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Construction of lake reference conditions for nutrient criteria based on system dynamics modelling

Libing Zhang[a,b], Lulu Wu[a], Chengguo Wu[a,b,*], Juliang Jin[a,b], Shouliang Huo[c], Yuliang Zhou[a,b]

[a] School of Civil Engineering, Hefei University of Technology, Hefei, China
[b] Institute of Water Resources and Environmental Systems Engineering, Hefei University of Technology, Hefei, China
[c] Institute of Water Environment, Chinese Research Academy of Environmental Sciences, Beijing, China

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ABSTRACT

Assessment of ecological status is crucial for establishing well-defined reference conditions for a lake. In this study, a model based on System Dynamics was developed to simulate the production, transport and distribution of the nutrients in Lake Chenghai, Yunnan Province, China. Application of the proposed model with a system retrieval technique yielded the variations in nutrient concentrations and eutrophication levels under different hydraulic conditions during the past several decades. Results showed that the proposed model is capable of describing the historical process of the lake's eutrophication after calibrating with the experimental data. The reference conditions for Lake Chenghai were proposed as follows: 0.0074–0.0091 mg/L for the total phosphorus concentration, 0.112–0.128 mg/L for the total nitrogen concentration, 0.859–1.081 ug/L for the chlorophyll *a* concentration, and 6.327–5.557 m for the Secci depth transparency. It provided an effective way to establish the nutrient reference conditions for the foundation of a lake's nutrient criteria, as well as the eutrophication control standards in China.

1. Introduction

Well-defined lake trophic status and reference conditions are the basis for the development of scientifically rational criteria and standards for water quality and trophic status of a lake, which are critical for effective eutrophication control and restoration of aquatic ecosystems (Xu et al., 2010). Developed countries, such as the United States, Japan, Australia, establish regional water quality criteria and standards for eutrophication control in the early 21st century, which were based on their characteristics of aquatic systems and environmental protection expectations. China is one of the largest developing countries, a series of water quality standards, such as “Hygienic standard for drinking water”, “Water quality standard for farm irrigation” and “Surface Water Quality Standard”, and so on, have been formulated, but still lacks special water quality criteria system for lakes, which now is substituted by surface water quality standards in some cases. Therefore, the development of water quality criteria system for lakes will be of great significance for both theoretical research and practical application (Meng et al., 2008; Xia et al., 2004). Total phosphorus (TP), total nitrogen (TN), and chlorophyll *a* (chl *a*) are generally used to characterize reference conditions for nutrient criteria of a lake. These represent the lake's conditions with the least anthropogenic disturbances and pollution, or the most attainable conditions (Painting et al., 2005). However, almost all lakes of China have been impacted more or less by human activities, and it is difficult to determine the degree of human impacts. Therefore, it is necessary to establish reference conditions of a lake. Previous studies have reported several methods to define the reference conditions, such as the statistical analysis of the historical data, model prediction and inference, reconstruction of the ancient limnology, and expert judgments (Andersen et al., 2004; Solheim, 2005; Chen et al., 1998). However, due to the regional differences in climate and geography, as well as the heavy interference of human activity to most of the lakes and the general lack of historical monitoring data, the reported methods are not appropriate for direct use in China. In order to define the lake reference conditions of nutrients in China, the efforts have been made through preliminary studies. For example, Huo et al. (2009) analyzed the significance of several reported methods to develop lake nutrient criteria in China. The reference conditions for Lake Taihu were established through a population frequency distribution analysis, with respect to TN, TP, chlorophyll *a*, and Secchi depth (Zheng et al., 2009). Then, based on the eastern plain paleolimnology reconstruction information, along with the existing water quality data, Chen et al. (2010) estimated the ranges of the four parameters of the nutrient reference conditions for Lake

* Corresponding author at: School of Civil Engineering, Hefei University of Technology, Hefei, China.
E-mail addresses: wule9825@163.com, WUCGUO@KNIGHTS.UCF.EDU (C. Wu).

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Chaohu by using lake population distribution, trisection, and regression approaches (Yan and Wu, 1994; Fang and Yan, 2007).

It is widely known that a lake is a specific ecoregion, with nutrient production, transport, transformation, and so on, which is integrated with watersheds to form a relatively independent complex system. However, a lack of integrated and systematic data currently exists for lake eutrophication in China (Liu and Guo, 2008; Zhang et al., 2007). Lake water resource system is a complex system which will have an impact on both the regional socio-economic development and ecological system balance (Long et al., 2004; Rijsberman and Van de Ven, 2000), while it is difficult to model the lake watershed system for its uncertain influence factors of unclear administrative attribution and boundaries, incomplete information, and so on (Endter Wada et al., 1998; Gaiser et al., 2008; Gibson et al., 2000).

Conventional mechanical description and inference approaches are not sufficient to establish a complete systematic model for such a complex system (Chen, 1999; Chou et al., 2007; Cheng, 1999). The motion of all systems in the world is assumed as the motion of fluid according to System Dynamics method (SDM), which overall adopts the causal loop diagrams and stock and flow diagram to represent the structure and nonlinear feedback relationship within the system (Jøgensen, 2003; Wang et al., 2007). Therefore, the primary objective of this research was to present a SDM model coupled with system retrieval technique and eutrophication assessment method to characterize the production, distribution, and transport of nutrients in the Lake Chenghai by developing the causal feedback diagrams between kinds of nutrients concentration and its influencing factors under different influence scenarios of watershed hydrology, ecology, and human activities (Zhang et al., 2008). And finally the threshold of nutrient reference conditions was obtained which would provide an effective basis to establish the nutrient reference conditions for the establishment of lake nutrient criteria and eutrophication control standards in China. Besides, due to the advantages of intuitivism, practicality, flexibility, and convenience, SDM has been widely applied in socio-economic, strategic military and resource utilization systems by coupling with other mathematical models (Wang, 1996).

2. Material and methods

Lake Chenghai, known as the Black Sea or Black Wuhai, is located in the central Yongsheng County in Yunnan Province, between Liangguan and Star Lake, 45 km from the county center (Jin, 1995). It is located at 26°27′–26°38′ north latitude, and 100°30′–26°49′ longitude, and is part of the Jinsha River system. It is one of the nine plateau lakes in Yunnan Province, and is also one of the world's three lakes with growing spirulina (the other two are Lake Cocoa in Mexico and Lake Chad in Africa). It presents the status quo of a long and narrow lake. The catchment area is 318.3 km^2 with the land area of 243 km^2, shoreline length of 45.1 km, and water area of 74.6 km^2. The north-south length of the lake is 19.0 km, with a maximum width of 5.4 km. The average width of the lake is 4.3 km, with a storage capacity of 1.98 billion m^3. The average water depth is 25.7 m, with the deepest water depth of 35.0 m. The inclination of Lake Chenghai's bed is large. However, the shallow water is less than 0.87% of the water depth up to 20 m. Chenghai Lake originally emptied into the Jinsha River until 1609, after which the water level declined year by year until no more water entered into the Jinsha River. It gradually evolved into an inland lake with no outlet. However, a part of the lake includes a groundwater excretion, which is not derived from river input (Fig. 1).

2.1. Natural basin ecosystem model of Lake Chenghai

Lake Chenghai is located in the Jinsha River Valley, and has a subtropical plateau monsoon climate. The annual average temperature of the lake is approximately 18.7 °C, with no frost occurring at any time during the year. In the lake area, the wet and dry seasons are obvious, although the four seasons are not distinct. The sun illumination is sufficient, and the duration of sunshine ranges between 2500 and 2750 h. The ≥10 °C accumulated temperature reaches between 5000 and 6000 °C every year.

2.1.1. Water resources and environment subsystems of Lake Chenghai's basin

According to the statistics from the hydrological station of Hekou Street (26°28′ N and 100°39′ E) during the last 20 years, its average annual rainfall was 733.6 mm, and the rain period was between 90 and 100 days. Rainfall during the dry seasons was extremely rare, and the annual evaporation was 2040 mm, with the drought index of approximately 2.4, yielding a seasonally arid environment. The precipitation during the rainy season accounted for 92% of total annual precipitation. The lake water was mainly from watershed runoff and precipitation. The lake's elevation is 1501 m, and the highest point in the watershed is 3280.0 m, which is located in the western basin of the lake. In this study, according to the field observations, it was found that the remains of algae were still visible on the bank of the lake above 30 m, which further demonstrated the fact that the water's course to the sea experienced significant levels of fluctuations in the past. According to the historical statistics of 276 years (between 1690 and 1965), the water flowed over 30 km south into the Jinsha River, and formed the Cheng River system. Since then, the total water has dropped 37.8 m due to water depletion and reduced rainfall. Therefore, Lake Chenghai has become a closed lake without outflow, with many years of fixed ground water recharge. Its water supply is mainly from groundwater and lake precipitation. The basin rainfall data from 1970 to 2009 is shown in Fig. 2.

Lake Chenghai is located in the dry heat zone of the Jinsha River. The lake evaporation is three times that of the entire basin precipitation. The long-term water deficits have led to continuous decline in the lake's water level. To prevent the continued decline, a diversion tunnel project was built in August, 1993. At present, local government is building a massive water diversion project to bring water from the Yongsheng River into the lake. Also, irrigation projects were controlled in order to maintain the water level of Chenghai Lake. When the "diversion complement sea" project was completed in 1994, the lake's water level tended towards stability. Therefore, it could be seen that the lake's water was derived mainly from the runoff and precipitation of lakes basin. The roles of the rainfall and evaporation were the dominant factors in controlling the water level. In accordance with the existing discharge data regarding the watershed rainfall, evaporation, and water storage, a dynamic system model of lakes water subsystem was constructed as Fig. 3.

2.1.2. Subsystem of the Chenghai River Basin land resource

In the new generation of the mid-Tertiary (dating back to 12 million years), the Himalayan orogeny formed a fault graben, which was trapped in the low-lying places in polywater from the highland lakes, and is geologically referred to as the fall of the lake. The lake is ringed on three sides (east, west, and north) by mountains. The terrain is flat in the south, and clastic rock in the east, with a slow slope. In the north, carbonate rock forms a mountainous terrain in the middle, and basalt forms an endless steep mountain range in the west. The landscape is generally high in the northwest, low in the southeast, high on two sides, and low in the center. The rock of the lake is mainly Permian basalt and tuff, Jurassic mudstone, sandstone, limestone, Devonian limestone, and so on. Around the lake, zonal soil is spread mainly in the form of red, red brown, and farming soil along the lake. The lake has sparse vegetation, and the soil erosion is severe. The lake has also developed widely basalt, sandstone, dolomitic limestone, and shale. The land in the Lake Chenghai watershed is mainly used as forested, agricultural, urban construction, residential land areas, with rural hills, lakes, and so on. The woodland area is less than normal, and accounts for only 23.19% to the total forest area. The vast majority of the land is woodland and