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Dynamic characteristics of nutrients and causal analysis in eutrofic reservoir: a case study of Shibianyu reservoir

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ABSTRACT

Eutrofication and the resulting proliferation of phytoplankton have become a serious problem of reservoirs around the world. In order to make effective algae control measures through reducing concentrations of nutrients, in this study both the dynamic characteristics of nutrients and its source were investigated in Shibianyu reservoir located in north-western of China. The results showed that a 2.8 mg/L of annual average total nitrogen concentration in Shibianyu reservoir was observed, which exceeded the source water quality standard during whole monitoring years, and the maximum concentration reached 5.1 mg/L in spring. Moreover, it was observed that there is high total phosphorus concentration during the mixing period in winter or the heavy rainfall period. The hypolimnion became anoxic during the stratified period to increase the release of nutrients from the sediments. The nutrients of upper water increased rapidly when stratification disappeared because the high concentrations of pollutants in the bottom water were carried into the upper water. The continuous heavy rains led to significant increase of nitrogen and phosphorus in summer because a large number of sediment was flushed into reservoir. The excess nutrients promoted algae to multiply. Intense cyanobacterial blooms have been observed in Shibianyu reservoir. It is premise to improve water quality in Shibianyu reservoir that the infusion of nutrient must reduce during rainstorm period. Inhibition of endogenous pollutants release would be the key to control and improve the water quality in Shibianyu reservoir.

Keywords: Causal analysis; Nutrients; Reservoir; Stratification; Water quality

1. Introduction

Eutrofication of water reservoir resulting in toxic cyanobacterial blooms represent a serious hazard to human health, and the restoration of eutrophic water bodies can be challenging [1]. The occurrence of toxic cyanobacterial blooms in reservoirs is a worldwide environmental problem and has become the research focus nowadays. Although, essential resource for algae growth can be potentially limited, the main drivers of change in phytoplankton communities are usually identified as nutrient availability (in particular C, N, P, and Si for diatoms) and light [2].

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Thermal regime is strongly associated with hydrodynamics in water, and it plays an important role in the dynamics of water quality and ecosystem succession of stratified reservoirs [3]. In summer, stratification limits oxygen transfer from the surface to the lower hypolimnion. Dissolved oxygen (DO) in hypolimnion reduced rapidly due to the consumption of DO in sediment and water. The hypolimnion becomes anoxic during the stratified period, increasing the release of nutrients from the bottom sediments [4,5].

Nutrient inputs to the reservoir from point sources, as well as diffuse sources in the drainage basin are the key reason for eutrofication. Moreover, pollutants released from sediment on the bottom under anaerobic conditions intensify the deterioration of the water quality of stratified reservoirs [6,7]. Understanding of the dynamic characteristics of nutrients and its source would be of special importance in the development of control strategies for reducing contaminant levels [8].

Shibianyu reservoir is located in Shaanxi province, northwest of China. It was built in 1975, began to supply water to Xian city in August 1990, and has formed into a multi-operation business pattern for controlling flood, generating electricity, supplying water, and etc. Shibianyu reservoir has a total capacity of 28.1 million m^3 and supply 30 million m^3 water to Xian city every year. As the city's emergency water resource, Shibianyu reservoir water quality plays an important role to insure urban water security. In recent years, intense phytoplankton blooms have been observed in Shibianyu reservoir. A large number of phytoplankton flocs float on the surface of water in summer and autumn season, and seriously affects the reservoir water supply safety.

Because of an incomplete understanding of eutrofication mechanisms in the Shibianyu reservoir, an effective management strategy has not been developed. Our objectives are to investigate (1) dynamic characteristics of nutrients, (2) the causes of eutrofication, and (3) control measures suggested. The results are important in improving water quality of the Shibianyu reservoir and the change in process of the aquatic ecosystem, and it can also help to forecast and prevent the deprivation of water quality after the water was stored.

2. Materials and methods

2.1. Study area description

Originating from the Qinling Mountain, Shibianyu River is the main stream of the Shibianyu reservoir in Shaanxi Province. This river is 30 km long with a catchment area of 132 km^2 with annual rainfall, evaporation capacity and runoff volume are 898, 948.5 mm, and 0.97 million m^3, respectively. The reservoir's upstream region is mountainous with few population and industry. There are seven natural administrative villages with a population of 1,683, mainly dispersed around the Shibianyu River. In order to determine the influence of the upstream water quality on the reservoir, 10 sites were chosen for water quality monitoring from the upstream to the reservoir (Fig. 1). From site 1 to site 4 in upstream of the reservoir they are largely unmodified and consist primarily of hills covered with forest with little human activity. However, surrounding landscapes from site 5 to site 7 are destroyed extensively by human activity. S8, S9, and S10 are located in river area, transition area, and deep water area of reservoir, respectively.

2.2. Sampling methods

Water samples were collected, approximately, weekly throughout the period from March 2011 to August 2012. Reservoir depth, temperature, DO, turbidity, and chlorophyll-a were measured every meters interval *in situ* using a Hydrolab DS5X multiprobe 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 necessary. Samples from sites within the reservoir were taken 0.2 m above the sediment surface and 0.5 m below the water surface using a 1.5 L Van-Dorn bottle. Additional surface water samples (1 L) for phytoplankton identification and enumeration (Olympus microscope, Japan; Shineso Algacount, China) were preserved immediately with a few drops of acidic Lugol's solution. Unless, otherwise stated, all samples were transported to the laboratory on ice where they were immediately frozen, and stored at 4˚C for analysis.

The analyzed indices included total nitrogen (TN), total phosphorus (TP), ammonia (NH_4^+-N), dissolved total nitrogen (DTN), and dissolved total phosphorus (DTP). TN and TP were measured by ultraviolet spectrophotometry and ammonium molybdate spectrophotometry after alkaline potassium persulfate digestion under high temperature, and the concentration of NH_4^+-N was determined by Nessler's reagent colorimetric method. Water samples were filtered through the Whatman GF/C membrane to obtain samples for DTN and DTP analysis. Grain nitrogen (PN) is equal to TN minus dissolved nitrogen, and particle state phosphorus is equal to TP minus dissolved phosphorus [9].

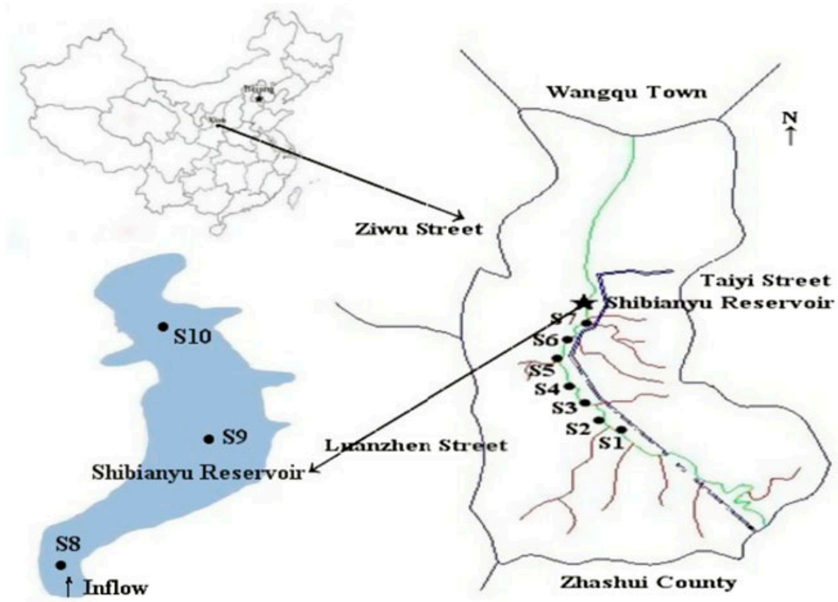

Fig. 1. Illustration of Shibianyu reservoir showing the location of sampling and monitoring sites : S1–S7 are located in the upstream of Shibianyu reservoir. S8, S9, and S10 are located in the river area, transition area, and deep water area of the reservoir, respectively.

Water level, rainfall, inflow, and outflow data were provided by Shibianyu reservoir hydrological station adjacent to the dam.

3. Results and discussion

3.1. Dynamic characteristics of nutrients

Fig. 2 shows that a 2.8 mg/L of annual average TN concentration of source water in Shibianyu reservoir was observed, which exceeded the source water quality standard (specified 1.0 mg/L) during whole monitoring years. The concentration of TN in the reservoir water increased abruptly in spring, and with a highest concentration of 5.1 and 4.4 mg/L in 2011 and 2012, respectively. After April, the concentration of TN began to reduce, and remained in 2.5 mg/L or so in summer. The concentration of TN had a slight increase in September or October, with the highest concentration reaching 3.5, 3.9 mg/L in 2010 and 2011, respectively. The abrupt rise of the nitrogen and phosphorus concentration in the surface water occurred in the winter of 2010, but did not appear in the winter of 2011.

Most of the time the concentration of TP (with an annual average concentration of 0.041 mg/L) could meet the water quality standard of surface water environment. However, it is observed that its concentration exceeded the specified 0.05 mg/L listed in the water quality standard during the mixing period in winter or the rainstorm period.

3.2. Cause analysis for the abrupt rise of the nitrogen and phosphorus in winter

Intensive researches were carried out to explore the causes of the abrupt rise of the TN and TP concentration in upper water of Shibianyu reservoir in winter. At first, the extraneous pollution sources were investigated. Tables 1 and 2 shows the change of nutrients in the sampling points of upstream in winter. The concentration of TN and TP hardly changed during the whole winter. In addition, no paroxysmal pollutions were detected there. Therefore, the pollutants were believed to have originated from inside of the Shibianyu reservoir.

Further study revealed the mechanism causing the abrupt rise of the nutrient concentration in the reservoir. Thermal regime was strongly associated with hydrodynamics in water, and it played an important role in the dynamics of water quality and ecosystem succession of stratified reservoirs [5]. As shown in Fig. 3(a), Shibianyu water body's thermal stratification structure started to form in spring. In the end of May, Shibianyu reservoir has been able to form a stable thermal stratification. A little different from other reservoirs thermal stratification structure, with a warmer, less-dense epilimnion, a transitionary

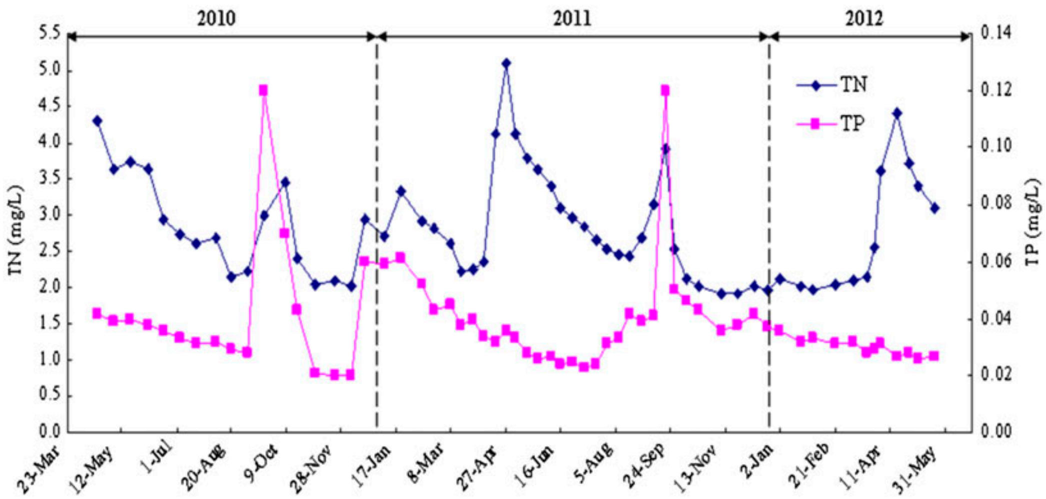

Fig. 2. Dynamic characteristics of nutrient in the upper water of Shibianyu reservoir from 2010 to 2012.

Table 1
Dynamic characteristics of TN in the sampling points of upstream in winter

$TN/mg\,L^{-1}$	22 Nov	7 Dec	19 Dec	6 Jan	21 Jan	9 Feb
S1	2.25	2.04	2.13	2.22	2.13	2.13
S2	2.26	2.06	2.18	2.15	2.16	2.15
S3	2.35	2.14	2.21	2.26	2.19	2.21
S4	2.49	2.15	2.36	2.24	2.16	2.16
S5	2.17	2.14	2.12	2.19	2.18	2.23
S6	2.14	1.91	2.23	2.28	2.21	2.22
S7	2.31	2.12	2.19	2.22	2.19	2.21
S8	2.16	2.12	2.15	2.19	2.17	2.30

Table 2
Dynamic characteristics of TP in the sampling points of upstream in winter

$TP/mg\,L^{-1}$	22 Nov	7 Dec	19 Dec	6 Jan	21 Jan	9 Feb
S1	0.022	0.021	0.021	0.019	0.020	0.019
S2	0.019	0.020	0.021	0.018	0.019	0.019
S3	0.017	0.018	0.019	0.018	0.019	0.018
S4	0.019	0.017	0.018	0.016	0.018	0.016
S5	0.022	0.019	0.021	0.020	0.019	0.020
S6	0.019	0.018	0.019	0.017	0.018	0.017
S7	0.018	0.019	0.023	0.020	0.022	0.019
S8	0.023	0.021	0.022	0.019	0.021	0.019

thermocline, and a colder, more-dense hypolimnion at the top, middle, and bottom, respectively, Shibianyu reservoir has a zone of constant temperature between epilimnion and metalimnion.

This structure limited oxygen transferred from the surface to the lower hypolimnetic water. Depletion of DO in the hypolimnion is exacerbated as algae, which grow in the photic zone, complete their life cycle and are degraded as they settle through the water column [10,11]. The depletion of DO in the hypolimnion of Shibianyu reservoir is shown in Fig. 3(b), DO was available in the hypolimnion at the beginning of the

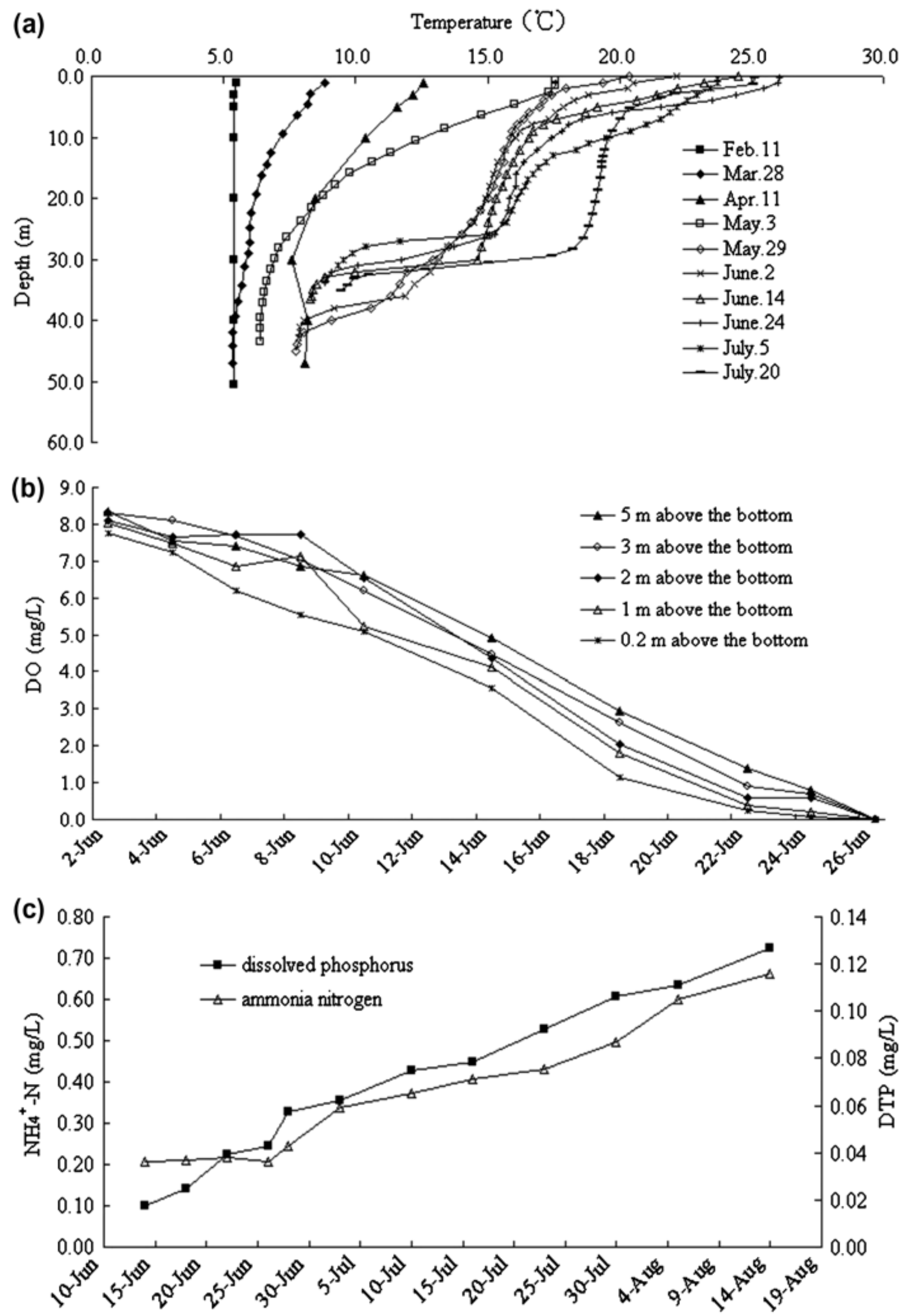

Fig. 3. Water temperature vertical distribution characteristics (a), DO concentration depletion in hypolimnion (b) and dynamic characteristic of ammonia nitrogen and dissolved phosphorus in overlying water above 0.2 m of sediment in S10 (the deepest point of Shibianyu reservoir).

stratified period closed to 8 mg/L (June 2). Due to the consumption of DO in sediment and water available DO in the hypolimnion was rapidly reduced. In the end of June, available DO in the hypolimnion was completely depleted.

The hypolimnion became anoxic during the stratified period, increasing the release of nutrients from the bottom sediments. Fig. 3(c) shows the dynamic characteristic of ammonia nitrogen and dissolved phosphorus in overlying water above 0.2 m of sediment in the bottom. Under aerobic conditions the concentration of ammonia and dissolved phosphorus in overlying water were quite low. Concentration of ammonia began to increase when DO concentration was lower than 2 mg/L, while dissolved phosphorus began to release from the sediment when the available DO in the hypolimnion was completely depleted. In the middle of August, concentrations of ammonia and dissolved phosphorus in overlying water reached 0.68 and 0.129 mg/L, respectively. Long periods of anoxia resulted in a more significant deterioration of water quality as reduced species continued to diffuse out of the sediment and enter the hypolimnion.

For summer stratified reservoir, in the end of every autumn, when the surface temperature is equal to or even less than the hypolimnion temperature, density is equal to or even more than the lower water, the upper and lower layer water mixed immediately. The strong convective mixing makes the high concentration of pollutants in the bottom water carried into the upper water, resulting in the nutrient of upper water increase rapidly. Water temperature of the deep layer in Shibianyu reservoir is kept at about 10℃ during summer stratification, and the surface water temperature changes with the variation of air temperature. In late December, when the surface temperature falls below 10℃ (Fig. 5(a)), stratification structure of water temperature disappears, and reservoir begins to mix. Mixing may be the main reason for the abrupt rise of the nitrogen and phosphorus concentration in the surface water of Shibianyu reservoir at the end of December 2010 based on data monitored by the Shibianyu reservoir management station.

Fig. 4(a) shows monthly rainfall in Shibianyu reservoir from 2001 to 2011. In Shibianyu reservoir there was an average annual rainfall of 675 mm from 2001 to 2010 year. The annual total rainfall of 2001 and 2002 was relatively less, 353 and 439 mm, respectively. The change of annual total rainfall from 2003 to 2010 was not obvious, and the mean value was 745 mm. However, the annual total rainfall of Shibianyu reservoir reached 1081.2 mm in 2011, more than 60.2% of the average annual total rainfall in the past ten years.

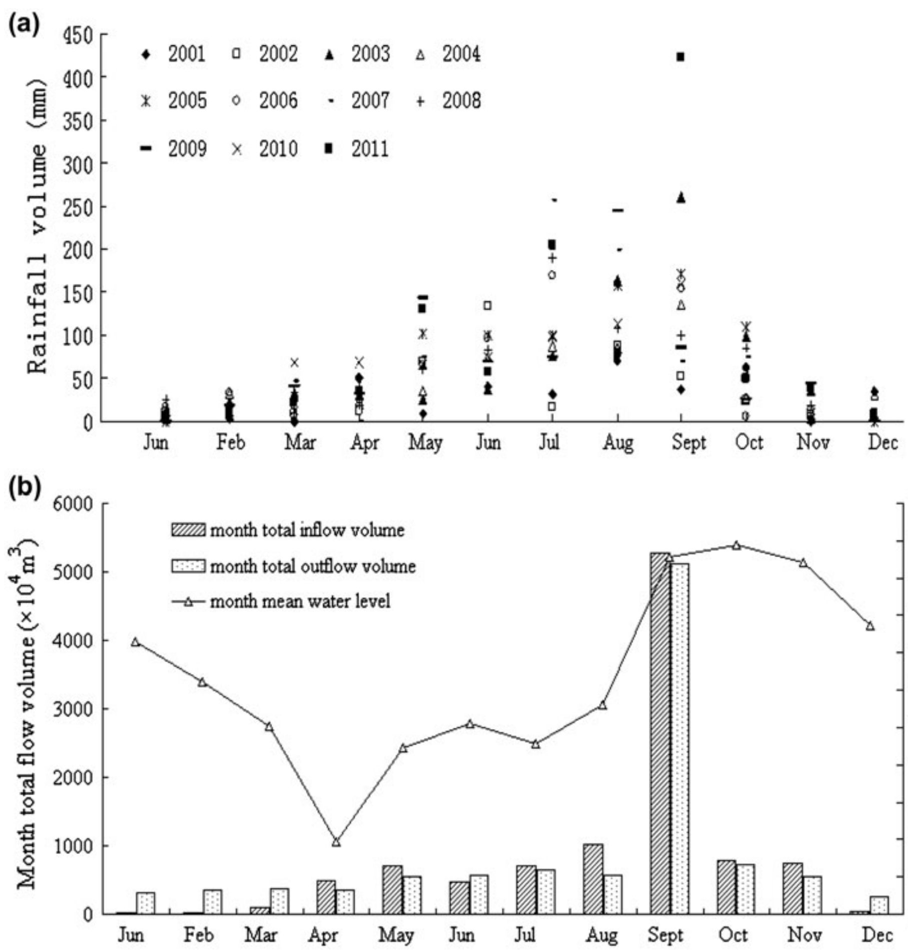

Fig. 4. Monthly rainfall changes in Shibianyu reservoir from 2001 to 2011 (a), and variation of monthly total inflow volume, monthly total outflow volume, and water level in 2011 (b).

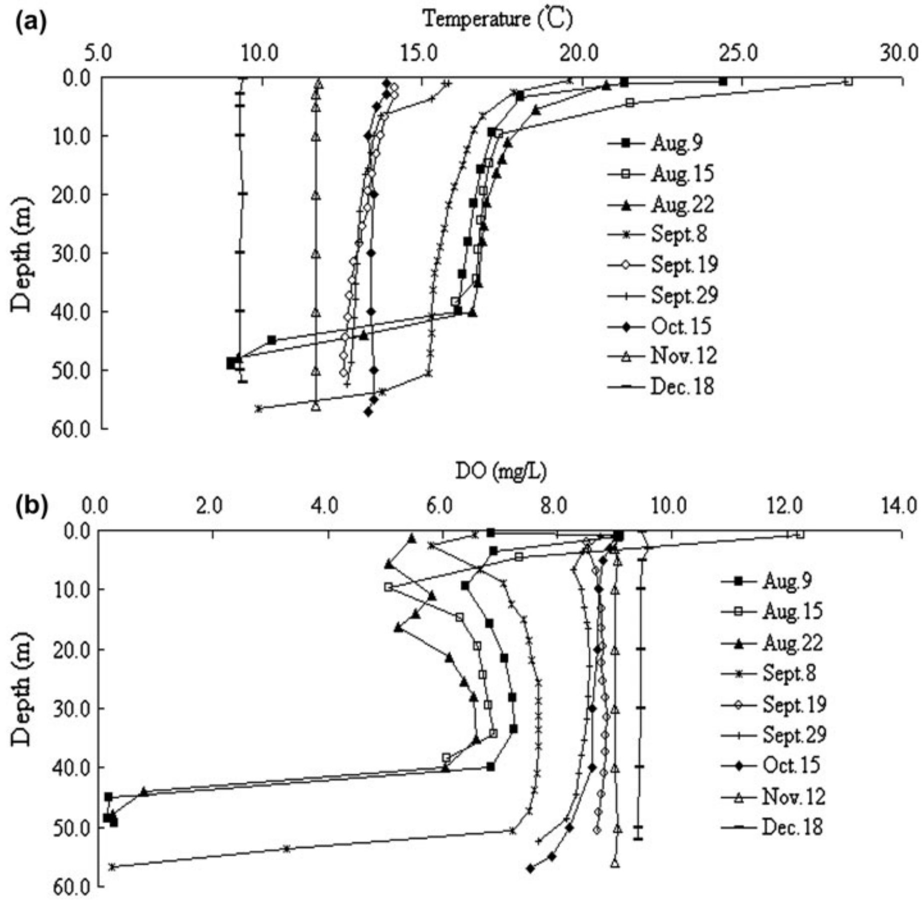

Fig. 5. Water temperature (a) and DO (b) vertical distribution characteristics in S10 (the deepest point of Shibianyu reservoir) from August to December 2011, describing the failure of the process of the reservoir temperature stratification.

As shown in Fig. 4(b), the rainfall of 2011 was mainly concentrated in May, July, and September. The corresponding monthly total rainfall reached 129.3, 219.7, and 407 mm, respectively. The annual total inflow volume and outflow volume in 2011 was 105.479 and 103.529 million m^3, respectively. The total inflow volume of September reached 52.8 million m^3, which is 1.9-times capacity of the Shibianyu reservoir, account for 53.4% of the annual total inflow volume. The total outflow volume in September reached 51.14 million m^3, 1.8 times of the capacity of the Shibianyu reservoir, account for 53.9% of the annual total outflow volume.

Thus, in Shibianyu reservoir the thermal layered structure was destroyed due to continuous heavy rains and huge inflow and outflow volume in September. The water temperature at the bottom rose from 9.9 to 12.6℃, and DO in the hypolimnion rose to 8.69 mg/L on September 19 (Fig. 5). After September, as water temperature reduced with air temperature, the stratification of temperature in the reservoir did not form again. Therefore, the whole area of water quality was mixed. This could explain why the problem of the abrupt increase of the nitrogen and phosphorus concentration in the surface water did not occur in the winter of 2011.

It also further proved that the hypolimnion became anoxic in the stratified period, increasing the release of nutrients from the bottom sediments, being the main reason for the abrupt rise of the nitrogen and phosphorus concentration in the surface water of Shibianyu reservoir during the period of mixing in winter.

3.3. Cause analysis for the abrupt rise of the TN in spring

After Shibianyu reservoir summer stratification was destroyed in September 2011, the reservoir water was kept in a mixed state, the problem of the abrupt rise of the nitrogen and phosphorus concentration in the surface water did not happen in the winter of 2011. However, the concentration of TN still suddenly

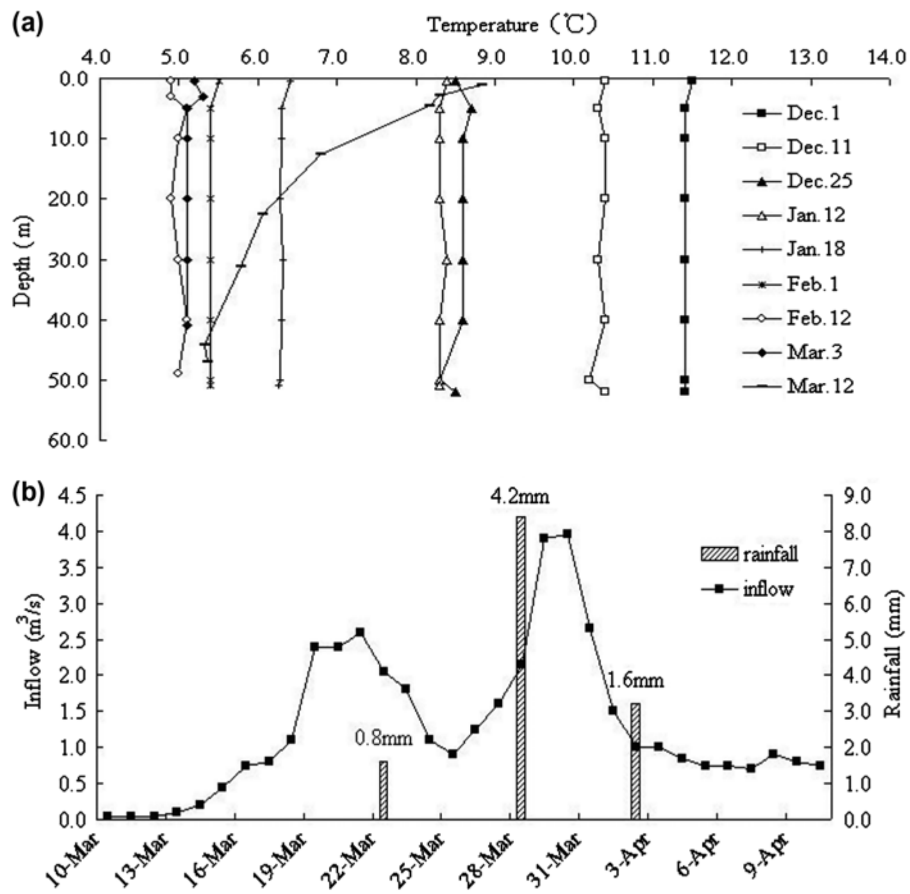

Fig. 6. Water temperature vertical distribution characteristics in S10 from December 2011 to March 2012 (a), and explaining why the reverse winter stratification did not exist in Shibianyu reservoir, and variation of inflow and rainfall from March to April 2012 (b).

increased in the middle of March 2012. A further study revealed the reason for the abrupt rise of the nitrogen concentration in spring.

During the winter when the surface water is frozen, the icy top shields the wind mixing effects and the water underneath becomes relatively stable. The presence of ice, a low-density layer, prevents the exchange of thermal energy between the water and the atmosphere. This insulating layer induces a winter thermal stratification with temperatures between 0 and 4℃ from the top to the bottom of the water column [12]. Thus the high-density water of the lower layer stays on the bottom and does not mix with the upper layer of water. Consequently, the water in the lower layer gradually becomes anoxic because of the inadequate supply of DO, and this in turn deteriorates the conditions for aquatic organisms [13].

Shibianyu reservoir's minimum temperature in mid-February was about 4.9℃ (Fig. 6(a)), there was no ice, and water was mixed (the difference of water temperature between surface and bottom was less than 0.5℃) during the whole winter. In the Shibianyu reservoir there is no reverse stratification in winter. So, it can be a preliminary judgment that the internal release is not reason for the abrupt increase of nitrogen in spring. Fig. 6(b) shows the rainfall and inflow changes from March 10 to April 10. The temperature of Shibianyu reservoir began to rebound in the begin-

Table 3
Dynamic characteristics of TN in the sampling points of upstream in spring of 2012

TN/mg L	28 Feb	5 Mar	12 Mar	22 Mar	4 Apr	10 Apr
S1	2.05	2.04	3.37	4.63	4.34	3.09
S2	2.06	2.06	3.85	4.89	4.34	3.09
S3	2.15	2.14	3.75	4.95	4.15	3.05
S4	2.19	2.15	3.62	4.82	3.92	3.01
S5	2.04	1.91	3.71	4.16	4.08	2.74
S6	2.01	1.91	3.70	4.13	4.93	3.26
S7	2.66	2.72	5.05	5.97	5.58	4.69
S8	2.10	2.09	3.81	4.58	4.72	3.08

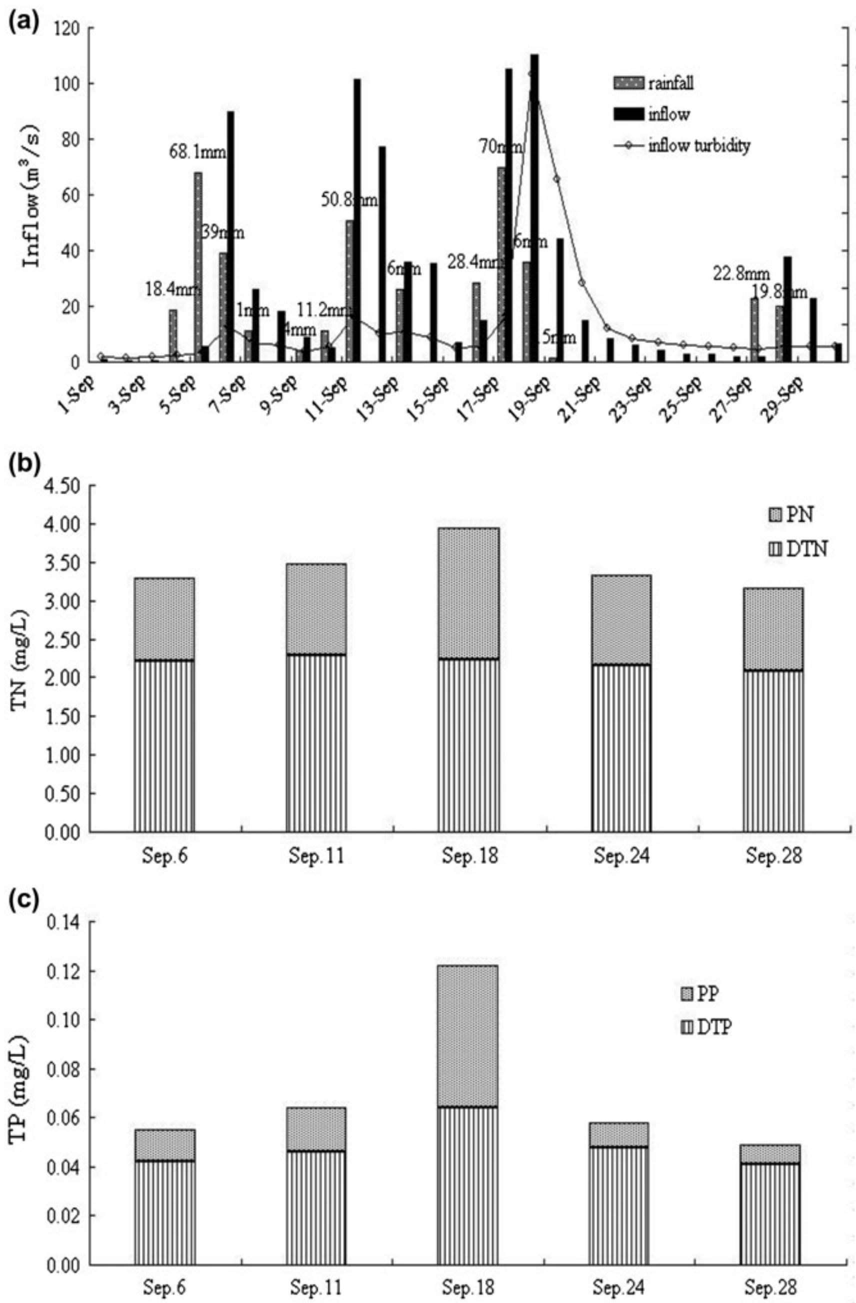

Fig. 7. Variation of inflow, rainfall, inflow turbidity (a), and nitrogen (b), phosphorus (c) concentration, and composition of S8 (inflow water) during the period of heavy rainfalls in September 2011.

ning of March, influenced by the temperature, the snow on the mountain began to melt, this led to increasing inflow of Shibianyu reservoir from 12 March (during this period there is no rain). Meanwhile, the concentration of the TN at upstream monitoring points was beginning to increase (Table 3). The water level of the reservoir was relatively low during this period, so the water quality of inflow had a significant impact on the reservoir's water quality and led to the rise of nitrogen concentration in reservoir.

3.4. *Cause analysis for the abrupt rise of the nitrogen and phosphorus in autumn*

The rainfall of Shibianyu reservoir was mainly concentrated in July to September (Fig. 4(a)). The total

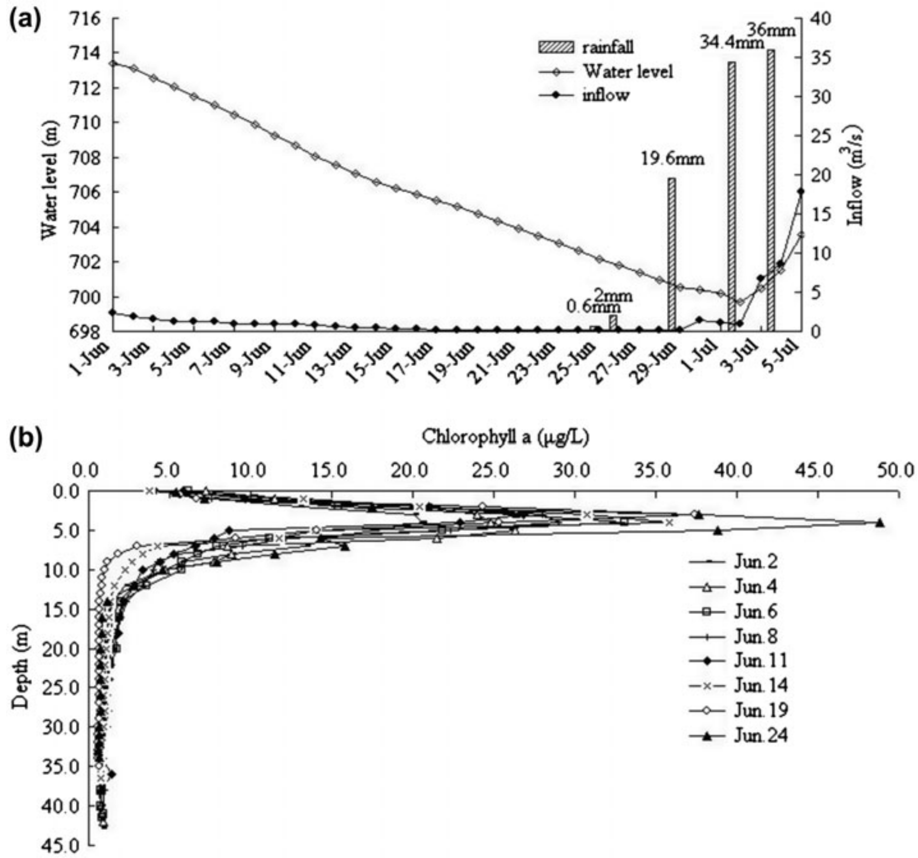

Fig. 8. Variation of inflow, rainfall, and water level (a) and chlorophyll a vertical distribution characteristics (b) from June to July 2012.

Fig. 9. Large of blue green algae flocs appeared in the surface of Shibianyu reservoir.

rainfall reached 407 mm in September 2011, and mainly in the form of heavy rains (Fig. 7(a)). The inflow of Shibianyu reservoir changed greatly during this period. The maximum inflow reached 110.4 m^3/s. Inflow turbidity of Shibianyu reservoir was usually lower than 10 NTU. However, sediment in the inflow site was washed by the fast inflow velocity, and increased the inflow turbidity during the rainfall period. Continuous heavy rains caused upstream landslides, and a large number of sediment was flushed into the reservoir. So, in the reservoir, water turbidity increased rapidly on 17 September. A lot of suspended matter was carried by the inflow, which resulted in increasing of nitrogen and phosphorus concentration in the reservoir [14].

As Fig. 7(b) and (c) shows, the concentration of nitrogen and phosphorus reached 3.9 and 0.112 mg/L, respectively on September 17, and included particulate nitrogen phosphorus account for 43.4 and 47.5%, respectively. Particulate pollutants were easily precipitated in the reservoir area, eventually leading to increasing of the reservoir endogenous load. Finally, the reservoir water quality deterioration was intensified.

3.5. Algae growth

Under proper water temperature and light condition, high concentration of nitrogen and phosphorus in Shibianyu reservoir provided enough nutrients for algae multiplication [15]. In Shibianyu reservoir, a stable layered structure was formed in the beginning of June. As Fig. 8(a) shows, during prolonged drought periods, the reservoir water level declined from 713.43 m down to 700.37 m in June. The increasing water temperature, adequate lighting conditions, and stable water layered structure promoted the bacillariophyta multiplication [16]. As Fig. 8(b) shows, the content of chlorophyll a was about 50 μg/L, including *Fragilaria* accounting to 87% at the end of June.

After prolonged drought periods, there was a high frequency and intensity of rains in July. Such changes in the rainfall patterns led to favorable conditions for cyanobacterial growth due to a greater nutrient input into water bodies during heavy rains, combined with potentially long-time periods of high evaporation and stratification, and the rapid increase of water temperature and light illumination after rainfall [17]. A large number of green phytoplankton aggregates appeared on the surface of the reservoir after several days of rainfall (Fig. 9), about 70 μg/L of chlorophyll a, including *Microcystis aeruginosa* accounting to 92%.

3.6. Control measures suggested

3.6.1. Mixing and oxygenated by water-lifting aerator

For Shibianyu reservoir in summer, stratification limits of oxygen transfer from the surface to the lower hypolimnion, DO in hypolimnion reduced rapidly due to the consumption of DO in sediment and water. The hypolimnion became anoxic in the stratified period, increasing the release of nutrients from the bottom sediments. Summer stratification also promotes the phytoplankton multiplication.

An effective countermeasure for water-lifting aerator is to mix and oxygenate in order to improve the anoxic condition in the lower layer water, due to stratification [18]. The water-lifting aerator can directly oxygenate lower layer water and lessen the circulation in the lower anoxic water, thus promoting the diffusion of DO. In addition, when the algae get to the bottom area without sunshine, their growth is restrained, and eventually they die because upper and lower water layers can mix and make the algae in the upper layer move downward to the lower layer [19]. Therefore, water quality of Shibianyu reservoir may be dramatically improved by water-lifting aerator during the period of summer stratification.

3.6.2. Strengthening of upstream protection

Heavy rainfall leads to landslides, a large number of suspended solids into the reservoir results in an increase of nutrients put into the reservoir, which is another serious problem of Shibianyu reservoir. Thus, strengthening upstream mountain protection is an effective method to reduce pollutants put into the reservoir during the period of rainstorm.

4. Conclusion

Eutrofication of Shibianyu reservoir due to algae bloom under sufficient nutrient and stable thermal stratification structure condition, seriously affects the quality of supplied water. It is observed that Shibianyu reservoir's stable temperature layered structure is formed in the beginning of June, DO available in the hypolimnion rapidly reduces due to the consumption of DO in sediment and water. The hypolimnion becomes anoxic in the stratified period, increasing the release of nutrients from the bottom sediments during the period of mixing in winter. Therefore, the water quality of Shibianyu reservoir may be dramatically improved by a water-lifting aerator during the period of summer stratification. In addition, continuous heavy rains in Shibianyu reservoir cause upstream landslides, and a large number of sediment is flushed into the reservoir leading to a significant increase in the water turbidity, nitrogen, and phosphorus concentrations. It is possible to improve the water quality in Shibianyu reservoir by strengthening the upstream mountain and reducing the infusion of nutrients during rainstorm period.

Acknowledgments

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