Perspectives and Challenges of Applying the Water-Food-Energy Nexus Approach to Lake Eutrophication Modelling

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Abstract

The water-food-energy (WFE) nexus is about balancing competing interests to secure the sustainability of services provided by interconnected sectors. Ignoring the interconnections could cause serious consequences. For example, eutrophication caused by overemphasizing on food production maximization could threaten water security. Worldwide eutrophication intensification is one of the most important causes of the lake water quality deteriorations. Water quality models are usually important decision making tools for policy makers. This study attempts to explore the possibilities of applying the WFE nexus concept into water

quality models. We propose the most significant challenge is lack of a common modelling framework to streamline connections between up- and downstream models. As the most important water quality issue, eutrophication modeling should increase its visibility in the United Nations Sustainable Develop Goals.

Keywords

Lake eutrophication; water quality modeling and management; water-energy-food nexus; sustainable development; challenges in integrations

1. Introduction

A disturbed water-food-energy (WFE) dynamics could intensify the nutrient discharges from human activities to water, resulting in nutrient enrichment, subsequent eutrophication and harmful algal blooms in the waterbodies [1–4]. About 150 Tg N is fixed from N_2 each year by consuming large amounts of electricity (~3% of total electricity supply) [5], which is far beyond the planetary boundary (~62 Tg/year) [6]. The majority of synthetic fertilizer is applied in croplands [5, 7], but the low usage efficiency is resulting in a vast amounts of excessive nutrient discharges into aquatic ecosystems [5]. On the other hand, urbanization has aggravated imbalances between food productions and consumptions [8, 9]. Nutrients in human excreta are regarded as contaminants and treated by wastewater treatment facilities while simultaneously releasing GHGs such as CH_4 and N_2O [10, 11]. Water quality issues (e.g., eutrophication, toxic algal blooms, coastal hypoxia and dead zones) [12] occurred in waterbodies, but they are closely related with human activities in the catchment. Therefore, it is acknowledged that water quality and resource management needs the efforts across systems, across sectors and across disciplines [13–15].

Eutrophication is not a new topic, but it is one of the most troubling water quality issues confronting human-being in recent decades [16]. Eutrophication can seriously damage the functions of ecosystem services of waterbody on provisioning, regulating and maintenance and cultural functions [17]. It was estimated that the combined costs were ~$2.2 billion per year as a result of eutrophication in the US freshwaters [18]. Natural eutrophication occurs slowly in aquatic ecosystems, but this process could be accelerated by human activities by several routes, such as intensified nutrient discharges and global warming [3, 19]. Since the 1990s, water quality has deteriorated in many rivers and lakes in Africa, Asia and Latin America. Over 75% of closed waterbodies worldwide have experienced a certain degree of eutrophication [20]. So far, most of human mitigation measures are devoted to reduction of nutrient discharge into aquatic ecosystem (e.g., building WWTPs, reducing fertilizer usages, afforestation). Regardless of economic costs, the mitigation measures seem to be successful in some lakes, while fails in many other lakes [21]. Some other factors might also impact the occurrences of algal blooms (e.g., climate changes). A recent study indicated that lake warming might have counteracted the management effort to ameliorate lake eutrophication since the 1980s [2].

Eutrophication modeling has provided an important tool to assess the ecological status of lakes and pave the way to establish the sound management strategies in the eutrophication mitigation and water quality improvement. These models were firstly developed in the 1970s (well-known as the Vollenweider models) and have been widely applied in the water management. One primary goal of these models was to provide quantitative tools to predict the responses of lakes and reservoirs to nutrient discharge and provide quantitative nutrient reduction strategies [22]. For many cases, the nutrient loading was estimated by measured nutrient concentrations and runoffs in the in-flow rivers [23–25]. Thus, nexus between lake and watershed systems was weak and less quantified in most cases. Initially, water quality model was simple and designed to characterize variations of in-lake nutrients with changes of nutrient loadings [26]. With continuous developments of numeric calculation capacities, more spatial (1D–3D) and temporal dynamics of hydrologic and ecological processes were incorporated into the eutrophication modeling [25, 27–29]. These progresses have helped to improve water quality management and set more appropriate control targets for the nutrient loadings.

By addressing challenge from water, food and energy securities, nexus approach towards resources management has been developed in the new frameworks of the UN Sustainable Develop Goals (SDGs), and initiated in the implementations. Main objectives of the nexus are to synthesize the individual systems of WFE and identify a coherent and harmonized way for the sustainable development of cross-sectoral policies [30]. In this brief review, we firstly sketched out the current conditions and the drivers for lake eutrophication. Then, we summarized applications, advantages or limitations of eutrophication models which have been widely applied. Finally, we analyzed the potential integrations between eutrophication modeling and the WFE nexus and proposed potential challenges and opportunities ahead.

2. Eutrophication and current conditions

"Eutrophication" is originated from the Latin translation. "Eu" refers to "well", and "trophe" refers to the "nourishment". Scientifically, "eutrophication" is used to denote a process of nutrient enrichments from natural or anthropogenic sources and the subsequent changes in trophic states of waterbodies. Usually, eutrophication could lead to the dramatic growths of phytoplankton and depleting oxygen due to algal decay. From 1900s to 2000s, the world population has increased from about 1700 to 7000 million. Synthetic fertilizer has played an irreplaceable role to support the growing populations [5, 31]. For instance, before 1900s, animal manure provided majority of phosphorus fertilizers. After 2000s, ~80% of P fertilizer was contributed by phosphate rocks (~17 million tons of P), while only 3 million tons P are delivered to human diets [31]. Nitrogen (N), another essential element for human, has similar patterns. Large volume of synthesized N fertilizer got lost during food production [5]. Artificially fixed N originated from Haber-Bosch industrial production, and agricultural fertilization is equivalent to N fixed from natural processes [32]. One third of excessive N is transported from the lands to seas, leading to severe eutrophication issues [33, 34].

Lake eutrophication has become common nowadays, as summarized in Table 1. In USA, median TP in lakes was about 37 μg/L in 2012. But, an unexpected increasing trend was observed from 2007 to 2012 with causes unclarified [35]. In the European lakes, median TP concentration was ~ 23 μg/L in 2018 [36]. Now, many European lakes are recovering from eutrophication following the controls of P inputs, providing a paradigm of successful water managements [37]. Compared with developed countries, lake nutrient monitoring in developing countries was usually performed in limited numbers of lakes and fragmented time periods [38]. This might increase the uncertainties for scientific community to know the overall nutrient conditions. In China, a nation-wide water nutrient monitoring network has been set up since 2005, which provides us a window to explore the temporal nutrient dynamics in the developing countries. Since the reform and opening in 1978, China has experienced a period of rapid economic development. Since the early 2000s, many lakes and reservoirs have become eutrophic. For instance, in the Lake Taihu, TP, TN and Chl a concentrations in 2006 were over 100, 2000 and 50 μg/L, respectively [39–41]. In the Lake Dianchi, TP, TN and Chl a concentrations in 2006 were about 200, 4000 and 40 μg/L, respectively [40]. After the 2005, mitigation measures have been implemented to improve water quality in China. The construction of wastewater treatment plants has grown rapidly. In 2005, the percentage of municipal wastewater being treated on a national scale was only ~40%, while it had reached over 90% in 2017 [42, 43]. Nowadays, over 5,000 WWTPs in operation could treat over 60×10^9 m^3 domestic wastewater, which can largely reduce the nutrient discharges into waters. An action aiming at reducing the fertilizer applications was also initiated in 2015 [44]. Based on data set during 2006–2014, median TP concentrations declined from 80 (3–247) μg/L in 2006 to 51 (3–128) μg/L in 2014 on the national scale [4]. Similar trends had also occurred for other contaminants such as COD and NH_4^+-N [45].

3. How to model eutrophication in lakes?

In the past decades, aquatic modeling has been developed by environmental scientists as important tools for water quality management. A recent review of the development in eutrophication models for aquatic ecosystems pointed out the appealing diversity in this field and advocated for maintaining the diversity; while called for the further efforts in standardization, comparison and ensemble runs towards an interdisciplinary approach [46]. Some eutrophication models are simple and focused on changes of water qualities, while other models could be far more complicated by coupling the hydro-ecological dynamics. Eutrophication modeling for freshwater lakes and reservoirs started with the seminal work from Vollenweider, Ran and Lee [47]. Based on the regressions between lake TP and Chl a concentration, plankton biomass in lakes could be properly estimated [48]. Even nowadays, these models (or derived equations) are also still very popular due to the simplicity in the simulations [49]. After 1980s, 2D/3D ecological models for lake eutrophication started to emerge in many countries. These models were capable of simulating the physicochemical and biological processes in ecosystems through a series of equations [22, 50].

Since the 1990s, many process-based models such as the AQUATOX, CAEDYM, CE-QUAL-ICM, EFDC and PCLake have been developed and applied in various waterbodies (Table 2). Compared to statistical models concerning the causal relationships as a 'black box', the process-based models need a theoretical and mechanistic understanding about in-lake ecological processes. The ordinary or partial differential equations are fundamental for simulations of the dynamic processes. Each model has its advantages and limitations, as summarized by Eleni et al., 2017 [22]. For example, CAEDYM could simulate the grazing pressures from zooplankton to phytoplankton, but it doesn't consider sediment diagenesis; EFDC may simulate high-resolution variation of internal nutrient process, but zooplankton and detritus are excluded and there is a high demand for input data; PCLake could simulate dynamics in the aquatic food chains, but needs a detailed information for trophic structures for the model validations [38]. A recent advance in this field is the general framework for aquatic biogeochemical models (FABM) [51] linking the multiple hydrodynamic (from 1D to 3D) and biogeochemical models (e.g. FABM-PCLake) [52].

On the other hand, our understanding about the detailed ecological processes in aquatic ecosystems is still advancing and the progresses will require further updates in the process-based models. A typical example is about the pattern of nutrient limitations in the lakes. Traditionally, 'P-limitation' for phytoplankton is usually assumed in the lakes; while recent studies reported that N might be more important for many other cases [21]. The complex interactions between N and P limitation in aquatic environments are still on debate. This suggests that differential dynamic equations would be necessary for different lake types [53]. Further, process-based models are usually more complicated than statistical methods. Modeling results need calibrations and validations against ideally high temporal–resolution monitoring data. These models had been developed and successfully applied in many lakes [22, 38] and performed well in explaining limnology phenomenon [38, 54]. However, these studies could only represent a small percentage of the lakes globally, resulting in potential uncertainties between modeling performances and real conditions [38].

Nutrient loading and climate change are two key boundary conditions for the successful simulations of the process-based models, since they are primary drivers for algae blooms in the lakes [3, 4, 55, 56]. A better performance of process-based models also asks for a high-quality input data, such as monthly or even daily–resolution data and specific types of nutrients (such as PO_4^{3-}-P, NO_3^--N, NH_4^+-N). For the lake ecosystems, high-quality nutrient loading data to model lake water quality is thus far still scare, particularly in the developing countries [38]. With development of automatic observation technology, high temporal and spatial resolution nutrient or weather monitoring data could be increasingly accessible. For instance, China has set up a nation-wide nutrient monitoring network in major rivers and lakes (http://mee.gov.cn). Information such as pH, DO, TN, TP and Chl a can be updated every four hours. Similarly, the daily weather information such as rainfall, air temperature and radiation, which is highly related to algae growth, is also available (http://data.cma.cn/). This could provide lake the modelers an excellent opportunity to evaluate their results and improve the reliability of the modeling results. However, this practice may be difficult for the other developing countries to follow in the near future due to the costs and complexity of setting up a monitoring network.

4. How to integrate eutrophication modeling in the WFE nexus?

Now, global community is facing unprecedented challenges that are directly linked to the way we currently understand and manage our resources. WFE nexus framework and tool offers a framework for systematic integrations of interconnected sectors in the planning and decision making processes [57]. WFE approach is central to sustainable development, it is thus important to update current eutrophication modeling under WFE framework. Water quality issues occur in rivers or lakes, but they are caused by human activity in watersheds. Mitigation measures aiming at improving the water quality are also closely connected to social development and human activity. A good example to demonstrate the complicated linkages is as follows: in order to reduce the nutrient inputs into the lakes, reductions of fertilizer applications in the croplands are encouraged. However, reducing the fertilizer usages could save electricity largely, since fertilizer production is a high energy-consuming industry [5]. GHGs such as CO_2 might favor the algae growths in the lakes [55]. On the other hand, reducing fertilizer application may also bring uncertainties in agricultural food productions. It should be noted there is a clear division between the scientific communities focusing on nexus approaches (e.g., data or social scientists) and those whose major focus is on aquatic ecosystems (e.g., limnologists).

For the current 3D dynamic water quality models, there are three general categories of variables: hydrologic variables (e.g., water flow, volume, lake stratification), environmental variables (e.g., radiations, temperatures, nutrient loadings) and biological variables (e.g., planktons, benthos) [48]. A variety of internal reactions are simulated in the lakes, such as denitrification, nitrification and mineralization. Reaction rate for internal processes was determined by the water chemistry variables related with reactions and water temperatures

[24, 25, 58]. Janssen et al., 2019, has proposed that an ideal algal projection model should include systems beyond the lakes, as follows: (I) environmental components (e.g., land activity; human discharge; economic scenario); (II) network components (e.g., hydrological process; damming or river connectivity; flow rate) and (III) aquatic ecosystem components (e.g., internal process; aquatic system structures) [38]. Environmental component quantifies various natural and anthropogenic nutrient sources into river networks. River network describes transports of water and nutrient into lakes. Lake ecosystem component simulates responses of water nutrients and algae growths to the climate changes and nutrient loadings [38]. Actually, this ideal model has many potential interactions with the nexus framework (Figure 1). For example, energy consumptions could produce GHGs and change climates, affecting land nutrient transports in environment component, hydrology processes in network component and aquatic structures in ecosystem component.

Environmental scientists have already attempted to link eutrophication with the drivers in watersheds. Watershed models (such as SWAT, INCA, HSPF and SPAAROW) have been developed to simulate impacts of human activities, economic scenarios and climate changes on watershed nutrient retentions or outputs [59–63]. Derived information could be applied as boundary conditions for eutrophication modeling. Several studies have been performed to connect the watershed model with eutrophication model. For instance, Huang et al., 2017, had coupled a Xinanjiang model with EFDC, and estimated the effectiveness of watershed nutrient reductions in reducing algal blooms in the Lake Chao, China [25]. Debele et al., 2018, have integrated two powerful hydrological and water quality models (SWAT and CE-QUAL-W2) to simulate combined processes of water quantity and quality both in the upland watershed and downstream waterbody. Their results indicate two models are compatible and could be applied to assess and manage water resources in complex watersheds comprised of upland watershed and downstream waterbodies [15]. Zhang et al., 2012, presents a MWRMS model to simulate hydrological and biogeochemical processes in small prairie watersheds. Another route to connect eutrophication modeling with the WFE nexus is climate changes. Climate change, largely linked with energy consumption, could influence lake eutrophication by changing non-point nutrient inputs [64], changing hydrologic processes [65] and impacting algae growths [66]. For example, by introducing the MIROC5 model of CMIP5, Tong et al., 2020, has simulated impacts of lake warming scenarios on intensifying internal nutrient cycling in lakes and increased dominances of typical algae [67]. By interpreting high-resolution Landsat 5 satellite imagery, Ho et al., 2019 investigated long-term trends in summer phytoplankton blooms for 71 large lakes and indicated lake warming might already be counteracting management efforts to ameliorate eutrophication [2]. All these examples provide the evidences that eutrophication modeling could have different kinds of integrations with WFE approach, although such attempts on integrations are only rudimentarily implemented and still rooted in eutrophication-centered perspective.

It has been proposed that inclusion of the social-ecological dynamics is one of the major improvements for the next generation aquatic ecosystem models in the Anthropocene. Therefore, integrated WFE nexus and eutrophication models serve as unique tools to grasp the interactions between human activities and environmental consequences. A prospective strategy for such approach is to integrate the models addressing social-ecological dynamics (e.g. IMAGE-GNM) [68] and models tackling lake eutrophication (e.g. PCLake) [54]. The IMAGE-GNM models simulates social-ecological dynamics and synthesize the processes in human society (e.g. agriculture, industrial, urbanization) that could potentially generate excessive nutrient discharges and provides such external inputs as the major stressors to the lakes. Eutrophication models in turn quantify the response of the water quality, evaluate the status of the lake ecosystems towards critical transitions and inform the stakeholders the reduction targets of nutrient loadings. The stakeholders could assess the tradeoffs between social/economic development and ecological health/service and propose most effective lake management and restoration policies (as indicated in Figure 1).

5. Challenges in the integration and implications

WEF nexus consists of various disciplines which uses different research methodologies and inconsistent dimensions. Enhanced interaction between scientific communities working on nexus approach and ecosystem management should be encouraged firstly. The stronger integrations with the watershed activities, interactions between water quality and quantity dynamics and interactions with the global climate changes are making the integrations of eutrophication modeling into future nexus assessments increasingly feasible (Table 3). However, we propose that following questions should be considered in advance for future integrations:

I. What does eutrophication modeling provide to the WFE nexus?

WFE framework should take the eutrophication modeling as one important element. The interdisciplinary nature of the WFE nexus requires that the framework should define the interfaces where eutrophication are affected or might have effects [69]. The first step to integrate the eutrophication modeling into WFE nexus is to prove that the modeling result is useful in WFE framework. So far, most of eutrophication modeling targets at predicting temporal dynamics of water nutrients, predicting occurrences of algal blooms and toxins and provide control target for nutrient loading. These achievements could be important for the water quality managers or limnologists, but are rarely admitted by the community from other disciplines. It would be more valuable if the eutrophication modeling provides critical information for the other systems either as inputs or feedbacks. A potential attempt could be connected with the changes of ecosystem services due to the eutrophication. There is no doubt that eutrophication damages the 'ecological values' of freshwaters. It was estimated that the combined costs were about $2.2 billion annually as a result of eutrophication in the US freshwaters [18]. This could be a useful output under the WFE nexus perspective. However, similar attempts have been quite limited so far.

II. How to select a suitable model and smooth the input-output data?

Due to differences in disciplines, multiple nexus modeling tools and methodologies have been developed to solve target nexus problem. It can provide scientific communities the opportunities to pick up the suitable model. However, it will also make researchers puzzled when firstly stepping into the nexus approach [69]. We admit that every nexus problem could be different, but a common framework would be helpful to use the nexus approach. Based on general nexus framework, a list of candidate models should be evaluated for each part of the nexus link; currently, there is no single model to simulate the entire WFE nexus [69]. Study of the entire WFE nexus is achieved through linking the multiple models with different functions. Thus, a common data transfer protocol should be developed to link the different models. The candidate models all have different input and output format, different spatial and temporal resolutions. It is important to make sure that the output from upstream model could meet the input requirement of the downstream models.

III. How to assess the uncertainties for sub- and entire systems?

Uncertainties may propagate through the modeling chain, from the subsystem to whole nexus [63]. The process-based eutrophication models could be assessed by the sensitivity analysis or validated by input and output data. However, under the nexus framework, different models derived from different disciplines could have different methods to validate the results. A clear and unified uncertainty for the whole system is essential to obtain the accurate and reliable results. For the eutrophication models, a validation with the historical monitoring data is common. However, for economic models, uncertainties are evaluated by other means. Thus, a unified method for the uncertainty analysis is highly necessary, so that the outputs from different sub-models could be compared in the systematic framework.

6. Conclusions

Lake eutrophication is an important water quality issue worldwide, and it could seriously damage the ecosystem services. Variety of eutrophication modeling has been developed but it is rarely connected with the WFE nexus. Of course, it may be not necessary to consider eutrophication modeling in all the nexus assessments. WFE nexus is central to sustainable development, it is thus important to update the current eutrophication modeling under the WFE nexus. The coupled watershed–lake modeling has provided us a good opportunity to apply the eutrophication modeling in the nexus approach. However, challenges still exist, and it needs efforts from respective scientific communities across disciplines and sectors. We envision lake eutrophication models will continuously gain interests and its integrations with WFE nexus could provide a valuable contribution to the watershed policymaking and sustainability.

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Conflict of interests

The authors declare no conflict of interests.

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