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Modeling Turbidity Intrusion Processes in Flooding Season of a Canyon-Shaped Reservoir, South China

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Abstract

Continual runoff events in flooding season affect hydraulic structure and nutrient circulation strongly in reservoirs. The phenomenon of turbid current intrusion and water clarity decreasing was observed in flooding season in Liuxihe reservoir, Guangdong, south China. Numerical simulation techniques are used to study the hydrodynamic processes of runoff events. According to 2 years’ monthly measurements, daily inflow turbidity is estimated by inflow volume and precipitation. Then, a 1-D hydrodynamic coupled with water quality model is applied to simulate the thermal stratification and vertical turbidity distribution during the period with high turbid runoff events. The results show good performance in reproducing the reservoir thermal structure, the magnitude and distribution of turbidity in the reservoir. Based on these, 4 simulation cases are introduced to examine the effects of different reservoir management measures (e.g. different outflow volume and withdrawal depth) on suspended matters’ concentration (turbidity) and distribution in water column. The results can be the basis of water quality management measures of the reservoir administration and local government.

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Keywords: Liuxihe Reservoir, runoff event, turbidity, water quality, hydrodynamic processes

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1. Introduction

Turbidity current intrusion has been observed in many reservoirs [1, 2], which can supply large quantities of nutrients and organic carbon to the metalimnion. Some of these substances can be advected into the epilimnion, and may contribute to a seasonal increase in primary productivity [3]. Turbid water in a reservoir has negative aesthetic and recreational appeal and may affect adversely on bio-diversity, in addition to increasing water treatment costs [4].

In south China, freshwater reservoirs supply about 40% of the total water demand [5]. The trophic level of these reservoirs has increased in the last 20 years and has been associated with a decrease in water quality in many reservoirs [6, 7]. Influenced by Asian monsoon climate, more than 60% of annual precipitation concentrates in late spring to summer (April-July) in the last 50 years. Large discharge volume during that period disturbed water column, and entrained a lot of suspended matters from the watershed (including fine sediment, inorganic nutrients and organic matters) to the reservoir.

In this work, turbidity intrusion processes of a large canyon-shaped reservoir in south China were investigated to study thermal regimes and vertical distribution of suspended matters. A hydrodynamic model was applied to quantify the responses of suspended matters’ concentration (Turbidity) and distribution in water column to different reservoir management measures.

2. Methods and Material

2.1. Study Site

Liuxihe Reservoir (23°45′50″N; 113°46′52″E) is a large canyon-shaped reservoir located in a transition from tropical to subtropical zones at about 90 km northeast of Guangzhou city in Guangdong Province, southern China (Fig. 1). This impoundment, initially filled in 1958, is an important source of drinking water to residents in downstream areas, including Guangzhou city (population >14 million). The lacustrine zone has dendritic complexities, and the dam is located at its southwestern end. When full, this reservoir has a surface area of 14.9 km², with a mean and maximum depth of 22 and 73 m, respectively. Generally, the high water level is 235 m above sea level (a.s.l.) elevation (3.25×10⁸ m³ in capacity) and the dead water level is 213 m a.s.l (0.86×10⁸ m³ in capacity).

Liuxihe Reservoir is fed by two major rivers, Lvtian and Yuxi Rivers, which drain a catchment area of 264.4 km² and 192.3 km² respectively, and about 85 percent of the total watershed area (539 km²) (Fig. 1). The main outlet is at the Liuxihe hydropower station intake near the dam, with a base elevation of 206.5 m a.s.l and a diameter of 4.5m. Upstream and surrounding landscapes of the reservoir consist primarily of hills covered with forest. There is little human activity, ensuring inflow water is in a good condition. The main water body near the dam is part of the Liuxihe national forest park, and is used for recreation.
2.2. Field Observation

Extensive surveys of Liuxihe reservoir have been conducted monthly from April 2008 to July 2010. Temperature, turbidity, dissolved oxygen (DO), chlorophyll a, and conductivity profiles were measured in the reservoir and river arms using a multi-parameter water quality meter AAQ-1183IF (Alec Electronics Co., Japan).

A HOBO temperature data logger (accuracy: 0.2°C, Onset Co. USA) was deployed in Lvtian river (23°47′33.6″N; 113°50′30.7″E), recording inflow water temperature every 30 minutes. An automatic meteorological station was deployed on the top of a building near the south shore (23°44′53″N; 113°46′46.2″E) recording meteorological variables (solar radiation, air temperature, air pressure and relative humidity) every 20 minutes. The daily water level, inflow and outflow volume was obtained from the Liuxihe hydropower station.

2.3. Numerical Simulations

One dimensional, hydrodynamic model DYRESM couples dynamically with the Computational Aquatic Ecosystem Dynamics Model (CAEDYM) [8] is applied to analyze thermal stratification and turbidity distribution of the reservoir. This model has been used to study a number of lakes and reservoirs and has proved effective [9, 10].

The simulated period covered 88 days, from 17 March to 12 June 2010. Boundary and initial conditions (including Meteorological and hydrological data, inflow temperature, initial temperature and turbidity profile) are based on field measurement, while inflow suspended particles’ concentration is estimated by inflow rate and precipitation.

DYRESM parameters are based on calibrations in other lakes and reservoirs [11, 12]. Settling velocities are calculated as a function of the median diameter and the density of the particles according to Stoke’s Law in model CAEDYM, the characteristic of suspended particles (mineral composition and
particle size distribution) have been measured in 2010 [13]. To overcome the effects of the shape, roundness, and density of the particles on the settling velocity, an adjustment factor was introduced to the settling velocity in the Stokes formulation [4].

3. Results

3.1. Hydrological Conditions

As a result of the Asian monsoon climate, more than 60% of annual precipitation concentrates in late spring to summer (April-July) in the last 50 years. Hydrological conditions of studied period are shown in Fig 2. In March, daily inflow volume is around $10^8 m^3$, while since mid April, large inflow volume (around $4 \times 10^8 m^3$ everyday) accompany with intensive rainfall states the coming of flooding season. The outflow also increases in May to balance the water level, and lead to shorter water retention time.

![Fig. 2 Hydrological conditions of the studied period (17 Mar - 12 Jun)](image-url)
3.2. Inflow Turbidity Estimation

Significant turbid density flow always follows large rainfall events in many lakes and reservoirs [4, 14]. In Liuxihe reservoir, there is also high correlation between inflow volume and total suspended matters [15].

As inflow turbidity was not recorded daily during the simulated period, we assume it is determined by inflow volume and precipitation as Equation (1) described.

\[ T = f(I_i) + g(P_j) \]  

(1)

Here, \( T \) is inflow turbidity, \( I_i \) is \( i \) days’ accumulative inflow volume, \( P_j \) is \( j \) days’ accumulative precipitation. \( f(\cdot) \) and \( g(\cdot) \) are types of functional relation, e.g. linear, exponential, power, polynomial. We used 30 sets of measured data from 2008 to 2010 to fit the relationship among inflow turbidity, inflow volume and precipitation. To get a relatively accurate relationship, we tested various combinations of functions and variables, and used a nonlinear optimization technique PSO (Particle Swarm Optimization) [16] to search parameters in different function. The result shows that 2 days accumulative precipitation and 3 days accumulative inflow volume under exponential and power relations (see Equation (2)) can reproduce the inflow turbidity fluctuation best (with correlation coefficient \( R \) of 0.9204).

\[ T = 4.0080 \cdot e^{0.0301P_i} + 3.4547 \cdot I_i^{0.4823} - 14.2371 \]  

(2)

Fig. 3 shows daily inflow turbidity during the studied period (17 Mar-12 Jun) estimated by this method, the value and variation of measured inflow turbidity is reproduced well.

![Fig. 3 Estimated and measured inflow turbidity during simulated period](image)

3.3. Model Validation

The simulation results of DYRESM-CAEDYM were consistent with the measurements in lacustrine area of Liuxihe Reservoir (Fig. 4 and 5). The onset of thermal stratification is reproduced well and the position of the thermocline was predicted accurately. The numerical simulation also well reproduces the vertical distribution of turbidity.
Fig. 4 Measured and simulated temperature profiles

Fig. 5 Measured and simulated turbidity profiles
4. Discussion

The simulated period have special significance in a year. The reservoir experiences continuous warming, and the thermal structure turns from mixing to stratification. A clear thermocline appears at the end of simulated period. With the arrival of flooding season, increased precipitation and resultant increased inflow mobilized particulate material and thereby increased the suspended matter loading rate during runoff events. Low level (<10 FTU) and uniform vertical distributed condition of turbidity was ended in mid April (Fig 6 (a2)), and a clear turbidity peak (about 50-100 FTU) appears in metalimnion.

To examine the effects of reservoir management measures on turbidity level and vertical distribution in lacustrine area of the reservoir, 4 simulation cases were selected (Model Scenario: MS1-MS4): MS1 and MS2 employed surface (220 m a.s.l) and bottom (200 m a.s.l) withdrawal respectively; MS3 adopted early discharge mode (amplify water output by 50% before runoff event and reduce outflow by 50% after runoff event); MS4 adopted late discharge mode (reduce water output by 50% before runoff event and amplify outflow by 50% after runoff event).

Simulation indicates decrease withdrawal depth can be an effective measure to change the thermal structure and vertical distribution of turbidity in the reservoir. Surface withdrawal leads to shallow stratification (Fig.6 (b1)) and high turbidity always keeps at surface and upper layer (>215 m a.s.l, Fig.6 (b2)). As expected, bottom withdrawal causes deep stratification (Fig.6 (c1)) and imports turbid water into deep layer (Fig.6 (c2)). Numerical experiments on discharge management show that, lower outflow after runoff events (MS3) reserves high turbidity (>100FTU) at upper layer (Fig.6 (d2)). While higher outflow after runoff events (MS4) accelerates turbid water spread to deep layer, suspended matters are diluted but affect wider in water column (Fig.6 (e2)).
Fig. 6 Simulation results of temperature and turbidity profile. (a1), (a2): Base conditions; (b1), (b2): Surface withdrawal scenario (MS1); (b1), (b2): Bottom withdrawal scenario (MS1); (c1), (c2): Early discharge scenario (MS3); (d1), (d2): Late discharge scenario (MS4).
Comparison on average turbidity among simulation cases reveals that, the changes of withdrawal depth have great impacts on suspended matters’ concentration (turbidity) than discharge management (Fig.7a). Average turbidity is significantly reduced under surface withdrawal, while increased under bottom withdrawal. The reason is turbid inflow intrude reservoir water column at about 220m a.s.l in spring, and flow out through surface withdrawal without much mixing with lower layer. While bottom withdrawal cause more vertical disturbance in water column, and raise average turbidity. For turbidity peak values (maximum in water column), bottom withdrawal (MS2) and early discharge situation (MS3) perform extraordinary high after great runoff event at 7 May (Fig.7b), since more turbid water was held in the reservoir than other conditions. Unexpected, surface withdrawal (MS1) also has the lowest value at most of the simulated period.

The results of numerical simulation indicates that, withdrawal manipulation and discharge management have different effects on thermal structure and suspended matters’ distribution, which may be helpful to determine reasonable reservoir management measures.

Fig 7 (a) simulated mean turbidity of the water column; (b) simulated maximum turbidity of the water column
5. Conclusions

Turbidity intrusion processes in flooding season is studied in Liuxihe reservoir, daily inflow turbidity is estimated by inflow volume and precipitation using nonlinear searching technique. A 1-D hydrodynamic coupled with water quality model is applied to simulate the thermal stratification and vertical turbidity distribution during the period with high turbid runoff events, and the results reproduce field measurements well.

4 simulation cases are introduced to examine the effects of artificial operations on turbidity level and vertical distribution in the reservoir, including withdrawal manipulation and discharge management. The results show that, withdrawal manipulation has more effects on suspended matters’ concentration and distribution, and measures of low outflow rate and deep withdrawal after runoff events will increase maximum turbidity in water column significantly.

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