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Effects of storm runoff on the thermal regime and water quality of a deep, stratified reservoir in a temperate monsoon zone, in Northwest China

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HIGHLIGHTS

- Inflow of storm runoff disturbed the Reservoir's stratification significantly.
- Density flow above the bottom increased DO and inhibited pollutants release.
- Oxygen consumption of bottom water was speeded up after the inflow of storm runoff.
- Anaerobic conditions led to the bottom water quality deteriorate.

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ABSTRACT

Jinpen Reservoir is a deep, stratified reservoir in Shaanxi province, located in a warm temperate zone of Northwest China. Influenced by a temperate monsoon climate, more than 60% of the annual precipitation is concentrated from late summer to autumn (July–September). In recent years, extreme rainfall events occurred more frequently and strongly affected the thermal structure, mixing layer depth and evolution of stratification of Jinpen Reservoir. The reservoir's inflow volume increased sharply after heavy rainfall during the flooding season. Large volumes of inflow induced mixing of stratified water zones in early autumn and disturbed the stratification significantly. A temporary positive effect of such disturbance was the oxygenation of the water close to the bottom of the reservoir, leading to inhibition of the release of nutrients from sediments, especially phosphate. However, the massive inflow induced by storm runoff with increased oxygen-consuming substances led to an increase of the oxygen consumption rate. After the bottom water became anaerobic again, the bottom water quality would deteriorate due to the release of pollutants from sediments. Heavy rainfall events could lead to very high nutrient input into the reservoir due to massive erosion from the surrounding uninhabited steep mountains, and the particulate matter contributed to most nutrient inputs. Reasonably releasing density flow is an effective way to reduce the amounts of particulate associated pollutants entering the reservoir. Significant turbid density flow always followed high rainfall events in Jinpen Reservoir, which not only affected the reservoir water quality but also increased costs of the drinking water treatment plant. Understanding the effects of the storm runoff on the vertical distributions of water quality indicators could help water managers to select the proper position of the intake for the water plant in order to avoid high turbidity outflow.

1. Introduction

Reservoirs provide important ecosystem services such as supplying raw water to cities, irrigation, controlling flood and generating electricity. Therefore, adequate reservoir management is of utmost importance, especially in relation to the expected population growth in China. The thermal regime in stratified reservoirs is strongly associated with the hydrodynamics of the reservoirs, and it plays an important role in the extraction dynamics of water quality (Wang et al., 2012a,b). Rainfall events represent disturbances to water bodies by initiating a change in the hydrological conditions that influence the thermal structure of reservoirs. On a global scale, it is predicted that the frequency of extreme rainfall events will change more dramatically than the mean precipitation rate; heavy rainfall events are predicted to occur more often in the near future while the total amount of precipitation is predicted to change only slightly (Allen and Ingram, 2002; Reichwaldt and Ghadouani, 2012).

Inflow of water from storm runoff is one of the main factors influencing the thermal structure. High volumes of inflow can induce mixing in early autumn, leading to the disturbance of the temperature profile (Liu et al., 2011). The density differences between the inflow and the background water in a reservoir may be due to differences in water

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temperature, concentrations of dissolved or suspended substances, or a combination of these. Inflows occur as overflows, interflows or underflows, depending on this density difference (Marti et al., 2011; Gassama et al., 2012). In general, significant turbid density flow always follows high rainfall events in many lakes and reservoirs including Jinpen Reservoir. The inflowing water will enter the reservoir as a plunging underflow if the density of the inflow water is considerably larger than that of the reservoir, and it may flow over the bottom and fill the reservoir from the bottom up if the inflow density is large enough (Chung et al., 2009; Wang et al., 2012a,b).

The hypolimnion becomes anoxic during the summer stratified period, leading to the release of nutrients from the bottom sediments. Longer periods of anoxia result in more significant deterioration of water quality as reduced species continue to diffuse out of the sediment and enter the hypolimnion (Beutel et al., 2007; McGinnis and Little, 2002). Storm runoff with high dissolved oxygen (DO) could effectively inhibit further release of contaminants from the sediments into the hypolimnion. However, easily-degraded organic matter entering into the reservoir will lead to an increase of the oxygen consumption rate in the water, causing an increased release of phosphate from the sediment once the hypolimnion becomes anoxic again (Burris et al., 2002; Gantzer et al., 2009). Heavy rainfall events can result in nutrient input up to 80% and 400% of the average annual input of N and P in reservoirs, respectively (Chorus and Mur, 1999; Rueda et al., 2007). The nutrient composition during high intensity events is mainly in particulate form rather than soluble form (Budai and Clement, 2007). Particulates easily deposit in the reservoir area, eventually leading to an increase of the endogenous nutrient load in the reservoir (Zhang et al., 2006; Thothong et al., 2011).

Jinpen Reservoir is the most important raw water source for Xi'an city. In recent years, deterioration of reservoir water quality has been related to the nutrient load and high turbidity during the flooding season. To draw less-polluted source water of lower turbidity for water plants during flooding seasons, systematical field work on hydrological, hydraulic and water quality measurements was performed in Jinpen Reservoir, and the effects of turbid density inflow on the thermal regime and water quality of Jinpen Reservoir were further analyzed with massive field data. Understanding of the effects of storm runoff on the reservoir water quality is critical to determine the optimal position of water intake, to ensure the raw water quality and to reduce water treatment costs.

2. Material and methods

2.1. Study site

Jinpen Reservoir (34°42′–34°13′N;107°43′–108°24′E) is a large canyon-shaped reservoir located in a temperate zone about 86 km southwest of Xi'an city in Shaanxi province, northwest of China (Fig. 1). Xi'an is the metropolis in Northwest China, which has a population of 8.6 millions. Jinpen Reservoir, initially filled in 2002, is the most important raw water source for Xi'an city with a daily water supply of 8.0×10^5 m^3 which accounts for 76% of the total water supply for this city. The reservoir is also used for flood control and generation of electricity. The storage capacity of the Jinpen Reservoir is 2.0×10^8 m^3. When full, it has a surface area of 4.55 km^2 with a mean and maximum depth of 44 m and 94 m, respectively. Generally, the normal high water level is 594 m above sea level (a.s.l.) and the lowest allowed water level is 520 m above sea level.

Seen from the Google Map (as shown in Fig. 1), the Heihe River is the main stream of Jinpen Reservoir in Shaanxi province which originates from the Qinling Mountain. This river is 91.2 km long with a catchment area of 1418 km^2 and its annual average rainfall, annual evaporation and runoff volume are 898 mm, 948.5 mm, 545.22 million m^3, respectively. Upstream and surrounding landscapes of the reservoir are largely unmodified and consist primarily of hills covered with forest with little human activity like agriculture. The water quantity is quarantined most of the time. However, in recent years, water quality and turbidity problems have increased dramatically due to storm runoff, including landslides and debris flow. These rainstorms cause the increasing content of suspended solids and high turbidity in Jinpen Reservoir, therefore leading to an acute water quality problem for Xi'an city. The water managers of Jinpen Reservoir want to draw raw water with low turbidity through optimizing the position of the intake for the water plant to avoid high turbidity outflow. In order to determine the influence of storm runoff on the thermal regime and water quality of Jinpen Reservoir, four sites were chosen for water quality monitoring from upstream to the reservoir (Fig. 1). S1 is located in the upstream river area; S2 and S3 are located in the transition area and deep water area of the reservoir, respectively, while S4 is located near the intake tower for the drinking water plants.

2.2. Field observations

Weekly water samples were collected from Jinpen Reservoir throughout the period from January 2011 to December 2012. During the flood period early autumn 2012, the sampling frequency was increased to almost once a day to investigate the effects of storm runoff on the thermal regime and water quality of Jinpen Reservoir. With increments of 1 m water depth the temperature, dissolved oxygen, turbidity and conductivity parameters were measured in situ using a Hydrolab DS5X multi-probe sonde (Hach, USA). Upstream samples were taken approximately 0.5 m below the surface using pre-cleaned high-density polyethylene (HDPE) bottles with preservative already added where appropriate. Samples from sites within the reservoir

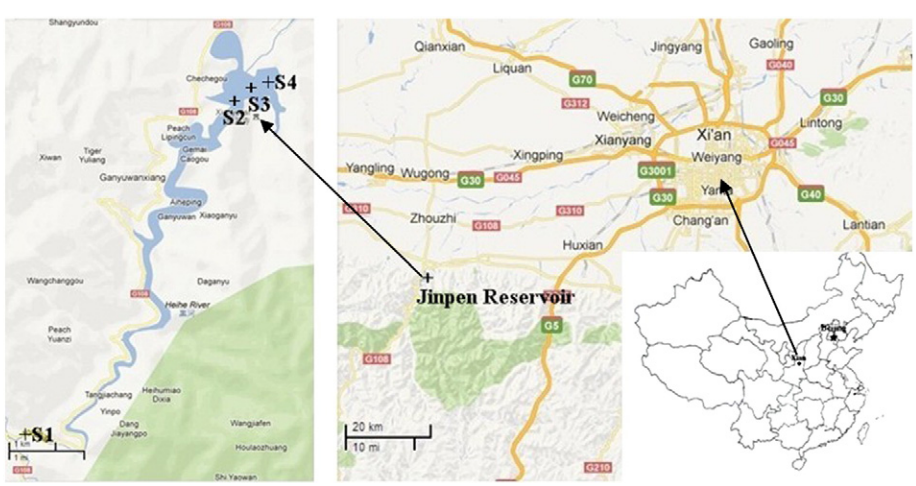

Fig. 1. Illustration of Jinpen Reservoir showing the location of sampling and monitoring sites.