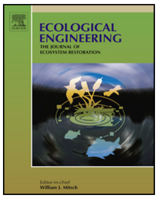
Ecological Engineering 58 (2013) 180–191

Contents lists available at ScienceDirect

Ecological Engineering

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



Changes in phytoplankton biomass due to diversion of an inflow into the Urayama Reservoir

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ARTICLE INFO

Article history:
Received 8 January 2013
Received in revised form 8 May 2013
Accepted 23 June 2013
Available online 27 July 2013

Keywords:
Bypass system
Reservoir management
Numerical simulation
ELCOM-CAEDYM model
Cyanobacteria

ABSTRACT

The three-dimensional hydrodynamic Estuary, Lake and Coastal Ocean Model (ELCOM) coupled with the ecological Computational Aquatic Ecosystem DYnamics Model (CAEDYM) was applied to Urayama Reservoir in order to examine the effect of an inflow bypass on the water quality in the reservoir. The bypass system functions by intaking water from upstream of the reservoir and transferring it to the reservoir selective withdrawal tower in order to avoid turbid-water withdrawal. The model was calibrated using data measured in 2009. Simulated results of water temperature, dissolved oxygen, turbidity, nutrients and four groups of phytoplankton (cyanobacteria, diatoms, chlorophytes and cryptophytes) were in good agreement with field measurements. Some bypass operational scenarios and model parameter test scenarios were performed. The results showed that the bypass operation altered the nutrient load and in-reservoir concentrations as well as the heat budget, which changed the water temperature, dissolved oxygen and other water quality parameters, including chlorophyll a (Chl*a*) concentration in the reservoir. Detailed examination of the growth of phytoplankton revealed that cyanobacteria were most affected by the bypass operation because of the interaction between the change of hydrological conditions and the buoyancy control of cells. The results suggested that the operation of the bypass system was useful in decreasing inflow nutrient loads as well as decreasing the transport of the algal biomass from upstream to the dam wall, which generally helped to decrease the magnitude of algal biomass near the offtake region of the reservoir.

1. Introduction

Algal blooms and prolonged periods of turbid water are major concerns in reservoirs worldwide (Smith, 2003). Many researchers have focused on optimizing reservoir operations to have effective water quality management (Gulliver and Wilhelms, 1994; Barbiero et al., 1997; Kovacic et al., 2006; Çalışkan and Elçi, 2009; Shammaa and Zhu, 2010). In order to cope with water quality problems, most reservoirs adopt one or more water quality improvement countermeasures (e.g., curtain weirs, selective withdrawal systems (SWSs), aeration systems, and bypass systems are typical options). A curtain weir can reduce algal biomass by curtailing the dispersion of nutrients from the upstream riverine zone to the downstream epilimnion, enhancing biological uptake upstream (Asaeda et al., 1996, 2001; Priyantha et al., 1997; Vermeyen, 2000; Vermeyen and Knoblauch, 2000; Morillo et al., 2006; Chung et al., 2008). Asaeda et al. (2001) concluded that the curtain method is most suitable for reservoirs or lakes with an elongated morphology, which reduces the required length of the curtain. SWSs are among the most common techniques used for water quality management in reservoirs. They allow for the withdrawal of water from different levels, which give dam operators some control over water quality (Fischer et al., 1979; Martin and McCutcheon, 1999; Yajima et al., 2006). SWSs also have the benefit of enhancing downstream environmental habitat and water supply quality as temperature, dissolved oxygen (DO) and suspended solids (SS) may be regulated to some extent (Michael et al., 2004; Australian Capital Territory, 2006). A third technique involves aerator systems, which continuously bring deep water toward the surface of the reservoir, eroding stratification and disrupting the growth of phytoplankton inhabiting the euphotic zone (Reynolds et al., 1983; Steinberg, 1983; McQueen et al., 1986; Jungo et al., 2001; Hawkins and Griffiths, 1993; Heo and Kim, 2004). In contrast, bypass systems are used to transfer highly turbid water directly from the upstream of the reservoir to the downstream end of the reservoir, or alternatively, transfer clear-water directly to the downstream end from upstream in circumstances when the

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http://dx.doi.org/10.1016/j.ecoleng.2013.06.030

water in the reservoir is turbid and does not meet water quality guidelines for release (Sumi et al., 2004; Japan Water Agency, 2009).

Urayama Reservoir which is the focus of this paper has the latter type of bypass system and can release clear-water taken from upstream in order to supply clean drinking water to the downstream end when the reservoir becomes very turbid (Japan Water Agency, 2009). However, this bypass system only focuses on turbidity or sedimentation and the potential to manage other water quality problems has not been considered to date. In order to optimize water quality management in reservoirs using a bypass system, there is a need to understand its broader effects. Specifically, Urayama Reservoir, in addition to its high turbidity, has problems with algal blooms. Growth of phytoplankton in a reservoir is generally controlled by both physical and chemical factors including light availability, water temperature and nutrient concentrations (Smith and Shapiro, 1981; Smith, 1983; Tilman et al., 1986; Cloern, 1999; Imai et al., 2009) and hydrological factors such as the bathymetry, retention time and related factors (Spigel and Imberger, 1987; Donaghay and Osborn, 1997; Chan et al., 2002; Robson and Hamilton, 2004). Bypassing of upstream water clearly reduces not only suspended sediments in inflows but also reduces the nutrient load into the reservoir, which has the potential for reducing algal blooms.

A simulation model can be a powerful tool to aid in the interpretation and understanding of changes in phytoplankton communities. Algal blooms in a reservoir have a close relationship with hydrodynamic changes in particular, the inflow regimes and subsequent mixing processes that distribute inflow nutrients (Comerma et al., 2001; Friedl and Wüest, 2002; Mašın et al., 2003). Stratification, vertical mixing and wind drift that may lead to localized niches for phytoplankton also play a part (Kennedy et al., 1982; Šimek et al., 2001; Botelho and Imberger, 2007). Hence the need for an ecological model directly coupled with a three-dimensional hydrodynamic model. Generalized Environmental Modeling System for Surfacewaters (GEMSS) (Na and Park, 2006), Environmental Fluid Dynamics Code (EFDC) (Wu and Xu, 2011) and Estuary, Lake and Coastal Ocean Model coupled with the Computational Aquatic Ecosystem DYnamics Model (ELCOM-CAEDYM) (Missaghi and Hondzo, 2010; Vilhena et al., 2010; Leon et al., 2011) are three well-known water quality simulation models. As reservoirs most commonly have problems with cyanobacterial blooms, some models only deal with cyanobacteria (Recknagel et al., 1997; Tufford and McKellar, 1999; Na and Park, 2006; Lindim et al., 2011; Missaghi and Hondzo, 2010). However, single species simulations cannot predict the changes in the composition of phytoplankton communities or related dynamics such as nutrient cycles. By comparison, simulation of multi-species competition is more complex because it must explicitly account for the functional advantages of different phytoplankton groups, such as buoyancy control by cyanobacteria (Bonnet and Poulin, 2002; Fuente and Niño, 2008; Estrada et al., 2009; Gal et al., 2009; Vilhena et al., 2010). ELCOM-CAEDYM was therefore selected for this study, as it is a model that meets these criteria for dynamic representation of multiple phytoplankton groups.

In this paper, we have described an application of the coupled, three-dimensional hydrodynamic and ecological model, ELCOM-CAEDYM to Urayama Reservoir. The main objective of the modeling was to provide a tool that could be used to evaluate the effect of the clear-water bypass operation on algal biomass in the reservoir. The model was calibrated against the data of 2009 when it showed the largest maximum total Chl*a* concentration in the summer season after the beginning of the bypass operation. Then several scenarios considering the bypass operations and model parameters were applied.

2. Material and methods

2.1. Study area

Urayama Reservoir is located in the Arakawa River basin (Fig. 1). Its initial impoundment finished in February 1999 and the normal operation started in April 1999. The reservoir is designed for a return period of a 100-year flood event and the discharge from the reservoir is 110 $m^3\,s^{-1}$ at the maximum design flood inflow of 1000 $m^3\,s^{-1}$. It supplies water for irrigation and maintenance flow as well as municipal water supplies of 20,000 $m^3\,day^{-1}$ for Chichibu City, 230,000 $m^3\,day^{-1}$ for Saitama Prefecture and 100,000 $m^3\,day^{-1}$ for Tokyo Metropolis. Additionally, it has the ability to generate 5000 kW of power output at the peak discharge of 4.1 $m^3\,s^{-1}$ for the generator.

The reservoir has a watershed of 51.6 km^2, total reservoir capacity of $58 \times 10^6\,m^3$, maximum water level at elevation 393.3 m and a controlled water level at elevation 372.0 m during the flood season. There are two main inflows comprised of the Urayama River and the Okubodani River. Flood inflow events have been known to introduce large amounts of turbid water to the reservoir, causing prolonged turbidity problems not only in the reservoir but also in the downstream reach. In particular, in 1999 and 2001, a large flood caused an overturning in the reservoir, which was followed by high turbidity throughout the entire water-body for more than three months (Japan Water Agency, 2003). Since then, the Japanese Ministry of Land, Infrastructure, Transport and Tourism began a project to construct a clear-water bypass channel (1 m diameter, 6 km long), which enables clear-water to be taken from upstream of the reservoir, transporting it to the top of the selective withdrawal tower and discharging it directly from the tower thereby avoiding the withdrawal of turbid water (Fig. 1). The transferred water by the bypass does not mix with the water in the reservoir. The construction was completed in May 2007 and since then it has been operated often during the flood season except when the inflow turbidity at the upstream intake point exceeds 10 $mg\,L^{-1}$ kaolin, which is approximately 7.8 $mg\,L^{-1}$ of SS.

2.2. Introduction of 3D hydrodynamic and ecosystem model

A three-dimensional hydrodynamic and ecological model, ELCOM-CAEDYM, which was developed by the Centre for Water Research at the University of Western Australia, was applied to Urayama Reservoir in this study. ELCOM solves the unsteady, hydrostatic, Boussinesq, Reynolds-averaged, Navier–Stoke equations, thermodynamic models and scalar transport equations to simulate the temporal behavior of stratified water bodies with environmental forcing (Hodges et al., 2000; Leon et al., 2007). Heat exchange at the water surface is governed by the classical concepts of heat transfer (Imberger and Patterson, 1981) and is separated into non-penetrative components of long-wave radiation, sensible heat transfer, and evaporative heat loss, complemented by penetrative short-wave radiation. Non-penetrative effects are introduced as sources of temperature in the surface layer of the model, whereas penetrative effects are introduced as source terms in one or more grid layers on the basis of an exponential decay of energy and an extinction coefficient.

CAEDYM is a process-based ecological model that can be configured to simulate up to seven phytoplankton groups and six suspended solids groups (each group can have its own diameter and density) as well as nitrogen, phosphorus, oxygen and silica. CAEDYM can also simulate macrophytes, zooplankton, fish and benthic invertebrates, but these groups were not activated in the present application (Hipsey *et al.*, 2009).