Acta Geochim (2017) 36(3):506–510
DOI 10.1007/s11631-017-0220-0

ORIGINAL ARTICLE

Hydrodynamic characteristics of Wujiangdu Reservoir during the dry season—a case study of a canyon reservoir

Haitao Zhang[1] · Baoli Wang[1,2] · Qiong Han[1] · Jie Shi[1] · Xiaolong Qiu[2,3] · Tiejun Wang[1]

Received: 23 March 2017 / Revised: 8 April 2017 / Accepted: 16 August 2017 / Published online: 28 August 2017

Abstract With the development of hydropower in the karst area of Southwest China, a series of cascade canyon reservoirs have been formed through the construction of dams. Given that hydrodynamic conditions in canyon reservoirs play a pivotal role in controlling the spatiotemporal distribution of physical and chemical properties of the stored water, hydrodynamic characteristics are of great importance in understanding biogeochemical cycles in those reservoirs. To further this understanding, a field campaign was conducted in the Wujiangdu Reservoir of Guizhou Province. It was found that from the reservoir inlet to the front of the dam, velocity (v) was negatively correlated and had a logarithmic relationship with distance along the ship track (s) under dry-season flow conditions [$v = -0.104\ln(s) + 0.4756$]. Analysis showed that dry-season flow velocity had no significant correlation with water temperature, pH, or dissolved oxygen (DO). However, when velocity decreased to 0.061 m/s, water depth increased abruptly. In addition, DO displayed a sudden drop and the trend in pH changed from increasing to decreasing, while water temperature showed an opposite trend, indicating the existence of a transition zone from the river to the reservoir.

Keywords Canyon reservoir · Hydrodynamic characteristics · A transition zone · Wujiang River

11th International Symposium on Geochemistry of the Earth's Surface.

✉ Baoli Wang
baoli.wang@tju.edu.cn

Haitao Zhang
hitoucmail@tju.edu.cn

Qiong Han
hanqiong2015@tju.edu.cn

Jie Shi
shijie0926@tju.edu.cn

Xiaolong Qiu
qiuxiaolong@mail.gyig.ac.cn

Tiejun Wang
tiejun.wang@tju.edu.cn

1 Institute of Surface-Earth System Science, Tianjin University, Tianjin 300072, China

2 State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002, China

3 University of Chinese Academy of Sciences, 100049 Beijing, China

1 Introduction

To exploit the abundant hydropower resources in the karst area of Southwest China, a series of dams has been built on major rivers in the region (Wang et al. 2005). Due to the unique morphology of the karst area (e.g., steep river valleys), cascade canyon reservoirs have been developed (Han et al. 2009), significantly affecting hydrodynamic conditions and biogeochemical cycles in the rivers (Vörösmarty et al. 1997; Kelly 2001; Liu et al. 2009). The canyon reservoirs show considerable spatial heterogeneity in physical and chemical properties, such as water temperature, pH, and CO_2 flux (Peng et al. 2013; Wang et al. 2015). This might be attributed to the hydrodynamic conditions in the reservoirs; however, there a dearth of studies on the effects of hydrodynamic conditions on physical and chemical properties of water stored in canyon reservoirs. To reduce this knowledge gap, a field campaign was conducted during a dry season (January 2017) in the

Wujiangdu Reservoir, located in Guizhou Province, Southwest China. Along the direction of the river channel (from the inlet of the reservoir to the front of the dam), flow velocity and water depth were measured, along with physical and chemical properties of the reservoir water (temperature, dissolved oxygen or DO, and pH). In addition, discharge rates were measured across selected cross sections of the river. Finally, the effects of hydrodynamic conditions on physical and chemical properties of the reservoir were investigated, based on field measurements.

2 Materials and methods

2.1 Study area

The Wujiangdu Reservoir is in central Guizhou Province with a drainage area of approximately 2.79×10^3 km^2. It was the first large reservoir built during the Wujiang River cascade development and has a storage capacity of around 2.3×10^9 m^3. The mean river discharge rate is 502 m^3/s and the mean annual runoff 1.58×10^{10} m^3. The reservoir area features typical karst formations (e.g., long and narrow valleys), and a slope of about 40°–60°.

2.2 Data collection

The reach under investigation flows from a point near the township of Liuguang to the hydropower station of Wujiangdu (Fig. 1). A total of 13 sampling locations were selected to represent the different sections along the reach. The trajectory of the sampling boat was recorded with GPS, and the distance along the ship track was calculated through the map scale. A SonTek M9 flow velocity measurement system was mounted to a boat and used to measure flow velocity at the middle of the cross sections at all 13 locations. At locations P1–P4, cross-sectional discharge rates were also measured using the M9 system. The frequency of data acquisition is 1 s per group. Water temperature, DO, pH, and water chemistry parameters were measured in real time using a YSI-EXO multi parameter water quality monitor.

3 Results and discussion

3.1 Variation of water depth

The elevation profile of the riverbed was obtained by subtracting water depth from water surface elevation. Water depth increased downstream from 85 to 49 km upstream of the dam. From 49 to 20 km from the dam, the elevation of the riverbed increased from 663.66 m at P7 to 681.5 m at P8 (i.e., depth decreased). The water depth then increased from P8 to P13. The maximum water depth was 79.34 m at P13 and the minimum was 10.35 m at P1. From the starting point of the survey to the front of the dam, a distance of 84.5 km, the altitude of the river bed varied by about 70 m, with static head contributing more than velocity head to drive flow (Fig. 2).

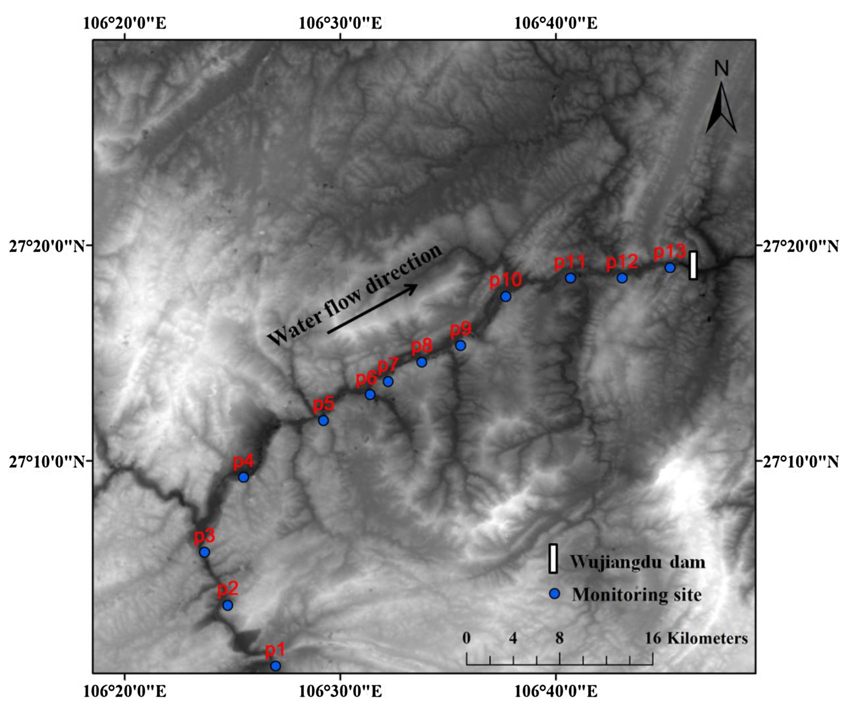

Fig. 1 Sampling sites

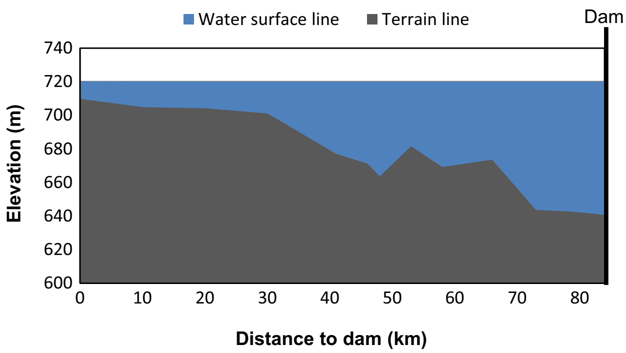

Fig. 2 Water surface and topography of the Wujiangdu Reservoir

3.2 Changes in hydrological factors and hydrochemical conditions

Flow velocity (v) gradually decreased from upstream to downstream with a maximum of 0.557 m/s at P1 and a minimum of 0.036 m/s at P13 (Fig. 3a). Velocity showed a logarithmic relationship with distance along the ship track (s): $v = -0.104\ln\ (s) + 0.4756$. This formula clearly shows the variation of velocity along the ship track distance (Fig. 3a). Flow velocity showed a logarithmic decrease with proximity to the front of the dam. When the distance along the ship track s approached 25 km (near P3 and P4), flow velocity decreased sharply, and then approached stagnation, indicating that the dam has a great influence on the hydrodynamic conditions that potentially affect hydrochemistry in the longitudinal direction. Based on a Kendall correlation analysis, flow velocity and water depth were significantly correlated ($r = 0.538$ at $p < 0.01$). Flow velocity decreased with increasing water depth (Fig. 3b). The pH varied between 7.30 and 7.85, with an average of 7.56. In general, pH decreased in the downstream direction (Fig. 3c). DO decreased from 9.79 to 4.67 mg/L, with an average value of 7.284 mg/L (Fig. 3d). The water temperature ranged from 14.87 to 16.00 °C, with an average value of 15.64 °C. Water temperature initially decreased downstream, but began to rise after P4 (Fig. 3e). Sediment is sorted by particle size longitudinally in the reservoir (Ji 2017). Therefore, the transparency of the reservoir increases longitudinally. Radiation heat flux in the reservoir mainly comes from the sun; as a result, the better transparency of downstream waters enables greater solar radiation, and temperature increased accordingly. In addition, the shadow of the deep valley upstream had great influence on water temperature.

From the variations in flow velocity, water depth, water temperature, pH, and DO (Fig. 3), we can see that at P4, most of the variables changed significantly. The river segment around P4 may be a transitional zone from the river to the reservoir. There was no significant correlation between flow velocity and water temperature, pH, or DO, which may be due to the weak hydrodynamic conditions of the reservoir during the dry season.

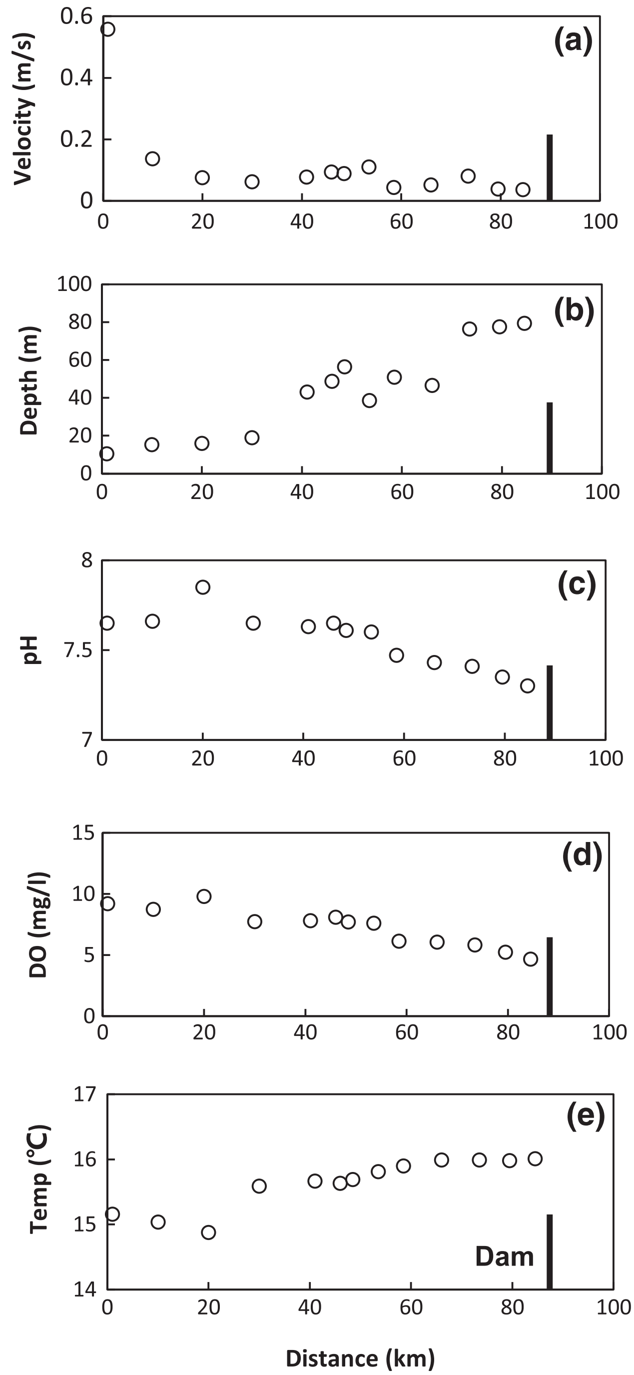

Fig. 3 Variation of velocity, depth, pH, Temp, DO along the Wujiangdu Reservoir

3.3 Characterizing of velocity variation

There were noticeable variations in flow velocity at the cross sections of P1 to P4 (Fig. 4). In fact, this stretch

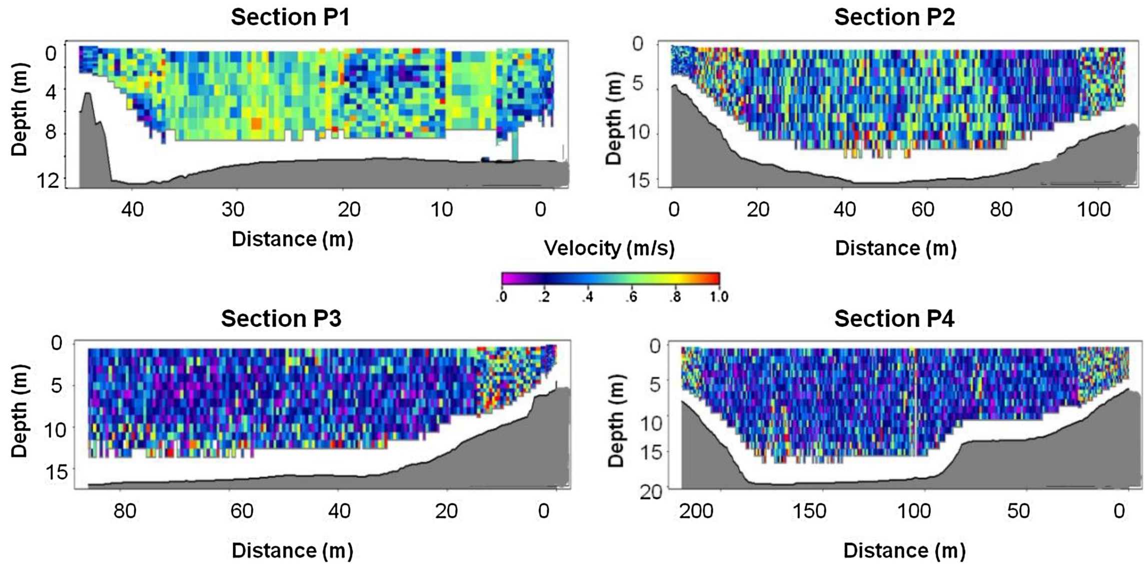

Fig. 4 The velocity variation of sections

exhibited the largest change in velocity, with a maximum average of 0.557 m/s at P1, and a minimum average of 0.061 m/s at P4.

At the P1 cross-section, velocity ranged from 0.249 to 0.715 m/s. The average water depth was 10.484 m and the discharge rate was 187.5 m^3/s. At the P2 cross-section, velocity ranged from 0.06 to 0.227 m/s with an average of 0.0926 m/s. The average water depth was 12.673 m and the discharge rate was 139.6 m^3/s. The riverway near P1 and P2 is a straight channel. The two cross-sections exhibited similar trends for velocity and water depth, with both values increasing near the center line.

Measurements started from the right bank at the P3 section. The right bank is a low slope and the left bank is a cliff. Measurements also started from the right bank at the P4 section where both sides are slopes. P3 and P4 did not show increasing flow velocity with water depth; the right bank had the smaller velocity, and the velocity increased towards the left bank. This is because the riverway at P3 and P4 is sinuous; the left bank is concave and the right bank convex. Due to centrifugal force, the river velocity is higher along the concave bank than along the convex bank. Water flows to the concave bank from the convex bank on the surface of the river and to the convex bank from the concave bank at depth. Additionally, water flow distributes the river bed such that the concave bank becomes steeper than the convex.

4 Conclusions

(1) Velocity (v) presented a logarithmic relationship with distance along the ship track (s), with $v = -0.104\ln\ (s) + 0.4756$. Correlation analysis showed no significant correlation between flow velocity and water temperature, pH, or DO, which may be due to the weak hydrodynamic conditions of the reservoir during the dry season.

(2) Near P4, the water deepened, the water surface widened, velocity decreased sharply, pH peaked, DO dropped suddenly, and water temperature bottomed out. This area may be a conversion node from river to reservoir.

(3) Section shape and sinuosity of larger rivers have a great influence on velocity. Generally, velocity decreased near the bank, and the maximum velocity was measured at the center of river. The velocity of the convex bank was notably lower than that of the concave bank, and the concave bank was erosional whereas the convex was depositional.

Acknowledgements This study was financially supported by the National Key Research and Development Programme of China (2016YFA0601001), the National Natural Science Foundation of China (Grant Nos. U1612441 and 41473082), and CAS "Light of West China" Program.

References

Han Z, Liu CQ, Wu P et al (2009) Damming effect on water dissolved chemistry components-a case study of Wujiangdu Reservoir water in summer, southwest China. Resour Environ Yangtze Basin 18:361–367 **(In Chinese)**

Ji ZG (2017) Hydrodynamic and water quality: Modeling rivers, lakes, and estuaries, 2nd edn. John Wiley & Sons

Kelly VJ (2001) Influence of reservoirs on solute transport: a regional-scale approach. Hydrol Process 15:1227–1249

Liu CQ, Wang F, Wang Y, Wang B et al (2009) Responses of aquatic environment to river damming-from the geochemical view. Resour Environ Yangtze Basin 18:384–396 **(In Chinese)**

Peng X, Liu CQ, Wang B et al (2013) Spatiotemporal characteristics and diffusion flux of partial pressure of dissolved carbon dioxide in the river–reservoir system as exemplified by the Liuchonghe river, Hongjiadu reservoir and Hongfenghu lake. Earth Environ 41:97–103 **(In Chinese)**

Vörösmarty CJ, Sharma KP, Fekete BM et al (1997) The storage and aging of continental runoff in large reservoir systems of the world. Ambio 26:210–219

Wang Y, Zhu J, Ma M, Yi CQ, Liu CQ et al (2005) Thermal stratification and paroxysmal deterioration of water quality in a canyon-reservoir, Southwestern China. Lake Sci 1:54–60 **(In Chinese)**

Wang B, Liu CQ, Wang F et al (2015) Carbon and nitrogen coupled biogeochemical cycle in cascade reservoirs of the Wujiang River. J Shanghai Univ (Nat Sci) 21:294–300 **(In Chinese)**