Evaluation of the impact of water conservancy projects on the ecosystem of Poyang Lake

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Abstract. Energy engineering, such as hydroelectric stations, greatly affects the environment. Under the effect of the Three Gorges Dam, the water level of Poyang Lake has decreased. The dry season of Poyang Lake has become longer, leading to many consequences. The government proposed that a sluice be built in Poyang Lake to regulate the water level. We established AQUATOX model of Poyang Lake with different water flow in and out to simulate the ecosystem with changing water volume (water level). The data used in this paper are the output of the AQUATOX model. This paper proposes and uses a framework for ecosystem assessment of the body of Poyang Lake. The results show that the ecosystem quality of the body of Poyang Lake will become increasingly worse if no action is taken. If the necessary connectivity (for migratory creatures) is ensured, building a sluice can improve the ecosystem quality of the body of Poyang Lake. We also discuss the possibility of using ecosystem stability and regime shift indexes in ecosystem assessments.

1. Introduction
Energy engineering, such as hydroelectric stations, greatly affects the environment. In China, the Three Gorges Dam is a large hydroelectric station in the Yangtze River. Since its operation, the water flow and sediment transport in the Yangtze River have changed substantially [1-4]. Sediment from the upper Yangtze River is deposited in the Three Gorges Reservoir, leading to decrease of sediment transport to the downstream. Nutrients and heavy metals absorbed in the sediment can be deposited in reservoirs and lakes, causing eutrophication and heavy metal pollution [5-8]. Additionally, given the decrease in sediment transport, riverbeds are under scouring and armoring, which pose threats to the lives of benthic animals [9] and biofilm bacterial communities [10]. Poyang Lake, a freshwater lake connected with the Yangtze River in China (28°22′~29° 45′N, 115° 47′~116° 45′E), is one of the lakes affected by the Three Gorges Dam. River bed scouring has caused the water level of the Yangtze River to decrease, leading to a decrease in the water level of Poyang Lake. The dry season of Poyang Lake has become longer, causing a water supply shortage. Thus, the government proposed building a sluice to regulate the water level of Poyang Lake.

To quantitatively understand the effects of these energy engineering projects on the ecosystem of Poyang Lake, we use a scientific ecosystem assessment method. An ecosystem assessment method typically combines different indexes and uses numerical methods to obtain an integral result. This index includes three parts: biological, physical and chemical [11-13]. Some researchers also consider social and economic effects [14, 15]. We call this widely used ecosystem assessment ‘Traditional ecosystem assessment’ (TCA).
Ecosystem stability theory and ecosystem regime shift theory derived from mathematical ecology have attracted increasing attention of many researchers in recent decades. In the field of engineering, ecosystem stability is defined in four parts: temporal stability, resistance, resilience and persistence [16-18]. Temporal stability is the opposite of variables’ time series’ variance. Resistance is the degree to which a variable is changed after perturbation. Persistence is the time a variable maintains its original value after perturbation. Resilience is the speed at which a variable reverts to the original value after perturbation. Regime shift theory is focused on the existence of regime shift and its leading indicators. Researchers have found that when variance [19], skewness [20] and first-order autocorrelation [21] increases, the ecosystem tends toward a regime shift.

This paper proposes a framework using TCA to assess the ecosystem quality of the body of Poyang Lake based on the effects of energy engineering structures. Then, we use temporal stability, skewness and variance to apply the assessment and discuss the possibility of using these indexes in ecosystem assessment.

2. Materials and methods

This paper includes two case studies: 1) assessment of the ecosystem quality of the body of Poyang Lake from 2010 to 2030 with changing water volume and 2) assessment of the ecosystem quality of the body of Poyang Lake before and after sluice building.

2.1. AQUATOX model simulation

The data used in this paper are the output of the AQUATOX model of the body of Poyang Lake. AQUATOX model is an open source software provided by USEPA. Its mechanisms and governing equations can be referred to in technical documentation [22]. The model’s input is water inflow, outflow, nutrient loadings and other physical, chemical and biological parameters. The model’s food web includes Diatoms, Green algae, tubifex, chironomid, rotifer, gastropod, shrimp, maminow, carp and catfish. The model was calibrated using relative bias and variance tests, as well as the relative mean bias test based on available data (Table 1). Most of simulations output match observations well. The calibration result is good enough to do relative ecosystem assessment. In the first case study, the change input is 20 years of inflow and outflow data, which contributes to the changing water volume, as illustrated in Figure 1. River water inflow from Xin River and Rao River are repeated data from 2003 to 2007 because of data from 2007 to 2012 are unavailable. Other water inflow and outflow are repeated data from 2003 to 2012. Extreme weather such as floods in 2020 were not considered. The output is a 20-year unstable long-term series of variables from 2010 to 2030. In the second study, the input is based on two different outflows contributing to two different annual water volume processes, as illustrated in Figure 2. The outflow before sluice building comprises data from 2001 to 2002. The outflow after sluice building, for the 2001~2002 period is calculated. The sluice operation condition is: close on 2001/9/1, 2001/10/10, 2001/11/12; open on 2001/9/27, 2001/10/21, 2002/2/6. When the sluice closed, there is still water outflow from Poyang Lake to Yangtze River but smaller. We change the inflow and outflow slightly to make the input data more ordinary without identifying a specific year but retaining values representative of the sluice-building condition. The output is a 1-year stable time series of variables. The output is not associated with a certain specific year, and we use this output only to briefly discuss the effect of sluice building.

Table 1. Model calibration result.

| Output variable | Ammonia nitrogen | Carbon dioxide | Solute oxygen | Diatom | Green algae | Chlorophyll | Biological oxygen demand |
|-----------------|------------------|---------------|--------------|--------|-------------|-------------|-------------------------|
| Relative bias   | 0.82             | -0.08         | 0.26         | 0.23   | -1.62       | -0.13       | -0.28                   |
| Variance bias   | 0.05             | 0.01          | 6.45         | 0.02   | 0.00        | 1.30        | 0.18                    |
| Output variable | Tubifex          | Rotifer       | Gastropod    | Shrimp |             |             |                         |
| Relative mean bias | 0.51           | 0.98          | 1.08         | 2.07   |             |             |                         |

*Calculation way of relative bias and variance bias can be referred to Taner’s paper [23]. Relative mean bias is calculated by Mean_sim/ Mean_obs.
2.2. Ecosystem assessment framework

The ecosystem assessment framework is given in Table 2. The relevant relationships between the direction of change for each index and the ecosystem state are established based on certain literature [11] [14] [24] [25], where a positive sign represents an increase in the index value and a negative sign represents a decrease, and each index is associated with movement toward a ‘better state’. Because the seasonal cycle of the water volume time series is approximately 4 years, in the first case study, the mean value of the variable is calculated as a 4-year moving average. In the second case study, the mean value of the variable is calculated as a 1-year average.

**Figure 1.** Changing water volume from 2010 to 2030.

**Figure 2.** Annual water volume process before and after sluice building.

**Table 2.** Ecosystem Assessment frame.

| Class1 | Class2 | Index       | Better State | Calculation way                                                                 | Unit            |
|--------|--------|-------------|--------------|---------------------------------------------------------------------------------|-----------------|
|        |        | Phytoplankton |              | Sum up all phytoplankton mean biomass in the unit of mg/L dry                    | mg/L dry        |
|        |        | Zooplankton | +            | Sum up all zooplankton mean biomass in the unit of mg/L dry                      | mg/L dry        |
| Structure |        | BZBP.ratio | +            | Zoooplankton divided by the phytoplankton                                        | dimensionless   |
|        |        | Macrozooplankton | +     | Sum up all macrozooplankton mean biomass in the unit of mg/L dry                | mg/L dry        |
| Biological |       | Microzooplankton | -     | Sum up all microzooplankton mean biomass in mg/L dry                           | mg/L dry        |
|        |        | Carp         | +            | The mean biomass of Carp                                                        | g/m² dry        |
|        |        | Catfish      | +            | The mean biomass of Catfish                                                      | g/m² dry        |
|        |        | BP.ratio     | -            | Biomass divided by the production (calculated by AQUATOX)                       | dimensionless   |
| Functional |      | PR.ratio     | =1           | Production divided by the respiration (calculated by AQUATOX)                   | dimensionless   |
|        |        | exergy       | +            | Calculated according to ecosystem’s biomass and information                     | g/L             |
|        |        | TLI.TP       | -            | \( TLI(TP) = 10(9.436 + 1.624\ln TP) \)                                       | dimensionless   |
| Chemical |        | TLI.TN       | -            | \( TLI(TN) = 10(5.453 + 1.694\ln TN) \)                                       | dimensionless   |
|        |        | TLI.Chl      | -            | \( TLI(Chl) = 10(2.5 + 1.086\ln Chl) \)                                       | dimensionless   |
| Physical |        | Lakearea     | +            | Represented by Water volume                                                     | m³              |
2.3. Method of calculating the integrated score

In the first case study, the score for each index is calculated using Eq. 1 (for indexes with positive signs in Table 2) and Eq. 2 (for indexes with negative signs in Table 2). The PR ratio score is calculated using the same logic. The integrated score is calculated using Eq. 3 and is normalized by Eq. 4. The final normalized score is considered the ecosystem quality score.

\[
S_{ij}^+ = \frac{x_{ij} - \min(x_i)}{\max(x_i) - \min(x_i)} \quad (1)
\]

\[
S_{ij}^- = \frac{\max(x_i) - min(x_i)}{\max(x_i) - \min(x_i)} \quad (2)
\]

\[
T_j = \sum_i w_i S_{ij} \quad (3)
\]

\[
N_j = \frac{100 T_j}{\max(T_j)} \quad (4)
\]

where \(i\) represents the \(i^{th}\) index, \(j\) represents the \(j^{th}\) day, and \(w_i\) represents the weight for the \(i^{th}\) index. Here, the average weight was selected.

In the second case study, the score for each index is calculated using Eq. 5 (for indexes with positive signs in Table 2) and Eq. 6 (for indexes with negative signs in Table 2). The PR ratio score is calculated using the same logic. The integrated score is calculated using Eq. 3.

\[
S_{ij}^+ = 1 + \log \left( \frac{x_{ij}}{\min(x_i)} \right) \quad (5)
\]

\[
S_{ij}^- = 1 - \log \left( \frac{x_{ij}}{\min(x_i)} \right) \quad (6)
\]

where \(i\) represents the \(i^{th}\) index and \(j\) represents the \(j^{th}\) sluice condition (before or after sluice building).

2.4. Ecosystem stability and regime shift indexes

In this paper, we use temporal stability, skewness and variance to do the assessment of the first case study. The calculation methods for these indexes in this paper are listed in Table 3. Similar to the mean value, we use a moving 4-year time series to calculate temporal stability, skewness and variance. Comparing the ecosystem stability and regime shift indexes results and the TCA results, we discuss the possibility of using ecosystem stability and regime shift indexes in ecosystem assessments.

| Class                  | Index          | Calculation methods                              | Unit          |
|------------------------|----------------|-----------------------------------------------|---------------|
| Ecosystem stability    | Temporal       | \(\frac{1}{C.V.} = \frac{\text{mean}}{\text{s.d.}}\) | dimensionless |
| theory                 | stability      | The reciprocal of the coefficient of variation |               |
| Regime shift           | variance       | Statistical variance of variables’ time series. | dimensionless |
| theory                 | skewness       | Statistical skewness of variables’ time series. | dimensionless |

3. Results and discussion

3.1. Ecosystem quality changes in the recent and next 20 years

To observe these results clearly, the normalized score of each day in one year was averaged. The final result is illustrated in Figure 3, which shows that the ecosystem quality remains constant from 2015 to 2023 but shows a sharp decrease from 2023 to 2027 and a slow increase from 2027 to 2030 but still does not return to high quality. The changing trend in ecosystem quality is consistent with the changing trend in water volume, indicating that, if the decrease in the water volume of the body of Poyang Lake is not resolved, the ecosystem of Poyang Lake will remain a low-quality ecosystem.
Figure 3. Ecosystem quality score from 2015–2030.

3.2. Ecosystem quality changes after sluice building
The ecosystem quality scores before and after sluice building are shown in Table 4. Table 4 shows that almost every index, except for the zooplankton index, indicates that ecosystem quality after sluice building will improve. The final integrated score shows that sluice building increases the ecosystem quality of the body of Poyang Lake, but the degree of increase is small. Additionally, the connectivity of Poyang Lake to its rivers is questionable after sluice building, which may affect the lives of migratory creatures. Therefore, the need for sluice building should be carefully considered with more detailed simulations. However, according to these results, sluice building is recommended if the lake to river connectivity can be ensured.

Table 4. Ecosystem quality score before and after sluice building.

| indexes       | after | before | indexes       | after | before |
|---------------|-------|--------|---------------|-------|--------|
| BP.ratio      | 1     | 0.975739 | microzooplankton | 1     | 0.787698 |
| BZBP.ratio    | 1.008208 | 1      | phytoplankton | 1     | 0.942809 |
| Carp          | 1.020629 | 1      | PR.ratio      | 1     | 0.971067 |
| Catfish       | 1.057798 | 1      | TLI.Chl       | 1     | 0.988601 |
| exergy        | 1.030908 | 1      | TLI.TN        | 1     | 0.994438 |
| lakearea      | 1.094112 | 1      | TLI.TP        | 1     | 0.997852 |
| Macrozooplankton | 1.045947 | 1      | zooplankton   | 1     | 1.048983 |
| Integrated score | 14.2576  | 13.70719 |               |       |        |

3.3. The possibility of using ecosystem stability and regime shift indexes in ecosystem assessment
Figure 4 shows that calculating by chlorophyll (Chl) variable, skewness and variance exhibit a sharp increase in 2023, the transition year for the TCA results. This performance verifies the theory that increases in variance and skewness serve as indicators of ecosystem regime shifts. Figure 5 shows that when calculated using the Catfish variable, the performance of the temporal stability (TS) index is similar to that of TCA.

These results show that using ecosystem stability and regime shift indexes to perform ecosystem assessments is possible. However, many problems remain. The most important problem involves the decision regarding which variable to use for calculating these indexes. The performances of ecosystem stability and regime shift indexes using different calculation variables vary drastically. Calculations using some variables lead to indexes that perform well, whereas calculations using other variables do not. Despite these problems, ecosystem stability and regime shift indexes can be useful assessment indexes with careful variable selection.
4. Conclusions
The construction of the Three Gorges Dam affected the water volume of Poyang Lake. This paper proposes and uses a framework for an ecosystem assessment of the body of Poyang Lake from 2010 to 2030 based on changing water volumes. This paper also assesses the effects of building a sluice. The results demonstrate that the ecosystem quality of the body of Poyang Lake will become increasingly worse if no action is taken. If the necessary connectivity (for migratory creatures) is ensured, building a sluice can improve the ecosystem quality of the body of Poyang Lake. This paper also discusses the possibility of using ecosystem stability and regime shift indexes in ecosystem assessments. The results show that ecosystem stability and regime shift indexes can be useful assessment indexes with careful variable selection.

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