

Spatial characters of nutrients in Wujiangdu Reservoir in karst river, SW China

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Abstract A preliminary assessment of the Wujiangdu Reservoir examined nutrient distribution and transport. Water samples were collected in the summer (July) of 2004, during the high-flow season. Inorganic nutrients (N, P, Si) and chlorophyll a (chl a) concentrations of the Wujiangdu Reservoir and its inflow rivers were analyzed. Other water parameters (dissolved oxygen, pH, temperature, and electrical conductivity) were measured as well. The results show gradually decreasing concentrations of NO_3^- -N and dissolved silicate in the surface water moving downstream to the dam of the Wujiangdu Reservoir. Additionally, soluble reactive phosphorus concentrations measured very low, with most falling below the sensitivity threshold of the method used in surface waters. Particulate phosphorus and NO_3^- -N were the predominant species of phosphorus and nitrogen in the reservoir, respectively. The concentration of nutrients in the Yeji River was the largest of all inflow rivers. The maximum concentration of chl a was found near the dam. These results reflect upstream conditions similar to that of a river, and reservoir conditions near the dam similar to that of a natural lake system.

Keywords Wujiangdu Reservoir · Nutrients distribution characteristics · Dam

1 Introduction

Increasing impacts of human activity, especially dams, have changed the properties and processes of rivers (Meybeck 1982; Degens et al. 1991; Hooper et al. 2001). A dam converts a river into an artificial lake, increasing water residence times and often improving light conditions in the water column, both preconditions for algal growth. There have been numerous studies on changes to the hydrological status of rivers caused by dams (Milliaman 1997; Humborg et al. 2002; Hungspreugs et al. 2002; Vörösmarty et al. 2003); nutrients blocked by dams (Friedl et al. 2004; Humborg et al. 2006, 2008; Matzinger et al. 2007; Teodoru et al. 2006), the biogeochemical cycle of elements in reservoirs (Jossette et al. 1999; Bellanger et al. 2004; Zhu et al. 2006), and other related subjects. In comparison, relatively little work has been done on the properties and processes of rivers in China that occur after dam construction (Yu et al. 2008; Wei et al. 2009; Wang et al. 2010). Although many studies have focused on damming, few have concentrated on reservoirs in karst areas. The Wujiangdu Reservoir was the first major dam completed in the middle and upper reaches of the Wujiang River, and plays an important role in determining the water quality of the Three Gorges Reservoir. As the largest reservoir in this karst area, the Wujiangdu is an ideal site to investigate the effects of damming on nutrients in waters of a karst area.

In the present study, the aim was to investigate the spatial distribution of inorganic nutrients in Wujiangdu Reservoir, SW China, in order to better understand the properties and processes of the Wujiang River affected by damming. Moreover, it is important to compare the features of the man-made reservoir to those of natural lakes.

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2 Materials and methods

2.1 Site description

The Wujiang River is the largest tributary on the right bank of the upper Changjiang River, and has a total length of 1037 km and a drainage area of 88,267 km². The Wujiang winds its way through central and north-eastern Guizhou Province and meets the Changjiang at Fuling City. It is the largest river in Guizhou Province, with a mean discharge of 1690 m³/s (Han and Liu 2004).

The study area is located in the subtropical monsoon climate zone. The average annual temperature is 12.3 °C, with extreme temperatures of 35.4 °C in summer and – 10.1 °C in winter. Annual precipitation in this area ranges from 1100 to 1300 mm, with the rainy season from May to October accounting for approximately 75% of total precipitation. In the study area, karstification is well developed and the riverine water chemistry is dominated by carbonate weathering.

The Wujiangdu Reservoir was constructed for electricity generation in 1979 and had been operating for 26 years as of 2004. To develop the “West-to-East power transfer” project, 13 cascade hydroelectric power stations were planned in the Wujiang River basin. The Wujiangdu Reservoir was the first of this series of reservoirs, and plays an important role in the water quality of Three-Gorges Reservoir.

The Wujiangdu Reservoir has a surface area of 47.5 km², a volume of 21.4×10^8 m³, a normal water level of 760 m above sea level, a working water head of 113 m, an average discharge of 502 m³/s, a backwater length of 82.94 km, a river slope gradient of 1.893‰ and a dam height of 165 m. Its average water residence time (ratio of volume to flow rate) is 0.14 years (Su 2002). It is located in a narrow, V-shaped valley. In addition to the Wujiang River, several smaller streams, such as the Xifeng, Pianyan, and Yeji Rivers, supply water to the impoundment (Fig. 1).

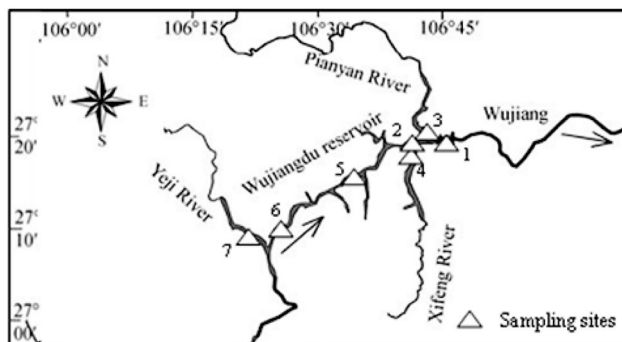


Fig. 1 Sketch map showing the sampling sites

2.2 Sampling and analytical methods

The sampling campaign was carried out in July 2004, which was during the high flow period. Sampling stations are indicated in Fig. 1. Stations 1, 2, 5, and 6 were within the reservoir, whereas stations 3, 4, and 7 were located on tributaries (inflowing rivers) of the reservoir. Water samples in the reservoir were collected at different depths. Samples near the dam (station 1) were taken from depths of 0, 5, 10, 20, 30, 40, 50, 60, and 75 m. At stations 2 and 5, water samples were collected near the surface, near the bottom, and at mid-depth. Water samples from the tributaries were taken only at the surface. Temperature, pH, electrical conductivity (EC), and dissolved oxygen (DO) were measured in situ by a portable multi-parameter instrument (pIONneer 65). A 1000-mL water aliquot was immediately filtered through a 0.45- μ m polycarbonate membrane filter in the field. The remaining volume of water samples, the filtered water, and filters with chlorophyll a (chl a) were kept in an ice-box in the dark and taken to the labs on the same day. Samples of total nitrogen (TN), total phosphorus (TP), total dissolved phosphorus (TDP), and filters with chl a were preserved frozen (– 20 °C) in the laboratory until analyses were conducted, and soluble forms of N, P and Si were analyzed within 12 h.

All analyses were carried out according to standard methods (State Environmental Protection Bureau, Compiling Committee for Monitoring and Analytical Methods of Water and Waste Water 2002). The concentration of nitrate nitrogen (NO₃[–]-N) was determined by the ultraviolet spectroscope method, with a detection limit of 0.08 mg/L. Nitrite nitrogen (NO₂[–]-N) was measured by the N-(1-naphthyl)-ethylenediamine method. Ammonia nitrogen (NH₄⁺-N) was determined by the Nesslerize method. PO₄^{3–}-P was assayed by the molybdenum blue method. Concentrations of TN and TP were determined by peroxysulphate digestion followed by nitrate and soluble reactive phosphorus (SRP) determination. TDP was determined using the same method as TP after filtration. Dissolved silicate was measured by the ammonium molybdate/ascorbic method. In the laboratory, the filters were ground with a tissue homogenizer in 90% ethanol, stored in the dark below 4 °C for at least 12 h and centrifuged to remove turbidity. Concentrations of chl a were determined by the spectrophotometric method (Párista et al. 2002).

3 Results and discussion

3.1 Distribution along the Wujiang River flow direction

Nutrient concentrations in the water are important ecologically, as phytoplankton may bloom if sufficient nutrients are present. Nitrogen, phosphorus, and silicate in the Wujiangdu Reservoir and its inflowing rivers were measured in this study. Results are presented in Tables 1 and 2.

In the Wujiangdu Reservoir, nitrogen is far more plentiful than phosphorus, a finding similar to that in the rivers. Moreover, SRP and TDP concentrations were always below the sensitivity threshold of the method used in the surface water, which we ascribe to scant phosphorus sources. NO_3^- -N was the predominant species of dissolved inorganic nitrogen (DIN) in the Wujiangdu Reservoir, representing more than 90% of DIN. Its concentration in the epilimnion ranged from 2.53 to 3.40 mg/L, which was lower than in Baihua and Hongfeng Lakes in Guizhou Province (Liang et al. 1998), but higher than in ErHai Lake (Hongxi et al. 1999) in Yunnan Province. NO_3^- -N concentrations decreased along the river flow direction. The same pattern was observed for both TN and dissolved silicate. This may be due to dilution and to biological activity in the reservoir. Biological uptake may be more important for dissolved silicate, which had a concentration gradient of 2.7 mg/L and a minimum of 0.9 mg/L near the dam. Total phosphorus exhibited a more complex distribution in the Wujiangdu Reservoir, where particulate phosphorus was the dominant type of phosphorus. Peak TP concentration at station 6 (in the upstream section of the reservoir) was probably associated with the high TP concentration in the Yeji River (Table 2). We can see from the results that inorganic nutrients in the Wujiangdu Reservoir were mainly from the Yeji River. Total phosphorus and nitrate concentrations were both very high in the Yeji River during

the study period. This may have been due to non-point source pollution, because the study occurred during a high flow period when the river water was very turbid. The TN:TP molar ratio ranged from 35 to 464 in the surface layer of the Wujiangdu Reservoir, which is much higher than in most Korean reservoirs (20–100) (Hwang 1998), indicating that phosphorus is a major factor affecting algal growth.

Chl a concentrations ranged from 0.84 to 4.46 mg/m³ (Table 1) in the surface water of the Wujiangdu Reservoir. This was probably due to the high turbidity and short retention time of the water, preventing the development of phytoplankton communities in the upstream section of the reservoir. Moreover, at the upstream site, low levels of suspended matter allowed the greatest light attenuation there, with phytoplankton increasing closer to the dam. Horizontally, pH increased towards the dam, in contrast to chl a. When biological activity is more intense, pH increases (along the river flow direction) because photosynthesis consumes carbon dioxide in the reservoir. Also along the river flow direction, increasing chl a concentrations and the accompanying decrease in dissolved nutrients (nitrate and dissolved silicate) indicated active phytoplankton production in general, and diatom growth in particular, near the dam in the reservoir.

3.2 Vertical distribution

Like most other deep subtropical lakes, the Wujiangdu Reservoir displays thermal stratification in the summer. Temperature, DO, and pH values decreased gradually with water depth. The water temperature showed a large difference between surface and bottom waters near the dam, with a range of 24.7–13.7 °C (Fig. 2). The concentrations of DO ranged from 9.05 to 1.71 mg/L, with the minimum (1.71 mg/L) near the bottom, highlighting the anoxic state of the bottom of the reservoir during the study period. The

Table 1 Concentrations of nutrients, Chl a and other parameters in the main stem of the Wujiangdu Reservoir

Sampling stations	Depth	NO_3^- -N	NH_4^+ -N	NO_2^- -N	TN	TP	TN/TP	DSi	Chl-a	DO	pH
6	Surface	3.24	–	0.036	3.51	0.07	110	3.6	1.67	8.60	7.9
5	Surface	3.24	0.05	0.036	3.67	0.04	202	4.2	0.84	7.86	8.0
5	Middle	3.29	0.05	–	3.62	0.05	72.4	4.4	0.84	8.54	8.1
5	Bottom	3.33	0.03	–	3.70	0.25	14.8	4.3	–	7.92	8.0
2	Surface	3.05	0.16	0.046	3.65	0.02	403	2.5	2.51	7.30	8.1
2	Middle	2.92	0.03	–	3.12	0.01	312	3.39	0.84	7.30	7.6
2	Bottom	1.60	0.41	–	2.17	0.28	7.75	4.53	0.28	1.46	7.2
1 (near the dam)	Surface	2.75	0.12	0.034	3.17	0.07	100	0.9	4.46	8.77	8.2

Solute concentrations are mg/L except for chl a mg/m³ (all in units of mg/L)

Table 2 Concentrations of nutrients, Chl a and other parameters in tributaries of the Wujiangdu Reservoir. Solute concentrations are mg/L except for chl a mg/m³

Tributaries	NO ₃ ⁻ -N	NH ₄ ⁺ -N	NO ₂ ⁻ -N	TN	TP	TN/TP	DSi	Chl-a	DO	pH
Xifeng River	2.53	0.08	0.032	3.01	0.03	221	1.12	8.65	8.51	8.4
Pianyan River	3.07	0.18	0.043	3.81	0.02	421	2.13	5.58	7.24	8.1
Yeji River	3.40	0.15	0.053	3.89	0.24	36	3.79	1.40	8.87	8.0

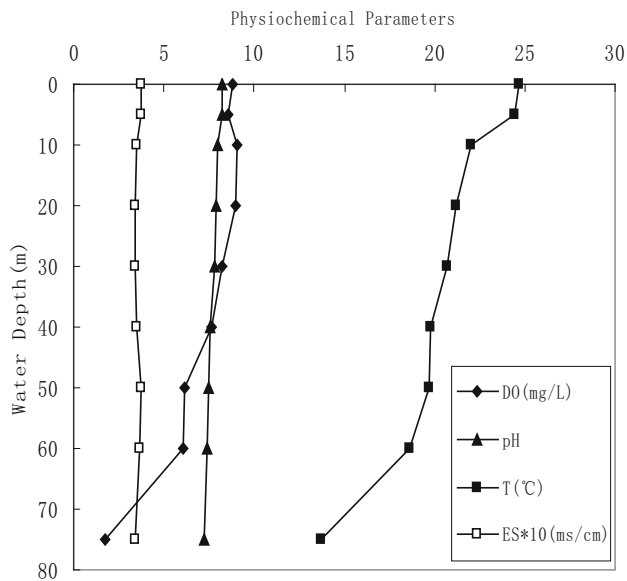


Fig. 2 The physiochemical parameters vertical distribution near the dam of Wujiangdu Reservoir

pH ranged from 8.2 to 7.2, with a mean of 7.7. EC in the water column showed a narrow range (341–374, mean ca. 356 μS/cm).

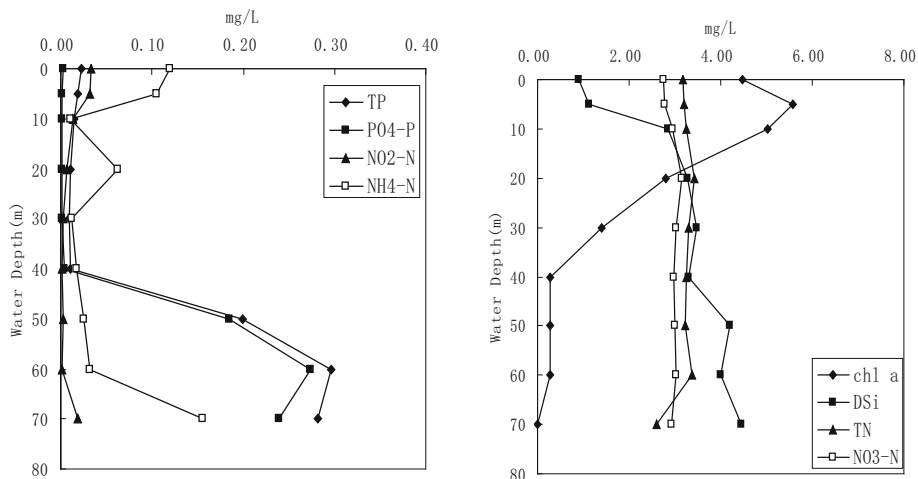
The vertical distribution of the inorganic nutrients and chl a in summer are presented in Fig. 3. NO₃⁻-N was the dominant form of all of the nitronium, reactive soluble

phosphorus, TP, and dissolved silicate in the water column. No vertical variation of its concentration was apparent, in contrast to TN. However, nitrite and ammonia concentrations increased with water depth. This may be explained by the higher degree of turbulence of the bottom waters, inducing sediment re-suspension. There was a striking variation of SRP, TDP, and TP. Their concentrations increased rapidly below 40 m, while SRP and TDP concentrations were below the detection limit in the first 40 m. This variation probably resulted from a preceding phytoplankton bloom in the surface water, while phosphorus concentrations below 40 m were likely due to the diffusion of much higher concentrations of SRP and TP in the interstitial waters of the sediment.

The minimum concentration of dissolved silicate (0.9 mg/L) was observed in the epilimnion. This may reflect high phytoplankton primary production in the surface water, as chl a values are consistent with this hypothesis (Fig. 3). From Fig. 3, we see that the highest value of chl a was also in the epilimnion (maximum chl a concentration of 5.58 mg/m³). The average chl a concentration was 3.85 mg/m³ above 30 m depth.

The vertical distribution of inorganic nutrients at station 2 was similar to that near the dam (station 1). However, the variation gradients at station 2 were less than those near the dam. For example, at station 2, the dissolved silicate concentration was 2.5 and 4.53 mg/L in the surface water and

Fig. 3 The vertical concentration profile of nutrients and chl a near the dam of Wujiangdu Reservoir



near the bottom water, respectively. At station 1, the dissolved silicate concentration was 0.9 and 4.44 mg/L, respectively. The concentration of nitrogen decreased with water depth, particularly for the NO_3^- -N form. The concentration of chl a at station 2 was lower than that at station 1. On the other hand, inorganic nutrient concentrations were higher at station 2 than at station 1. This probably resulted from floating net cage aquaculture. The degradation of organic matter and excreta of fish consumed oxygen, which led to a low concentration of DO (7.30 mg/L). At the same time, the food and excreta of fish decomposed and produced inorganic nutrients, which led to higher concentrations of inorganic nutrients. At station 5, the concentrations of inorganic nutrients varied narrowly throughout the water column except for TP, which had a much higher concentration near the bottom. This suggests that station 5 was negatively influenced by the tributary of the Yeji River. Accordingly, it is clear that the upstream in this reservoir shared characteristics of a river.

4 Conclusion

The upstream section of the Wujiangdu Reservoir is more like a free-river system because it is intensively running and mixing, while the section near the dam is more like a natural lake system. Compared to natural lakes, thermal stratification is not significant in the Wujiangdu Reservoir. This is probably due to the hydrodynamic effect being very intense, and the water residence time being very short in summer. The inorganic nutrient characteristics of the river water changed after damming, and the reservoir tended to develop like a lake. To gather more evidence on the river's nutrient characteristics after damming, we should focus our attention in the future on the phytoplanktonic and zooplanktonic species.

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