Lake eutrophication recovery trajectories: Some recent findings and challenges ahead

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1. Introduction

Cultural eutrophication (excessive plant growth resulting from nutrient enrichment by human activity) is the primary problem facing most surface waters today. The expectation that reduced nutrient inputs will reverse eutrophication effects originated from predictions derived from broad-scale relationships between chlorophyll a (Chla) concentrations, an indicator of algal biomass, and nutrient concentrations across lake ecosystems in the 1970s (Sakamoto, 1966; Vollenweider, 1968; Dillon and Rigler, 1974). These relationships have also been confirmed in coastal ecosystems (Guildford and Hecky, 2000; Hoyer et al., 2002; Smith, 2006). However, since all the case studies and experiments conducted in the 1990s indicate that there is a lack of empirical basis for using general relationships to predict oligotrophication reactions. Based on the assumption that eutrophication can be a completely reversible process, eutrophication and hypotrophication follow the same pathway. Therefore, the relationship between Chla and nutrient concentration can be used to predict the variation of coastal ecosystems that caused by oligotrophication (Carstensen et al., 2011). Indeed, the responses of lake ecosystems to oligotrophication may be more complex than expected as other control factors may change at the same time (Kemp et al., 2009). Lake ecosystems have been reported to follow convoluted trajectories following nutrient reduction, with internal loading, changes in food webs, the impacts of climate change, and 10–15-year time lags from nutrient reduction to reduced algal biomass having been proposed as the causes of the observed complex lake trajectories (Jeppesen et al., 2005). Regimes gradually shifting from clear-water, macrophyte-dominated ecosystems to turbid-water, algae-dominated ecosystem is a common phenomenon in shallow lake ecosystems, and reduced nutrient inputs often fail to fully reverse. Recent analyses, for example those from Lake Kasumigaura (Tomiyama, 1995), Lake Okeechobee (Steinman et al., 1999), Lake Balaton (Pádišák and Reynold, 1998), Lake Taihu (Qin et al., 2013) and Dianchi (Guo et al., 2013), have provided evidence that eutrophication recovery is slow or negligible.

A broad range of possible aquatic ecosystem responses to changes in nutrient loading have been defined from theory and observation (Scheffer et al., 2001; Tett et al., 2007; Zhang et al., 2009). The trajectory of ecosystems in a nutrient input versus algal biomass space is expected to be far more complex than the simpler proportional response implicit in many managerial schemes. We explore the evolutionary trajectory of lake eutrophication according to the empirical relationships between Chla and nutrient concentrations. We propose three basic scenarios and seven different trajectory modes of lake eutrophication recovery. Monitoring data from six lake ecosystems were analyzed to study the relationships between chlorophyll a and nutrients and their applicability in lake management. The combination of seven basic tracks can make decisions on the whole space, it will provide a visual management tool for governance decisions on specific lakes, avoiding the waste caused by blind pollution control measures with unclear objectives and inefficient methods. We believe that timely “artificial hand” adjustment measures in coordination with proper implementation can ensure that lakes have a greater chance of achieving a right-lateral repair pathway for the continuous control of phosphorus inputs and that the use of “natural hand” measures may help shortenthe recovery time.
recovery trajectories during eutrophication and subsequent oligotrophication. The first scenario that we depict is the “backtrack path”, which is similar to the “return to neverland” (Duarte et al., 2009). This trajectory is simple and reversible and implies a direct and reversible relationship between Chla and nutrient concentrations. Second, we depict the “left-lateral path”, which depicts the recovery trajectories located to the left of the original trajectory. This scenario involves a resistance of the ecosystems, which may return or never return to the original state due to an apparent time lag or hysteresis effect resulting from adverse changes in environmental conditions. The third scenario is the “right-lateral path”, which depicts recovery trajectories that are mainly located to the right of the original trajectory. This scenario involves a phenomenon in which ecosystems are restored due to favorable changes in environmental conditions despite an increase in nutrient concentrations. The initial features of the three basic paths and seven different trajectories were shown in Table 1.

A long-term monitoring data is used to study the general patterns of the relationship between Chla and nutrient concentration in six lake based ecosystems in three different regions. Our aim was to confirm whether the relationship between Chla and nutrient concentration followed similar pathways during eutrophication and oligophylization. We performed this examination by deconstructing the overall Chla-nutrient relationship to examine the variability between individual ecosystems and how these relationships change over time, and to strategies for nutrient management to remediate lake eutrophication.

2. Methods

The filtering trajectory method (FTM) was used to establish the empirical relationships between Chla and nutrient (total phosphorous and total nitrogen, TP and TN, respectively) concentrations. FTM is equivalent to a non-linear, temporal, sequential correlation and improves the single qualitative description of a single trajectory to the quantitative description of multi-period filtering (Zhao and Fu, 2019).
FTM was built using the locally weighted scatterplot smoothing (LOESS) (Cleveland, 1979), which is a powerful tool for viewing the relationship between two-dimensional variables. Under the LOESS filtering method, the selection of the upper limit of a bandwidth, \( W \), is typically limited to the years of data evaluated, where \( W \) is approximately twice the filtering period, \( T \). The annual average data are used in our analysis as a general default, where \( W = 11 \) (\( T = 5.5 \) years), i.e., filter node fluctuation of less than one-half the period of the primary sunspot cycle reflects the primary cycle of solar activity. When the data cover an extended time series, \( W = 22 \) (\( T = 11 \) years) is chosen. Thus, the filtering period, \( T \), is fitted to the primary sunspot period (the main energy source in a lake is solar energy, which influences periodic fluctuations in various environmental conditions) to reflect the trend with variation in the primary sunspot period filtered out. When the data cover a short time series, the \( W \) value of the upper limit should not exceed that of half of the entire data period. Additionally, \( W \) may be selected based on a trajectory with sufficient smoothness and resolution by comparing multiple periods. Moreover, comparing different filtering periods can provide useful information for further analysis.

The six typical cases of China’s lakes are as follows: the eastern plain lakes Dianshan Lake, Ge Lake and Chaohu Lake; the Yunnan-Guizhou Plateau lakes, Dianchi and Fuxianhu Lakes; and the northeast plain reservoir, Chaie Reservoir. Chaohu Lake is one of the largest Chinese freshwater lakes. Data on the annual means of TP, TN and Chla (1991–2015) for Chaohu Lake were obtained from the Environmental Science Research Institute of Anhui. Dianshan Lake is the largest freshwater lake in Shanghai. Data on the annual means of TP, TN and Chla (1990–2014) for Dianshan Lake were obtained from the Environmental Science Research Institute of Shanghai. Data on the Chla, TN, and TP (1990–2014) of Gehu Lake, the second largest freshwater lake in southern Jiangsu, were provided by the Environmental Science Research Institute of Jiangsu. Dianchi Lake, the largest freshwater lake on the Yunnan-Guizhou Plateau, is located near Kunming in Yunnan Province, southwestern China. The data on Chla, TN, and TP in lake water from 1988 to 2016 were provided by the Center for Environmental Monitoring in Kunming, Yunnan Province. The data on Chla, TN, and TP (1990–2011) from Fuxianhu Lake, the third deepest lake in central Yunnan Province, southwest China, were provided by the Environmental Science Research Institute of Yunnan. For the Chaie Reservoir, the major surface water source for Tieling City, Liaoning Province, northeast China, the annual means of Chla-TP, TN and Chla for 1996 to 2015 were provided by the Environmental Science Research Institute of Liaoning.

3. Results

We examined the adequacy of these scenarios by using a filtering method (FTM) to describe the trajectories of six lake ecosystems followed by the mean Chla concentration, a powerful indicator of ecosystem responses to nutrient concentrations, and the relationship with environmental conditions (Fig. 2) such as AT (atmospheric temperature), WT (water temperature) and RT (retention time). The six lake ecosystems examined followed different complex phytoplankton biomass trajectories, and the Chla-TP and Chla-TN had different trajectory combinations (Table 2).

The Dianchi lake experienced a clear and significant increase in nutrient concentrations from 1988 to 1999 followed by a significant reduction in nutrient concentrations, reaching values comparable to those in the early 1990s (Fig. 2F). Chla increased rapidly followed by increased nutrient concentrations and declined unequally rapidly during the initial phase of the Re-oligotrophication (2000–2006). A recent increase in diatom biomass despite sustained oligotrophication (2007–2011), the greater reduction of nutrient inputs to the lake and the implementation of water transfers for lake restoration resulted in a declining trajectory (2012–2016). However, the Chla concentrations leveled off with subsequent oligotrophication at levels almost four times as high as those observed under similar nutrient inputs at the onset of the eutrophication phase (Fig. 2F). The pattern of eutrophication and oligotrophication in Gehu Lake (Fig. 2D) closely resembles that in the Dianchi lake (Fig. 2F). However, in the Re-oligotrophic stage (2007–2015), the concentration of Chla decreased much more rapidly, and there was no plateau or recurrence. From 1991 to 2015, there was no clear decline in Chla concentrations in the oligotrophication phase for Chaohu Lake (Fig. 2E). Chla concentrations increased clearly during the oligotrophication phase followed by a temperature rise. In the later stage, Chla did not return to the same level as that observed in the rising stage, followed by a significant decrease in TP and temperature. All of the above ecosystems (Gehu, Chaohu and Dainchi) displayed convoluted trajectories that failed to return to the reference status upon nutrient reduction (Jeppesen et al., 2005; Carstensen et al., 2011). This failure in restoration is proposed to result from the spread of changes in environmental conditions (Duarte et al., 2009; Zhao and Fu, 2019).

The Chaie Reservoir ecosystem experienced a significant reduction in TP concentrations that resulted in a rapid decrease in Chla after 2000, but the Chla-TN and Chla-TP trajectories showed the opposite trend, in which TN concentration is increasing (Fig. 2B). For Fuxianhu Lake (Fig. 2A), the starting position of the trajectory was (Chla, TP, WT) = (0.80 µg/L, 10 µg/L, 18.1 °C), the end position was (Chla, TP, WT) = (2.12 µg/L, 8 µg/L, 18.2 °C), the average TP concentration decreased by 20%, and the Chla concentration increased three times. As Fuxianhu Lake is a slightly polluted deep-water lake, we can see the influence of environmental conditions such as climate warming on the baseline by comparing the endpoint with the starting point. These two lake ecosystems (Fuxianhu Lake and Chaie Reservoir) displayed the phenomenon of “cleaner lakes are dirtier lakes” (Finlay and Small, 2013; Bernhardt, 2013). Dianshanhu Lake experienced rapid eutrophication during the late 1980s. The trajectories for Chla-TP, Chla-TN and Chla-AT were very similar (Fig. 2C). At present, eutrophication (Chla concentrations) is lighter than it was a decade ago (at the same TP concentration). At the same time, it can be seen that the TP concentration threshold has more than doubled given that Chla = 10 µg/L.

4. Discussion

On the two basis of “left-lateral path” which were caused by delayed recovery and baseline shifts (Duarte et al., 2009; Kemp et al., 2009), we summarized three basic scenarios and seven different trajectory modes: systematically-one “left-lateral path” and three “right-lateral path” modes were added due to changes in background conditions (Fig. 1). The “left-lateral path” and “right-lateral path” scenarios consider lake ecosystems that flip between alternative stable states, whereas no states are necessarily stable under the changes in environmental conditions. When lakes have one or more environmental conditions (such as hydrology, meteorology, etc.) that have changed along the trajectory, the environmental conditions of the process involve non-stationary time processes. In this case, the rising path of eutrophication will change. If the trend is gradual, the rising path is deflected (a smooth transition from one sensitivity level to another sensitivity level). The ongoing shift in these important baselines implies that the response of lake ecosystems to eutrophication may deviate from a simple reversion of the eutrophication phase; for example, under the temperature rise due to climate warming, the upward trajectory will turn left. If there is a sharp change in trend or a sudden change in trend, the upward trajectory will shift (jump from one sensitivity level to another sensitivity level). For example, the residence time increases as the tidal range decreases, the lake gets a large amount of water from the external watershed, and then, the upward trajectory will be shifted to the right.

There is a strong evidence showing that little common trajectory for lake ecosystems comes out, which is a major challenge not only for
scientists but also for managers and policymakers who must consider possible environmental conditions changes of ecosystems to assess the likely outcomes of recovery efforts (Duarte et al., 2009; Kemp et al., 2005; Zhao and Fu, 2019). Conceptual model demonstrate the implications of shifts in Chla-TP trajectories for eutrophication sensitivity during the lake ecosystem recovery stage (Fig. 3). Assuming that the processes of continuous growth of nutrient load in the target lakes are the same, different stable background conditions will produce different ascending curves, and the comprehensive influence of background conditions are represented by curves with different “potential”. The

**Fig. 2.** Sample trajectories of annual mean Chla concentrations versus TP and TN concentrations for the six studied Chinese lake ecosystems (A: Fuxianhu Lake, B: Caihe Reservoir, C: Dianshanhu Lake, D: Gehu Lake, E: Chaohu Lake, F: Dianchi Lake). W is the number of years in the filtering window; the black line is the line corresponding to Chla/TP = 1, which denotes the efficiency of phosphorous utilization by algae, which denotes the limiting boundary between nitrogen and phosphorous. The arrow denotes the time direction, where one arrow in the figure denotes 1 year, the end of the arrow indicates the data for year i, and the arrowhead indicates the data for year i + 1.

**Table 2**

<table>
<thead>
<tr>
<th>Name</th>
<th>Average depth (m)</th>
<th>Residence time (year)</th>
<th>Average atmospheric temperature (°C)</th>
<th>Chla-TP trajectory feature</th>
<th>Chla-TN trajectory feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuxianhu Lake</td>
<td>90</td>
<td>167</td>
<td>17.9</td>
<td>left-lateral</td>
<td>right-lateral</td>
</tr>
<tr>
<td>Caihe Reservoir</td>
<td>10</td>
<td>1.1</td>
<td>7.51</td>
<td>right-lateral prosperity potential</td>
<td>right-lateral inverse potential</td>
</tr>
<tr>
<td>Dianshanhu Lake</td>
<td>2.5</td>
<td>0.08</td>
<td>16.74</td>
<td>right-lateral inverse potential</td>
<td>right-lateral inverse potential</td>
</tr>
<tr>
<td>Gehu Lake</td>
<td>1.3</td>
<td>0.14</td>
<td>16.71</td>
<td>left-lateral time delay</td>
<td>left-lateral inverse delay</td>
</tr>
<tr>
<td>Chaohu Lake</td>
<td>2</td>
<td>0.36</td>
<td>16.6</td>
<td>left-lateral inverse delay</td>
<td>left-lateral inverse delay</td>
</tr>
<tr>
<td>Dianchi Lake</td>
<td>5</td>
<td>4</td>
<td>15.83</td>
<td>left-lateral hysteresis</td>
<td>left-lateral and right-lateral</td>
</tr>
</tbody>
</table>
Ecosystem management must develop proper strategies to deal with shifting baselines and maintain ecosystem services at a sustainable level rather than trying to restore an ecosystem to a past state (Kemp et al., 2005). It is critical to develop a scientific understanding of the different trajectories proposed here (Fig. 1); to formulate effective conservation and restoration measures; to reduce economic costs, time costs and ecological loss; and to avoid taking inappropriate measures that will lead to poor governance.

The backtrack path (Fig. 1. (1)) is the most economical and effective repair paradigm due to the direct deterministic control of ecosystem status by nutrient inputs. When the nutrient limiting factor load of the lake was low, no algal migration or habitat change occurred, and the restoration path of the lake could be close to the original rising path, as long as the external load was reduced to the level before pollution, controlling the input of external nutrients is assumed to be the best response. Therefore, the precautionary protection of good lakes and the restoration of lightly polluted lakes are very important. Shallow lakes must implement nutrient load control (reduction or avoidance) and the protection of large aquatic plants (limitation of herbivorous consumption). When the nutrient limiting factor load of the lake could be close to the original rising path, as long as the external load was reduced to the level before pollution, controlling the input of external nutrients is assumed to be the best response. Therefore, the precautionary protection of good lakes and the restoration of lightly polluted lakes are very important. Shallow lakes must implement nutrient load control (reduction or avoidance) and the protection of large aquatic plants (limitation of herbivorous consumption, etc.) prior to achieving the migration of grass algae or the transfer of algae and should strive to achieve the backtrack path.

The left-lateral lake restoration pathway, which is achieved by nutrient loading reductions, often shows inefficiencies at the initial stage (Fig. 1. (2),(3)) or nullification (Fig. 1. (4)), the management of which is generally recognized as long-term, complex and arduous. The initial trajectory features of Gegu Lake (Fig. 2D), Chaohu Lake (Fig. 2E) and Dianchi Lake (Fig. 2F) all confirmed this phenomenon. However, we still believe that controlling the input of nutrients is still a necessary condition for achieving the left-lateral restoration trajectory. Under relatively stable environmental conditions, the decline in Chla will accelerate gradually due to nutrient loading reductions (Fig. 1. (2); Fig. 2D). Otherwise, the trajectory presented an apparent time lag or hysteresis effect in response to reducing the nutrient input. However, persistence is always effective (Fig. 1. (3); Fig. 2F). The left-lateral recovery path faces enormous economic and time costs for the management of heavily polluted shallow lakes, which should be restored as soon as possible.

If environmental conditions are improved before eutrophication, thus taking the restoration path below the pollution level, the original rising path, the right-lateral path restoration path, is achieved (Fig. 1. (5), (6), (7)). The right-lateral restoration path is sometimes an effective remediation paradigm as it is simple, time saving, economical, and effective. The right-lateral path also needs to reduce nutrient load. However, its core function is to improve the environmental capacity of nutrients and reduce the harm of eutrophication, such as by increasing the exchange flows, which can increase the nutrient thresholds of eutrophication level. Especially when the residence time is less than 14–20 days, the chance of spontaneous algae blooms is greatly reduced through the implementation of river nutrients standards (Strskraba and Tundisi 1999; U.S. Environmental Protection Agency, 1991). For example, the right-lateral return pathway of Dianshan Lake (Fig. 2C), which is a water diversion project from the Yangtze River to the Tai Lake basin, prevents the eutrophication of Dianshan Lake. However, this project has not contributed much to reducing the nutrient concentrations in Dianshan Lake. Chla concentrations were less than those a decade ago (at the same TP concentration), and the residence time was already less than 30 d. The right-lateral path may also require large construction costs, but the time cost is less than that of the left-lateral path. The right-lateral path has certain advantages over the left-lateral path; for example, this path can enhance water column transparency during lake ecological recovery, especially for lakes, which experience migrations of algae and difficulties in artificially restoring aquatic plants. Analyses of coastal eutrophication have evaluated backtrack and left-lateral paths (the baseline always tends to be unfavorable) and are rather pessimistic for the recovery of the baseline Chla state (Duarte et al., 2009). We believe that lake may still be able to achieve certain right-lateral recovery paths through artificial regulation.

Lake ecosystems did not improve following reduced nutrient inputs, which may provide a misunderstanding that “nothing was done” or “money was not well spent”. In retrograde stagnation recovery (Fig. 1. (4), Fig. 2E), the apparent efficiency of the initial stage of pollution load reduction is negative, but the actual efficiency is still positive. In reality, if the external load remains unchanged, unfavorable changes in environmental conditions will lead to an increase in Chla, the algae nutrient utilization efficiency is improved, which improves the sensitivity of lake eutrophication. However, the effect of load reduction cannot offset the effect of unfavorable changes in environmental conditions, which will necessitate future adjustments. For example, if the climate warms or increased water consumption leads to reduced water discharge from the lake, the nutrient control threshold will become more stringent (Huo et al., 2019; Havens and Paerl, 2015). The right-lateral path more clearly frames the question as to what the main indicator for the assessment of eutrophication treatment efficiency actually is (“nutrients or Chla”)? We believe that there are no problems with Chla evaluations from the perspectives of stability and trends. Chla is itself a manifestation of disasters (environmental conditions change, but the threshold for disasters does not change), and the nutrient concentrations vary with environmental conditions.

5. Conclusion

Substantial reductions in nutrient inputs and the failure of ecosystems to restore past ecological conditions are disturbing to scientists...
and managers. Nutrient control is inefficient, and eutrophication levels should be repaired via physical and bioremediation methods. These systems are facing the delayed healing or chronicity phenomenon and an almost irreversible state (it is difficult to foresee the recovery time given economic and technical constraints). Various factors, such as the socio-economic environment, lake use, and the use of high-input “shock treatments” and “death treatments”, need to be balanced. In our research, we aim to be able to judge the actual effects of recovery projects and determine the trends of future changes on the predicted trajectory.

Different eutrophication recovery trajectories provide us with a window to understand the lake ecosystem, and a lot of practical problems have been solved by statistical methods, inductive methods or empirical methods. Nowadays, the era of big data has made artificial intelligence more powerful than ever. Driven by the comprehensive development of data mining tools and artificial intelligence in the era of big data, more lakes “Trajectory pattern” will be identified, which will play a greater role in environmental management. It will play an important role on avoiding the outbreak of a large area of drinking water hazards and aquatic products crisis driven by climate change, economic development and world trade changes. Of course, the effective use of big data and artificial intelligence also needs to be based on the professional’s deep understanding of scientific issues in order to play its power. Furthermore, accumulating of more monitoring data and meeting the requirements of the era on sharing data are also important for China.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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