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Spatial−temporal hydrodynamic and algal bloom modelling analysis of a reservoir tributary embayment

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Abstract

The tributary embayments of Three Gorges Reservoir have been frequented by algal blooms over the past decade. We develop a three-dimensional hydrodynamic and water quality model to study the spatial and temporal variation of hydrodynamics and algal bloom dynamics in a eutrophic tributary embayment, Xiangxi Bay. The study area exhibits distinct longitudinal gradients in hydrodynamics, and could be generally characterized into four longitudinal zones: riverine, intermediate, lacustrine, and mainstream influenced. Compared with the typical longitudinal zonation for a pure reservoir, there is an additional mainstream influenced zone (about 5−10 km long) near the mouth due to direct effects of its adjacent reservoir mainstream. The transport and transformation of key water quality constituents associated with algal blooms, such as chlorophyll, nitrogen, phosphorus, and silicon are simulated satisfactorily. We further investigate the algal bloom dynamics by combining the model results and *in situ* water quality observations. There is a strong spatial dependence of algal bloom events (occurrence and distribution) in Xiangxi Bay: (*i*) during 2003−2012, some 73.9% of algal bloom events were first observed in a 10 km long reach within the intermediate and lacustrine zones, and (*ii*) the spatial pattern of chlorophyll concentrations is closely related to the longitudinal variance of hydrodynamics. A conclusion from this paper is that the relatively calm environment of the intermediate and lacustrine zones provides favourable conditions for algal growth, suggesting the possibility of using longitudinal zonation for risk assessment of algal bloom initiation and levels in reservoir tributary embayments.

Keywords: Hydrodynamics; Algal bloom; Longitudinal zonation; Water quality model; Tributary embayment

1. Introduction

Eutrophication, defined as the excessive enrichment of waters by nutrients, is widespread in lakes and reservoirs throughout the world (Smith, 2003). Under favourable environmental conditions, excessive nutrients in impounded waters can stimulate extremely rapid growth of microscopic algae or phytoplankton, forming algal blooms. Algal blooms may give rise to a variety of adverse effects, such as decreasing water transparency, emission of noxious odours, releasing toxins, and leading to hypoxia and fish kills (Mao et al., 2009). Three Gorges Reservoir (TGR) is one of the largest water resources projects in China and the world. In addition to its importance of flood control and hydropower generation, TGR is also of great ecological importance to fisheries and water resources. Whereas the TGR mainstream is still considered mesotrophic, episodic algal blooms have been reported to occur in the weakly flushed tributary embayments, implying the development of a eutrophic environment in parts of the reservoir. Understanding the causality and dynamics of algal blooms in the tributary waters is therefore important for the holistic management of the important reservoir.

It is generally established that hydrodynamic, nutrient and meteorological conditions are the main factors that contribute to algal bloom formation (Schindler and Fee, 1974; Anderson et al., 2002). Considering that meteorological conditions

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cannot be controlled or changed, bloom control should be mainly determined by pollution loading and hydrodynamic conditions. Moreover, as most of living biomass, contaminants, dissolved gases, and suspended particles are carried and mixed by turbulent motions, the interactions of various water quality variables may be significantly influenced by varying hydrodynamic conditions. That is, algal bloom studies must be based on a thorough understanding of the spatial and temporal variability in physical and biogeochemical processes.

TGR is periodically regulated by dam operations, and thus exhibits the characteristics of both rivers and lakes. The complexity of such a large-scale reservoir system presents considerable challenges for reservoir managers to characterize the hydrodynamics and algal bloom dynamics therein. Over the past decade, some site-specific studies have been conducted at a major tributary embayment of TGR, Xiangxi Bay. The bay is the closest major tributary upstream from the dam, and algal blooms occurred therein almost every year after the impoundment of TGR. Most of the research focused on the field investigation of the hydrological, hydrodynamics, geochemical and ecological driving variables (Ye, 2006; Ye et al., 2006; Yang et al., 2009, 2010). The spatial patterns of the embayment were also experimentally investigated, but limited to the subjects of phytoplankton and macroinvertebrate communities (Ye et al., 2007; Wang et al., 2011; Shao et al., 2010). Although several modelling studies on flow and water quality have been carried out for TGR's tributary embayments (Yu and Wang, 2011), the cause-and-effect relationship between flow regime and algal bloom distribution has hitherto not been fully studied; flow regime here refers to the pattern of flow variability in time and space for a particular waterbody, which might be characterized according to flow rate, frequency, duration, etc. (Poff et al., 1997).

The objective of this study is to better understand the potential role of flow regime in the occurrence and development of algal blooms in TGR, through the analysis of temporal and spatial patterns in a typical eutrophic tributary embayment. Obviously, it is difficult to obtain sufficient information of a large scale reservoir system through expensive long-term water quality monitoring or real time observations (Mao et al., 2009). Comparatively speaking, numerical modelling appears to be a suitable method to provide insight into the hydrodynamic and kinetic complexity of young man-made lakes for ecological purposes (Hernandez et al., 1997; Tufford and McKellar, 1999; Kuo et al., 2006). In order to meet our objective, we develop a three-dimensional hydrodynamic and water quality model for Xiangxi Bay. The time and spatial variations of key hydrodynamic and water quality parameters are then simulated and analyzed. The effects of hydrodynamics (e.g., gradient and regime) on algal bloom dynamics (e.g., occurrence and abundance) are finally discussed.

2. Material and methods

2.1. Study area

Three Gorges Dam is located on the upper Yangtze River of China. The waters blocked by the dam form a long (~650 km) and narrow (500–1000 m) reservoir, with a normal pool level of 175 m and a total reservoir storage capacity of 39.3 billion m^3. TGR has a mean depth of around 70 m and the maximum depth near the dam of around 170 m (Dai et al., 2006). On 26 October 2010, the reservoir water level was raised to the normal pool level for the first time, indicating the completion of the young reservoir. Covering around 75,098.13 km^2 drainage area and 1.6 hundred million people in central China, TGR plays the critical role of flood control, hydropower generation, and navigation improvement. In particular, it has a flood storage capacity of 22.15 billion m^3, which can lessen the frequency of downstream flooding from once every 10 years to once every 100 years. Nevertheless, the water quality and trophic state of TGR are currently receiving increasing attention, mainly due to the episodes of algal blooms.

Xiangxi River is one of the longest tributaries of TGR, located 34.5 km upstream from the dam. It flows south into the mainstream of Yangtze River at the Xiangxi Town (Fig. 1). The headwaters of the river are located approximately 94 km north of the mouth, and the drainage area is around 3099 km^2 (110°25′–111°06′ E, 30°57′–31°34′ N). Xiangxi River has three main tributaries: Jiuchong River, Gufu River, and Gaolan River. The study area experiences a humid subtropical climate, with a large day-and-night temperature difference in spring, concentrated heavy rainfall in summer, frequent cloudy/rainy days in autumn, and little snowfall in winter. The average annual temperature is 16.6 °C. The average annual rainfall and discharge are 1015.6 mm and 40.18 m^3/s, respectively, while 80% of the annual flow occurs in the wet season. There are several point sources from phosphate plants in the upper basin, and non-point sources from agricultural areas, aquaculture and livestock farms. After the impoundment in June 2003, a tributary embayment has been formed at the lower reaches of the Xiangxi River. The upper portion of the embayment is very narrow and shallow, compared to the mouth. The hydrodynamics of this embayment is currently weak (around 1–10 mm/s normally, and 0.1 m/s of flood peak), which is probably the main reason for the considerable degradation of water quality and the algal blooms (Cai and Hu, 2006; Ye et al., 2006; Zheng et al., 2011). The algal blooms observed at Xiangxi Bay are listed in Table 1. It is shown that, in the past 10 years after the impoundment, there has been an increase in the frequency and intensity of algal blooms in Xiangxi Bay. The blooms usually occurred with a life cycle of the order of days to a few weeks.

2.2. Hydrodynamic model description

The widely used Delft3D framework is applied to simulate the flow regimes and algal bloom dynamics of Xiangxi Bay (Delft Hydraulics, 2006a). It models flow phenomena of which the horizontal length scales are significantly larger than the vertical scales; namely, it solves shallow water equations (with the hydrostatic and Boussinesq approximations) derived from the Reynolds-averaged Navier–Stokes equations for incompressible fluid on Cartesian rectangular or boundary fitted grids. The σ-coordinate system is used for the vertical grid direction to transform the irregular bathymetry to dimensionless unit depth.