Research on the progress of urban lake water environment assessment

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Abstract. Urban lake water environment management and water ecosystem restoration have always been research hotspots in China and abroad. However, there have always been different opinions on the water environment situation, water environment evaluation and subsequent water environment regulation of urban lakes worldwide. Based on the investigation of water environment in China and abroad, this research summarizes the main water quality evaluation methods of urban lakes, and systematically analyzes and organizes the main evaluation methods, in order to provide references for the future evaluation and restoration of urban lakes.

1. Introduction

Domestic lake researches mostly focus on basin-type lakes, such as Taihu Lake, Dianchi Lake, Chaohu Lake, Dongting Lake, Poyang Lake, and there is little research on urban lakes. Urban lakes generally refer to small lakes located in urban or suburban areas of large and medium-sized cities. They have important functions such as regulating microclimate, reducing urban heat island effect and flood storage, providing cultural and sports entertainment, and regulating surface runoff⁷⁻². These functions provide multi-dimensional value for economy, society, culture, and nature, and are the basic guarantee for the implementation of urban ecological construction and the implementation of the national ecological civilization top-level design strategy. However, due to the expansion and construction of cities, the impact of residents' lives, and the pollution of point and non-point sources, urban lakes have become one of the most severely affected ecosystems by humans⁸. Therefore, the control of the water environment of urban lakes and the understanding of water quality assessment methods will play an important role in the management and restoration of urban lakes in the future.

2. Urban lake water environment situation

The understanding of lake and reservoir ecosystem pollution is relatively early in foreign countries. In the 1940s, Hasler pointed out that with the development of industry and economic growth, the health of lakes and reservoirs will inevitably be affected by it⁹.

In the 1960s and 1970s, the Organization for Economic Cooperation and Development (Organization for Economic Cooperation and Development) conducted basic research on lakes in the northern United States and southern Canada. It was clear that nitrogen and phosphorus were the main causes of lake eutrophication. At the same time, the United States The Environmental Protection Agency (EPA) found that 77.8% of the 574 lakes and reservoirs monitored nationwide were eutrophic water bodies, mesotrophic water bodies only accounted for 17.8%, and eutrophic water bodies only...
accounted for 4.5%.

China has a vast territory and many lakes. According to the records of "Chinese Lakes", the total area of lakes in China is 91019.6 km², of which there are 2759 lakes with an area greater than 1 km². A number of study results show that, from the late 1970s to the late 1980s, the proportion of eutrophic lakes in China rose from 41% to 61%, and rose to 77% in the 1990s.

According to statistics, during the 13th Five-Year Plan period, of the 111 important lakes (reservoirs) monitored of water quality, 7 lakes (reservoirs) of Class I water quality, accounted for 6.3%; 34 lakes of Class II, accounted for 30.6%; 33 lakes of Class III accounted for 29.7%; 19 lakes are in category IV, accounted for 17.1%; 9 lakes are in category V, accounted for 8.1%; 9 lakes are inferior to category V, accounted for 8.1%. The main pollution indicators are total phosphorus, chemical oxygen demand and permanganate index.

The main domestic urban lakes are Hangzhou West Lake, Nanjing Xuanwu Lake, Guangzhou Dongshan Lake, Wuhan East Lake, Beijing Kunming Lake, Guangzhou Liuhua Lake, etc. The main problems are small water environment capacity, weak regulation ability, poor self-purification ability, and fragile ecological environment. For example, Hangzhou West Lake has a surface area of 6.39 km² and an average water depth of 2.27m. It is a shallow urban lake. Since the 1950s and 1980s, the degree of eutrophication has been increasing and the water quality has deteriorated. In 1981, cyanobacteria blooms broke out; Since the 1950s, Nanjing Xuanwu lake’s water ecosystem has gradually collapsed under the influence of feeding fish and local dredging. It was in a state of severe eutrophication in the 1980s; the normal water area of Wuhan East Lake is 27.9km². The average water depth is 2.21m, and the maximum water depth is 4.75m. It was at a mesotrophic level in the 1950s and 1960s, and after 30 years of development, the water quality has developed into an eutrophic and super eutrophication level.

3. Urban lake water environment assessment research

3.1. Single factor evaluation method

The single-factor evaluation method compares the concentration of each parameter with the evaluation standard to determine the water quality category of each indicator, which can highlight the role of more polluting pollutants. The calculation formula is as follows:

\[ G = \max G_i \]

\[ G_i = \frac{c_i}{c_o} \]

In the formula, is the water quality category of the item pollutant; is the concentration value of the item pollutant; is the evaluation standard of the item pollutant.

3.2. Nemeiro Pollution Index Method

The Nemeiro pollution index method is to calculate the Nemeiro pollution index and standard index based on the actual concentration and standard value of the selected water quality index, and compare with the corresponding grade standard index to get the evaluation grade, which can highlight the role of the heavy pollution pollutants. The formula is as follows:

\[ I = \sqrt{\frac{l_{\text{max}}^2 + l_{\text{ave}}^2}{2}} \]

\[ l_{\text{ave}} = \frac{1}{n} \sum_{i=1}^{n} l_i \]

\[ l_i = \frac{c_i}{c_{si}} \]

In the formula, it represents the measured concentration of a monitoring indicator; it represents the standard limit of the corresponding monitoring indicator; it is a single pollution index; is the largest single factor index participating in the evaluation; is the average value of the single factor index.
participating in the evaluation; is the total number of monitoring indicators; It is the Nemeiro Index.

3.3. Fuzzy comprehensive evaluation method

The fuzzy comprehensive evaluation method is based on fuzzy mathematics, the basic principle: there is a certain characteristic of the thing to be evaluated, These n things constitute object set \( X = \{x_1, x_2, ..., x_n\} \). Factor set \( U = \{u_1, u_2, ..., u_n\} \) And evaluation set \( V = \{v_1, v_2, ..., v_m\} \). Suppose the weight distribution of factors is fuzzy subset \( A = \{a_1, a_2, ..., a_n\} \). In the formula, \( a_i \) is the weight \( u_i \) corresponding to the i-th factor, Which general provisions \( \sum_{i=1}^{n} a_i = 1 \).

Evaluation Steps of Fuzzy Comprehensive Evaluation Method

1. Establish a factor set. Assuming that there are a total of M water quality factors evaluated, the geometry of the evaluation factors can be expressed as \( U = \{u_1, u_2, ..., u_i\} \).

2. Establish an evaluation set. Assuming that the evaluation level is divided into M levels, the set is \( V = \{v_1, v_2, v_3, ..., v_i\} \).

For the establishment of single-factor membership function and fuzzy evaluation matrix, the membership function with higher value and lower grade is:

\[
r_i = \begin{cases} 
0 & (x \leq S_2) \\
\frac{x - S_2}{S_1 - S_2} & (S_2 < x < S_1) \\
1 & (x \geq S_1)
\end{cases}
\]  

(6)

\[
r_j = \begin{cases} 
\frac{x - S_{j+1}}{S_{j+1} - S_j} & (S_{j+1} \leq x \leq S_j) \\
\frac{S_{j+1} - x}{S_{j+1} - S_j} & (S_j \leq x \leq S_{j+1}) \\
0 & (x \geq S_{j+1}, x \leq S_j)
\end{cases}
\]  

(7)

The higher the value, the higher the membership function is:

\[
r_1 = \begin{cases} 
1 & (x \leq S_1) \\
\frac{S_2 - x}{S_2 - S_1} & (S_1 < x < S_2) \\
1 & (x \geq S_2)
\end{cases}
\]  

(9)

\[
r_j = \begin{cases} 
\frac{x - S_{j-1}}{S_{j-1} - S_{j+1}} & (S_{j-1} \leq x \leq S_j) \\
\frac{S_{j+1} - x}{S_{j+1} - S_j} & (S_j \leq x \leq S_{j+1}) \\
0 & (x \geq S_{j+1}, x \leq S_{j-1})
\end{cases}
\]  

(10)

\[
r_5 = \begin{cases} 
0 & (x \leq S_4) \\
\frac{x - S_4}{S_5 - S_4} & (S_4 < x < S_5) \\
1 & (x \geq S_5)
\end{cases}
\]  

(11)

Establish fuzzy evaluation matrix according to the above formula:

\[
R = [r_{ij}] = \begin{bmatrix}
r_{11} & \cdots & r_{15} \\
\vdots & \ddots & \vdots \\
r_{51} & \cdots & r_{55}
\end{bmatrix}
\]  

(12)

In the formula, i line \( R_i = (r_{i1}, r_{i2}, ..., r_{im}) \), \( i = 1, ..., m \), i is the membership degree of the i-th evaluation factor to the water quality standards at all levels; j-th column \( R_j = (r_{1j}, r_{2j}, ..., r_{nj}) \), j is the
degree of membership of each evaluation factor to the first-level water quality standard.

③ Determination of weight.

Assign each evaluation factor \( U_i \) to the corresponding weight \( a_i (a_1, a_2, ..., a_i, ..., a_n) \), get the weight set \( M (a_1, a_2, ..., a_i, ..., a_n) \) and \( \sum_{i=1}^{n} a_i = 1, i = 1, 2, ..., n \). Weight exceeding method calculation.

\[
a_i = \frac{c_i}{\bar{S}_i} \quad \left( \bar{S}_i = \frac{1}{K} \sum_{j=1}^{K} S_{ij} \right)
\]  

(13)

In the formula, \( \bar{S}_i \) is the average value of each evaluation standard, \( c_i \) is the measured concentration value; \( a_i \) is the weight of the first evaluation factor. \( K \) is the grading number of the water quality evaluation grade, \( S_{ij} \) is the standard value of the \( i \)-th evaluation factor in the \( j \)-th grade.

④ Establish a comprehensive evaluation matrix.

The above weight set and fuzzy comprehensive evaluation matrix are obtained, and the comprehensive evaluation model is:

\[
B = M \times R = \begin{bmatrix} a_1 & a_2 & \cdots & a_i & \cdots & a_n \end{bmatrix} \times \begin{bmatrix} r_{11} & \cdots & r_{15} \\ \vdots & \ddots & \vdots \\ r_{51} & \cdots & r_{55} \end{bmatrix}
\]

(14)

It is calculated that the corresponding water quality category where the maximum membership value of the matrix is located is the water quality category of the monitoring point.

3.4 Principal component analysis method

The principal component analysis method is a method of reducing the dimensions of the high-dimensional variable space \([17]\). In terms of water environmental quality assessment, the principal component analysis method can simplify the indicators based on the contribution of different water quality indicators to the water environment quality, thereby reducing unnecessary calculations, the analysis steps are as follows:

① Data standardization processing.

\[
x_{ij}^* = \frac{(x_{ij} - x_i)}{S_{ij}}
\]

(15)

In the formula, \( i = 1, 2, ..., n \) is the number of samples; \( j = 1, 2, ..., p \) is the original variable number of the samples.

② Calculate the covariance matrix \( M \) according to the standardized data, \( R = (r_{ij})_{n \times n} \), the correlation coefficient indicates the degree of correlation between the \( i \)-th index and the \( j \)-th index.

③ Calculate the eigenvalues and eigenvectors of the covariance matrix.

First solve the characteristic equation \( \lambda I - R = 0 \), find the characteristic value \( \lambda_j (j = 1, 2, ..., p) \), arrange them according to the size of the characteristic value, \( \lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_p \geq 0 \); then respectively find the characteristic vector \( u_j (j = 1, 2, ..., p) \) corresponding to the characteristic valued.

④ Determine the number of principal components. When the cumulative variance contribution rate reaches 85% or more, the first \( m \) principal components are taken.

\[
F_i = \beta_{i1} x_1 + \beta_{i2} x_2 + \cdots + \beta_{ip} x_p
\]

(16)

⑤ Calculate the scores and comprehensive scores of each principal component.

3.5 Comprehensive pollution index method

The comprehensive pollution index method is to make statistics on the relative pollution degree of each monitored pollution index. It is assumed that the contribution of each participating evaluation factor is basically the same, and then the individual pollution indexes are added and the arithmetic average value is calculated to obtain the comprehensive pollution index \([18]\). The calculation formula is:

\[
P_i = \frac{c_i}{c_o}
\]

(17)
In the formula, $C_i$ is the concentration value of the pollutant item, the evaluation standard of the pollutant item $C_o$, $P_i$ is the standard index of the pollutant item, and $m$ is the sum of the pollution index.

$$P = \frac{1}{m} \sum_{i=1}^{m} P_i \quad (18)$$

Table 1. Evaluation classification of comprehensive pollution index

| $P$       | Water quality level       | Water quality status                                                                 |
|-----------|---------------------------|--------------------------------------------------------------------------------------|
| $P \leq 0.40$ | Clean water               | Most items are not detected, and individual detections are also within the standard standard                              |
| $P = 0.41\sim 0.70$ | Slightly polluted water   | Individual items have been checked out and exceeded                                     |
| $P = 0.71\sim 1.00$ | Moderately polluted water | Two detected values exceed the standard                                                |
| $P = 1.01\sim 2.00$ | Severely polluted water  | A considerable part of the detected value exceeds the standard                        |
| $P \geq 2.00$     | Seriously polluted water | A considerable part of the detected value exceeds the standard several times or dozens of times |

3.6 Grey Relational Analysis Method

Grey correlation analysis [19-20] is a method of analyzing the degree of correlation between quantified factors in the system, by determining the reference and comparison sequence, the original data is dimensionlessly processed, and the correlation coefficient and correlation degree are calculated to determine the degree of relevance between the sub-sequence and the parent sequence. The evaluation steps are as follows:

① Determination of standard concentration matrix and sample matrix.

Assuming that there are $p$ sections of water bodies to be graded and evaluated, and each section is divided into $q$ individual water quality indicators to be evaluated, the sample matrix arranged is:

$$X_{p \times q} = \begin{bmatrix} X_1(1) & \cdots & X_1(q) \\ \vdots & \ddots & \vdots \\ X_p(1) & \cdots & X_p(q) \end{bmatrix} \quad (19)$$

According to the "Surface Water Environmental Quality Standard" (GB3838 – 2002) and the measured data of the water body, the water quality standard concentration matrix is determined, and the water pollution degree classification is recorded as $m$, the existing concentration matrix

$$S_{m \times n} = \begin{bmatrix} S_1(1) & \cdots & S_1(n) \\ \vdots & \ddots & \vdots \\ S_m(1) & \cdots & S_m(n) \end{bmatrix} \quad (20)$$

② Data normalization processing.

Use the piecewise function to calculate, because there are positive and negative points involved in the evaluation index, so it is calculated in two ways. Positive indicators:

$$M_i(U) = \frac{S_m(U) - S_i(U)}{S_m(U) - S_1(U)} \quad (i = 1, 2, \ldots, m; U = 1, 2, \ldots, n) \quad (21)$$

$$N_j(U) = \begin{cases} 1 & [X_j(U) \leq X_1(U)] \\ \frac{S_m(U) - S_i(U)}{S_m(U) - S_1(U)} & [S_i(U) > X_j(U) > S_1(U)] \\ 0 & [X_j(U) \leq S_m(U)] \end{cases} \quad (j = 1, 2, \ldots, m) \quad (22)$$

Negative indicators:
\[ M_j(U) = \frac{S_j(U) - S_m(U)}{S_1(U) - S_m(U)} \]  (23)

\[ N_j(U) = \begin{cases} 1 & [X_j(U) \geq S_1(U)] \\ \frac{X_j(U) - S_m(U)}{S_1(U) - S_m(U)} & [S_m(U) < X_j(U) < S_1(U)] \\ 0 & [X_j(U) \leq S_m(U)] \end{cases} \]  (24)

② The matrix obtained after normalization of the standard concentration matrix:

\[
S_{m\times n} = \begin{bmatrix} M_1(1) & \cdots & M_1(n) \\ \vdots & \ddots & \vdots \\ M_m(1) & \cdots & M_m(n) \end{bmatrix}
\]  (25)

③ Find the correlation coefficient sequence and the degree of correlation.

\[
\sum MN = \frac{\min_M \min_N \Delta_{MN}(U) + \rho \max_M \max_N \Delta_{MN}(U)}{\Delta_{MN}(U) + \rho \max_M \max_N \Delta_{MN}(U)}
\]  (26)

In the formula, \( \Delta_{MN}(U) = |M_j(U) - N_j(U)| \); \( \min_M \min_N \Delta_{MN}(U) \), \( \rho \max_M \max_N \Delta_{MN}(U) \) are the minimum and maximum values of \( \Delta_{MN}(U) \). \( \rho \) is the resolution coefficient, generally 0.5.

Relevance \( \tau_k = \sum_{i=1}^{n} w_i(k) \sum MN \), where \( w_i(k) \) represents the weight of the \( k \)th item of the monitoring section \( i \). The weighted calculation method of concentration exceeding the standard can be used.

\[
w_i(k) = \frac{M_i(k)}{\sum_{i=1}^{M} M_i(k)}
\]  (27)

\[
M_i(k) = \begin{cases} 1 & \cdots \cdots \cdots [C_k \leq L_i(k)] \\ \frac{C(k)}{L_i(k)} & \cdots \cdots [C_k > L_i(k)] \end{cases}
\]  (28)

In the formula, \( C(k) \) is the monitoring result of each monitoring index, \( L_i(k) \) is the upper limit of each level of water environmental quality standard corresponding to each monitoring index (for Grade V water standard, the lower limit); \( M_i(k) \) is a dimensionless number, which represents the multiple of each index exceeding the standard.

⑤ The final result obtained by the gray correlation analysis method should be the number of classifications corresponding to the maximum correlation degree.

4. conclusion

Urban lakes are an important part of the urban landscape. Domestic researches on urban lake water environment assessment have made certain progress. However, due to regional differences, lake function positioning, and lake water environment driving forces, there is currently no domestic research on urban lakes. Water environment assessment methods are summarized in this research.

There are many evaluation methods for urban lake water quality, among which the main lake water quality evaluation methods are: single factor evaluation method, Nemeiro pollution index method, fuzzy comprehensive evaluation method, principal component analysis method, comprehensive pollution index method and grey relational analysis method. Among them, the single factor evaluation method uses the worst principle, and the worst indicator grade determines the water quality grade; the Nemeiro pollution index method takes into account the influence of the average and extreme value of the single factor pollution index, but there still exist the influence of the maximum value on the result; The comprehensive pollution index method assumes that all indicators contribute the same to the evaluation factor, which obscures the effect of the largest pollution factor. For the above methods, Chinese scholars have done a lot of research and improvement work [21-24]. But the whole cannot be widely used in practice and lacks practical significance. Therefore, the coupling and improvement of
water quality evaluation methods are still the focus of future research.

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