Ecological Modelling 319 (2016) 9–20

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Review

A review of the models for Lake Taihu and their application in lake environmental management

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ARTICLE INFO

Article history:
Available online 13 August 2015

Keywords:
Lake models
Parameters estimation
Structurally dynamic modeling
Model application
Lake Taihu

ABSTRACT

Lake Taihu is well-known for its important role in the social and economic development of the region as well as its dramatic environmental degradation and the concomitant eutrophication and cyanobacterial blooms that have occurred over the past 30 years. As the degradation and algae bloom have progressed, a series of models for the lake were developed and published. This paper summarizes those lake models. The primary models of the lake water's current stemmed from the late 1980s and were typically two-dimensional, vertically integrated surfaces that relied on the application of the finite difference and finite element methods in the Cartesian coordinate system. As the eutrophication and algae bloom developed further, sediment re-suspension fluctuations, matter transformation and cycling models were constructed to capture the water quality variation and reveal the mechanism of nutrient supply to the algae. Ecological models have been constructed over the past 15 years to predict and warn against future algae blooms. Among these models, the Ecotaihu model (from its initial version to the latest version) successfully coupled physical, chemical and biological processes to become the most complete model of the lake system to date. The model also features the greatest array of applications. The development of multiple models of the lake's processes reveals that (1) the magnitude of observations and routine monitoring data promote the construction of more complex and powerful models; (2) the necessity of lake pollution controls and restoration is a driving force advancing the construction of complete lake models; (3) the model parameters have received more attention, and the inclusion of more model parameters identified through on-site observations and experiments would reduce the Ecotaihu model's output deviation and broaden the model's application; and (4) an updated version of the Ecotaihu model that incorporates the river basin network model and the atmospheric model will be developed in the near future and will be based on the structural dynamic model.

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http://dx.doi.org/10.1016/j.ecolmodel.2015.07.028
0304-3800/

1. Introduction

Lake Taihu, situated in a high density network of rivers, including the Yangtse River, Qiantang River and Hangzhou Bay (Fig. 1), is one of the five largest freshwater lakes in China. It has a water volume of 44.33×10^8 m^3, a catchment area of 36,500 km^2, a length of 68.5 km and an average width of 34 km, and its mean water depth for normal water levels is less than 2 m. In total, 228 rivers and tributaries are connected to the lake. These rivers usually flow into the lake from the north and west and flow out of the lake to the east and south. Of these rivers, 166 are controlled, while the others run freely. Xitiaoxi River, located on the southwest edge of the lake, is the largest inflowing river in the system, with a multi-year mean inflow of 26.8 m^3 s^{-1} and a maximum inflow of 62.0 m^3 s^{-1}. The average annual flow of all other inflowing rivers combined is less than 14.0 m^3 s^{-1}. The largest outflowing river is the Taipu River, with a 70.6 m^3 s^{-1} mean annual outflow and 114 m^3 s^{-1} maximum outflow. The second largest outflow is the Wangyu River, which has an average annual outflow rate of 29.2 m^3 s^{-1} and a maximum outflow rate of 64.7 m^3 s^{-1}. The outflow from these two rivers accounts for almost 65% of the total outflow from Lake Taihu. The contribution to the average annual outflow of other outflow rivers is less than 10.0 m^3 s^{-1}. The total annual outflows and annual inflows of Lake Taihu were 71.18–110.06 $\times 10^8$ m^3 with a multi-year mean of 88.8 $\times 10^8$ m^3 and 73.84–118.8 $\times 10^8$ m^3 with a multi-year mean of 96.26 $\times 10^8$ m^3, respectively, from 2000 to 2012 (Zhang, 2014).

Lake Taihu is dominated by a monsoon climate. The wind above the water surface is extremely mutable. The monthly winds vary dramatically from month to month. The wind generally blows from the northwest in January; from the north, with a considerable proportion blowing in a southwesterly and northeasterly direction in February; in a southeasterly direction with a large concentration from the southeast and northeast in March; from the southwest and southeast in April; primarily from the south in May; from the east and the south in June, July and August; in and to the southwest in September; to the east in October; and generally to the southeast in November and December. The north and west wind speeds are greater than those in the other directions. The maximum wind speed observed in the lake is 23.1 m/s. The multi-year average monthly wind speeds range between 3.04 m/s and 4.04 m/s, with a mean of 3.75 m/s.

The water temperature in the lake exhibits significant changes throughout the year, increasing from February to August and declining from October to January of the next year. The multi-year mean water temperature is 17.3 °C, with a maximum and minimum of 38.0 °C and −3.5 °C, respectively. The maximum and minimum temperature variations within a year are 39.5 °C and 26.7 °C, respectively. The annual precipitation and the average annual evaporation in the lake basin area are 1000–1400 mm and 941 mm, respectively.

The basin of the lake is integral to China's development. The basin contributed 17% and 10.8% of the national GDP in 2003 and 2010, respectively, and had a population density of 1079 people per square kilometer (8 times the national average) in 2003 and 1749 people per square kilometer (12.27 times the national average) in 2013. Lake Taihu provides water resources for agriculture, industry and human consumption. The thirteen water plant intakes located in the eastern part of the lake draw approximately 10×10^8 m^3 of tap water from the lake each year. Therefore, the lake plays an extremely important role in the area's economic and social development.

However, with the increasing population and rapid economic growth in the basin, large amounts of pollutants have been discharged into the lake since the 1980s. Consequently, the lake water quality and ecosystem have deteriorated. The water quality had degraded from Grade II-III in the early 1980s to Grade IV–V or worse in the 2010s. As part of the degradation of water quality, rapid lake eutrophication has occurred. An algae bloom expanded from the northern tip of the Meiliang Bay in 1990 to the southern bay mouth in 1994 and then to the center part of the main lake in 2007. In the summer of 1990, the algal bloom was distributed in the northern part of Meiliang Bay and lasted more than one week, halting production at 118 industrial plants and depriving people in Wuxi city of drinking water. In late May 2007, an unprecedented algae bloom broke out in the northern part of the lake and resulted in the intrusion of black water into the Wuxi city water plant tap water intake, affecting approximately 2 million people and disrupting the daily life of residents.

Consequently, considerable scientific research has been devoted to the lake to illuminate changes in water quality, eutrophication, ecosystems and nutrient cycling and the inner mechanisms that characterize algal blooms to reveal how they are jeopardizing the water quality. Unlike rivers, seas, or oceans, due to the low inflow and outflow of lakes relative to their surface area, the inflow- and outflow-driven water currents are very small, and wind-driven currents dominate water movement. In addition to water currents, vertical mixing is governed by wind-induced waves. Because the wind usually changes dramatically within a very short time, the hydrodynamic processes involved are extremely complex. This results in highly complex patterns of nutrient cycling, variations in water quality and algae spatial distributions overlaid with intricate changes in temperature and river inflow and outflow. The huge scale of the lake also means that long-term on-site observations and lab experiments with sufficiently high temporal and spatial resolutions to reveal variations in water quality, eutrophication, algae blooms and the intrinsic mechanisms for the lake protection and management would be unimaginably costly in terms of both financial and labor resources. Modeling offers the advantages of lower financial costs and high repeatability (without the limitations arising from weather and other factors) and have thus attracted researchers' attention.

Models of the lake hydrodynamics were first developed in the 1980s. Models coupling the transportation of matter to water quality variation were introduced in the 1990s, while models with a wide spectrum of complexity have been applied to the lake's environmental management since the beginning of the 2000s. Among these models, the Ecotaihu model couples hydrodynamic, chemical and the biological processes and has been applied to diagnose and assess the restoration of the lake ecosystem and improvements to water quality. Recently, structurally dynamic models that account for adaptation and shifts in species composition in the lake ecosystem based on the Ecotaihu model are being proposed and constructed. Furthermore, the Ecotaihu model has been coupled with the basin river network model and improved and modified to detect and predict water blooms as well as to set water quality targets. This review is therefore based on the history of the models and their present status as they relate to our attempt to answer the following three questions:

(1) What are the trends in lake model development?
(2) How can the models be improved?
(3) To what extent can the models support lake management and avoid the bottleneck of model applications?

2. Model development

2.1. Hydrodynamic model

Because of a lack of sensitive, high-accuracy and low-speed current meters, the measurement of the water current in Lake Taihu in the 1980s was very different from that in the present, in part due to extremely unstable wind-driven water currents and very