Basin</th>
<th>Area (km²)</th>
<th>Boundary coordinates</th>
<th>Sample points</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>East Beira Lake (Including Floating market)</td>
<td>0.437</td>
<td>(79.853803 N, 6.931759 E) to (79.861083 N, 6.920822 E)</td>
<td>21</td>
</tr>
<tr>
<td>2</td>
<td>Southwest Beira Lake</td>
<td>0.113</td>
<td>(79.845795 N, 6.930410 E) to (79.855453 N, 6.916004 E)</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>West Beira Lake</td>
<td>0.071</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Galle Face Beira Lake</td>
<td>0.039</td>
<td>(79.855453 N, 6.916004 E)</td>
<td>3</td>
</tr>
</tbody>
</table>

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 lake boundaries sampling stations 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.
Table 2
- Coordinates and details of sampling stations in the four basins of Beira Lake

<table>
<thead>
<tr>
<th>Station number</th>
<th>Location</th>
<th>Detail of sampling location</th>
<th>Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Floating market (East Beira Lake)</td>
<td>Close to water inlets of the lake from the surrounding catchment</td>
<td>X: 79.854078  Y: 6.933241</td>
</tr>
<tr>
<td>2</td>
<td>Floating market (East Beira Lake)</td>
<td></td>
<td>X: 79.855685  Y: 6.932758</td>
</tr>
<tr>
<td>3</td>
<td>Floating market (East Beira Lake)</td>
<td></td>
<td>X: 79.857012  Y: 6.932371</td>
</tr>
<tr>
<td>4</td>
<td>East Beira Lake</td>
<td>Close to the water inlets of the lake</td>
<td>X: 79.84834   Y: 6.93151</td>
</tr>
<tr>
<td>5</td>
<td>East Beira Lake</td>
<td></td>
<td>X: 79.84929   Y: 6.931687</td>
</tr>
<tr>
<td>6</td>
<td>East Beira Lake</td>
<td></td>
<td>X: 79.85178   Y: 6.931333</td>
</tr>
<tr>
<td>7</td>
<td>East Beira Lake</td>
<td></td>
<td>X: 79.85533   Y: 6.929647</td>
</tr>
<tr>
<td>8</td>
<td>East Beira Lake</td>
<td>Close to the middle of the lake</td>
<td>X: 79.8535    Y: 6.930164</td>
</tr>
<tr>
<td>9</td>
<td>East Beira Lake</td>
<td></td>
<td>X: 79.85143   Y: 6.930745</td>
</tr>
<tr>
<td>10</td>
<td>East Beira Lake</td>
<td>Within the lake</td>
<td>X: 79.85158   Y: 6.930315</td>
</tr>
<tr>
<td>11</td>
<td>East Beira Lake</td>
<td></td>
<td>X: 79.85281   Y: 6.92953</td>
</tr>
<tr>
<td>12</td>
<td>East Beira Lake</td>
<td></td>
<td>X: 79.85483   Y: 6.928345</td>
</tr>
<tr>
<td>13</td>
<td>East Beira Lake</td>
<td>Close to water inlets into the lake</td>
<td>X: 79.85632   Y: 6.928046</td>
</tr>
<tr>
<td>14</td>
<td>East Beira Lake</td>
<td>Within the lake</td>
<td>X: 79.85623   Y: 6.926681</td>
</tr>
<tr>
<td>15</td>
<td>East Beira Lake</td>
<td>Close to water inlets into the lake</td>
<td>X: 79.85806   Y: 6.925819</td>
</tr>
<tr>
<td>16</td>
<td>East Beira Lake</td>
<td>Within the lake</td>
<td>X: 79.85698   Y: 6.925261</td>
</tr>
<tr>
<td>17</td>
<td>East Beira Lake</td>
<td>Close to water inlets into the lake</td>
<td>X: 79.85905   Y: 6.924455</td>
</tr>
<tr>
<td>18</td>
<td>East Beira Lake</td>
<td>Within the lake</td>
<td>X: 79.85853   Y: 6.923829</td>
</tr>
<tr>
<td>19</td>
<td>East Beira Lake</td>
<td>Close to water inlets into the lake</td>
<td>X: 79.85952   Y: 6.923313</td>
</tr>
<tr>
<td>20</td>
<td>East Beira Lake</td>
<td>Within the lake</td>
<td>X: 79.86017   Y: 6.921609</td>
</tr>
<tr>
<td>21</td>
<td>East Beira Lake</td>
<td>Close to water inlets into the lake</td>
<td>X: 79.85558   Y: 6.925451</td>
</tr>
<tr>
<td>22</td>
<td>Southwest Beira Lake</td>
<td>Near an active wastewater drain</td>
<td>X: 79.853321  Y: 6.9190636</td>
</tr>
<tr>
<td>23</td>
<td>Southwest Beira Lake</td>
<td>Within the lake</td>
<td>X: 79.8537263 Y: 6.9181154</td>
</tr>
<tr>
<td>24</td>
<td>Southwest Beira Lake</td>
<td>Near to active wastewater and drain/pipes</td>
<td>X: 79.8519645 Y: 6.9182259</td>
</tr>
<tr>
<td>25</td>
<td>Southwest Beira Lake</td>
<td>Close to an active wastewater drain/pipe and an inactive wastewater pipe</td>
<td>X: 79.850298  Y: 6.918063</td>
</tr>
<tr>
<td>26</td>
<td>Southwest Beira Lake</td>
<td>Near active wastewater pipe and inactive wastewater pipe</td>
<td>X: 79.8509335 Y: 6.9171818</td>
</tr>
</tbody>
</table>
Sample collection and experimental analysis of water quality parameters

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Analytical method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrate</td>
<td>Cadmium reduction method (Hach method 8039)</td>
</tr>
<tr>
<td>Nitrite</td>
<td>USEPA Diazotization method</td>
</tr>
<tr>
<td>Reactive Phosphorus</td>
<td>USEPA PhosVer 3® (Ascorbic acid method)</td>
</tr>
<tr>
<td>Ammonium Nitrogen</td>
<td>Salicylate method, Hach method 10205</td>
</tr>
<tr>
<td>BOD$_5$</td>
<td>ASTM standard</td>
</tr>
<tr>
<td>COD</td>
<td>USEPA reactor digestion method using DRB200 Reactor (HACH)</td>
</tr>
<tr>
<td>Chlorophyll-a (Chl-a)</td>
<td>Spectrophotometric methods as per Standard Methods for the Examination of water and wastewater – 20th edition</td>
</tr>
<tr>
<td>pH, Salinity, Temperature</td>
<td>HANNA Combined pH/ Temp/ MV meter (Model – HI991001Ph/temp)</td>
</tr>
<tr>
<td>Total Dissolved Solids (TDS), Electrical Conductivity (EC), and Secchi disc depth</td>
<td>In-situ measurement</td>
</tr>
</tbody>
</table>
Assessment of Water Quality Index, Trophic State Index, and PCA of Beira Lake

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.

Removal of outliers

Since several factors including anthropogenic activities affect water quality, frequently prone to some outliers. 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 data, eliminating the abnormal variation in the WQI, TLI, and TSI.

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 BOD$_5$ 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 (N, 2016). Therefore, temperature, pH, TDS, EC, salinity, TDS, nitrate, nitrite, reactive phosphorus, nitrogen-ammonia, BOD$_5$, 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 subindex values and no conversion process was carried out. Quality rating for the $n^{th}$ parameter as given in Eqs. 1 and 2.

$$Q_n = \left\{ \frac{V_n - V_{i0}}{S_n - V_{i0}} \right\}$$
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, $V_i$ 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.

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

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.

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

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.

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

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.
Table 4
Categorization of WQI classes

<table>
<thead>
<tr>
<th>WQI</th>
<th>Water Quality Status</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–25</td>
<td>Excellent</td>
<td>A</td>
</tr>
<tr>
<td>26–50</td>
<td>Good</td>
<td>B</td>
</tr>
<tr>
<td>51–75</td>
<td>Poor</td>
<td>C</td>
</tr>
<tr>
<td>76–100</td>
<td>Very Poor</td>
<td>D</td>
</tr>
<tr>
<td>&gt; 100</td>
<td>Unfit for Consumption</td>
<td>E</td>
</tr>
</tbody>
</table>

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 10m unit intervals.

Determination of the Trophic Level Index (TLI) at each sampling station

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. 5–9).

\[
TLI = \frac{1}{4}\{TL(Chl-a) + TL(SD) + TL(TP) + TL(TN)\}
\]

5

Where, Chl-a, SD, TP, and TN are chl-a concentration in µg/L, secchi disc depth in meters (m), total phosphorus in µg/L, and total nitrogen in µg/L at the considered sampling station.

\[
TL(Chl-a) = 2.22 + 2.54\log(Chl-a)
\]

6

\[
TL(SD) = 5.10 + 2.60\log\left(\frac{1}{SD} - \frac{1}{40}\right)
\]

7

\[
TL(TP) = 0.218 + 2.92\log(TP)
\]

8

\[
TL(TN) = -3.61 + 3.01\log(TN)
\]

9

Principal Component Analysis (PCA)
PCA is a variable reduction technique where larger groups of variables are reduced to a smaller set of artificial variables that are known as Principal Components (PC). These PCs are responsible for the most variance of the original variables. Concerning past research conducted by Acharya et al., 2012, PCA has been used successfully for the clarification of the main PCs from the measured set of water quality parameters to identify the main propelling features that contributed to the Lake Taihu eutrophication status (Acharya et al., 2012). 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.

The PCA was conducted on the data obtained by testing the water quality parameters to classify and recognize the key factors (principal components) that have caused the eutrophication and algae growth in the lake. 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.

Results And Discussion

Elimination of outliers in water quality data of the Beira Lake

Box and whisker plots (Fig. 4) were used to identify and eliminate outliers in the water quality data. Water quality parameters such as temperature, pH, TDS, EC, salinity, DO, secchi disc depth, nitrate, nitrite, reactive phosphorus, ammonium-nitrogen, BOD$_5$, COD, and Chl-a in the selected sampling locations were used to plot the box and whiskers for the two water bodies of Beira Lake. Stations 28 and 31 have recorded an extremely higher concentration of NH$_4^+$-N, meanwhile, station 28 recorded an extremely higher concentration of Chl-a and was considered an outlier.

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. Such a scoring system enabled simplicity and clear understanding. The WQI is a measure of water quality taking into account various physical, chemical, and biological parameters. In this study, the WQI was used to determine whether the water is safe for drinking, swimming, or other recreational activities.

The WQI shown in Fig. 5 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 & 13) indicated 'good' quality water which is located on East Beira Lake which is surrounded by less active and inactive stormwater pipes.

Poor WQI (Category E) was mainly found at Southwest Lake where the lake is surrounded by several active wastewater pipes which bring 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 & 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 illegally. Accordingly, the Floating Market area of Lake is completely unfit for consumption. This 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 with the variation of the WQI in the lake where the higher the WQI, the higher TLI. TLI indicates that all sample stations within Beira Lake were hyper-eutrophic thus classifying the whole of Beira Lake as
"hypereutrophic" as of Fig. 6. The sampling locations 6, 8, 9 & 13 have best WQIs 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 to obtain a qualitative evaluation of the pollution status of East Beira Lake. The study of Weerasingha & 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 & 10 - East Lake), the rest of the sample stations indicated acceptable levels of DO values for the existence of aquatic life and plants.

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 reallocation of the stormwater runoff, unauthorized reallocation of domestic wastewater, and industrial wastewater discharges. It is only evident that the industries operating in the surrounding catchment area that releases their sewage into the waters of East Beira Lake are responsible. Furthermore, 48% of the sample stations indicated that BOD$_5$ levels exceeded the provided threshold values which indicated high levels of pollution within the basins.

Key factors for Eutrophication at Beira Lake

PCA was utilized to identify the most prominent factors contributing to eutrophication within the considered water mass, East Beira Lake. The results of the carried out PCA are displayed clearly along with the Eigenvalues and the considered total variances for East Beira Lake. Worthy to note that 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 conducted by the factor analysis.

The PCA was run separately to Southwest Beira Lake, West Beira Lake, and Galle Face Lake, waterbody 2 of Beira Lake. The Pearson correlation coefficient between the variables showed that a linear relationship exists. Identified outliers were removed from the data set prior to the analysis (Sharma, 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, which indicates there are sufficient variables within the data set to conduct the PCA. Bartlett's test of Sphericity showed a significance 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 is assessed by the Eigenvalue. The eigenvalue shows how the variance is distributed among the factors. Eigenvalues greater than 1 have been considered. An eigenvalue less than 1 describes fewer facts than a single item would have explained IBM-SPSS (Vadde et al., 2018; Li, et al., 2013; 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 maximizes the variances of the loadings on a given factor while it increases the difference between high and low loadings on the factor considered. 15 experimental variables on the varimax rotated PCs on five significant varifactors 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 6.
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 6. Therefore, abiding by Rugieri 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 (Southwest Beira Lake, West Beira Lake, and Galle Face Lake) combine 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 BOD$_5$ 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 contribute to waterbody 2. PC1 recognizes the significance of the contributions made to East Beira Lake 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 & Handapangoda, 2019). Therefore, it is proven that the negative impact of industrial and anthropogenic activities surrounding Beira Lake severely 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 (South-West Beira Lake, West Beira Lake, and Galle Face Lake). This includes highly positive loaded BOD$_5$, with extremely negative loaded pH. PC3 gives an alkalinity index with degrading BOD$_5$ 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 µg/l 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. 4(b), the pH of Beira Lake was greater than 7 where the lake status is alkaline. The Secchi disc depth (Fig. 4(i)) varied from 27 cm to 10 cm, which indicated that the water clarity of the whole Beira Lake system is considerably poor.

### Table 6
Rotated component matrix of water quality parameters of PCA for the waterbodies of the Beira Lake

<table>
<thead>
<tr>
<th>Variables</th>
<th>Waterbody 1</th>
<th>Waterbody 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PC1</td>
<td>PC2</td>
</tr>
<tr>
<td>Salinity</td>
<td>0.462</td>
<td>0.734</td>
</tr>
<tr>
<td>TDS</td>
<td>0.588</td>
<td>0.752</td>
</tr>
<tr>
<td>EC</td>
<td>0.286</td>
<td>0.148</td>
</tr>
<tr>
<td>pH</td>
<td>-0.365</td>
<td>-0.777</td>
</tr>
<tr>
<td>Nitrite</td>
<td>0.759</td>
<td>0.624</td>
</tr>
<tr>
<td>COD</td>
<td>0.324</td>
<td>0.185</td>
</tr>
<tr>
<td>Reactive Phosphorous</td>
<td>0.764</td>
<td>0.677</td>
</tr>
<tr>
<td>Temperature</td>
<td>0.260</td>
<td>0.836</td>
</tr>
<tr>
<td>DO</td>
<td>-0.532</td>
<td>-0.764</td>
</tr>
<tr>
<td>Secchi disc depth</td>
<td>0.638</td>
<td>0.231</td>
</tr>
<tr>
<td>BOD$_5$</td>
<td>0.744</td>
<td>0.753</td>
</tr>
<tr>
<td>Nitrate</td>
<td>0.758</td>
<td>0.146</td>
</tr>
<tr>
<td>Ammonium Nitrogen</td>
<td>0.774</td>
<td>0.132</td>
</tr>
<tr>
<td>Chl-a</td>
<td>0.324</td>
<td>0.782</td>
</tr>
<tr>
<td>Eigenvalues</td>
<td>4.116</td>
<td>2.561</td>
</tr>
</tbody>
</table>
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. 7. 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 stations are 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 concentration distribution; however, these values are well above the allowed value of 10 µg/l NO$_3$ indicating the hypertrophic status of Beira Lake.

**Conclusion**

The study assessed the extent of eutrophication based on the indices, TLI and the WQI, representing. 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 supports 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 condition. The TLI reveals that the lake water is completely unfit for consumption, indicating a hypereutrophic state. 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, whereas land use around the catchment indicates 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 of utmost need to eliminate nutrient pollution caused by anthropogenic activities. Buffer strips, with deep-rooted vegetation along lake, floating wetlands etc., can be introduced to aid in trapping and absorbing runoff, increasing nutrient filtering, and preventing nutrients from entering local water bodies.

**List Of 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

Declarations

Competing interests

There are no competing interests to declare.

Authors’ contributions

Dilshi Dharmarathna: Field visits, sample collection and laboratory analyses of water quality, Data analysis and writing the manuscript.

Ridmi Galagedara: Field visits, sample collection and laboratory analyses of water quality, Data analysis and writing the manuscript.

Sivaperumaan Himanujahn: Field visits, sample collection and, Data analysis and writing the manuscript.

Shiromi Karunaratne: Field visits, Data analysis, review and writing the manuscript.

Bandunee Athapattu: Field visits, Data analysis, review and writing the manuscript.

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Availability of data and materials

The data and materials used in this study are available upon request.

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References


**Figures**
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Positioning of sampling locations within the four basins of the Beira Lake using 100m x 100m grids
Figure 2

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Process flow diagram of assessing data for water quality indices and statistical analysis of Beira Lake
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Box and whisker plots of the water quality parameters of catchments in Beira Lake
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Magnitude of TLI with the variation of WQI in the catchment covering four basins in the Beira Lake
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Stormwater, wastewater inlets and the distribution of Chl-a (µg/l) concentration in the entire Beira Lake