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A novel flushing strategy for diatom bloom prevention in the lower-middle Hanjiang River

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ABSTRACT

There are many concerns over the environmental consequences of river regulation in China, such as the Three Gorges Project and the South-to-North Water Diversion Project (SNWDP). In this study, however, we attempted to find the positive role of these constructions in solving environmental problems. We explored the possibility for preventing downstream diatom blooms by using the water storage in the Danjiangkou Reservoir. And we developed a flushing strategy accessing the proper flushing time and water quantity to control the diatom growth. First, we set up a Generalized Additive Model (GAM) to analyze the dynamics of the bloom-formation species, *Stephanodiscus hantzschii*, in response to the environmental variation. The model took into account the time lags between the biovolume and the environmental parameters. The model indicated that, air temperature explained the most variance in biovolume, followed by soluble reactive silicon (SRSi), turbidity, TP, dam release, PAR, pH and total nitrogen (GAM, $R^2 = 0.759$). Afterwards, we applied the model to a new predictive dataset, in which values were simulated according to the assumed dam release and air temperature. The GAM predicted fewer releases for flushing by using this dataset than the measured data, implying a prospect of saving water when using this strategy. Finally, we drew a contour map to present the operating procedure of this strategy. Our flushing strategy is to regulate the dam release above a critical value dependent on the air temperatures predicted over the following few days.

1. Introduction

Algal blooms in rivers can cause severe environmental problems, such as toxicity (Atkins et al., 2001), odor and taste (Jones and Korth, 1995). Exploring the factors affecting the formation and development of river blooms is of great significance in river management and protection. Among all the environmental factors affecting the algal proliferation in rivers, the flow conditions have been paid much attention and well studied. River blooms usually exist in low-flow reaches, which contain pools, backwater reaches or other storage zones (Reynolds, 1992).

Many factors can affect the flow conditions in rivers. River regulation projects, over exploitation of river water, some local meteorological and topographic characters may cause low-flow conditions, even thermal stratification in rivers

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(Bormans and Webster, 1998; Ha et al., 2003; Phlips et al., 2007; Thebault and Qotbi, 1999). The anthropogenic regulation of rivers can greatly change the hydrological conditions in rivers. Despite their crucial roles in irrigation, flood protection and water supply, these regulation constructions can result in many environmental problems. There are growing concerns about the potential effects of river regulation on the future environment in China. The controversy over the large-scale water conservation, such as the South-to-North Water Diversion Project (SNWDP), never stopped (Stone, 2008; Xie, 2003).

The SNWDP is designed to divert water from rivers in South China to North China, to abate the droughts in this area. The Hanjiang River serves for the water source for the middle route of the SNWDP, which will be completed and begin to divert water in 2014. It is expected to reduce the downstream flow greatly, by extracting $9.5 \times 10^9\ m^3$–$13 \times 10^9\ m^3$ water a year from the Danjiangkou Reservoir in the middle reaches of the river (Fig. 1). By taking so much water from the river, the SNWDP is expected to have many negative effects on the water quality in the lower Hanjiang River. One potential point is that the low flow may aggravate the downstream blooms in the river. Severe diatom blooms have frequently occurred in the lower Hanjiang River during the low-flow period, and greatly impaired the water quality in the river. There are several large waterworks along the river, but the blooms threatened the drinking purpose of the river water. For instance, Zongguan Waterwork (in the lower reach of the river) supplying drinking water to 1.25 million people in Wuhan City released heavy odors during diatom blooms in 2000. Blooms in the Dongjing River, one branch of the Hanjiang River, even compelled several waterworks to suspend the production of potable water in 2008.

Having recognized the importance of hydrological conditions in river blooms, water researchers suggested suppressing algal blooms by increasing the river discharge (Maier et al., 2001, 2004; Webster et al., 2000; Jeong et al., 2007). Because the flow of the tributaries of the Hanjiang River is very low during the bloom period, the Danjiangkou Reservoir becomes the only water source for flushing downstream blooms. However, as the SNWDP will play an important role in the agricultural and industrial development of North China, water storage of the Danjiangkou Reservoir must be always sufficient for water diversion. Therefore, it will be only permitted to drain finite water from the reservoir to prevent blooms in the downstream section. What's more, flushing strategies without elaborate plans will cause an enormous waste of water. Although much attention has been paid to the formation mechanism of blooms in lentic ecosystems, little work was done to investigate river blooms in China, let alone the prevention strategy. In this study, we carried out a comprehensive investigation on the environmental factors and the phytoplankton in the Hanjiang River. Our goal is to examine the key factors affecting the formation and development of diatom blooms in the lower Hanjiang River, and develop a flushing strategy for bloom prevention in large lowland rivers by regulating the dam release at the middle reaches.

2. Material and methods

2.1. Study area

The Hanjiang River, located between 106 and 114°E and 30–34°N (Fig. 1), is the largest branch of the Yangtze River. The Danjiangkou Reservoir at the middle reach of this river is the source of water for the middle route of SNWDP in China. The Hanjiang River is about 1570 km long, and its basin area covers 170,400 km^2. The basin has a subtropical monsoon climate with an annual precipitation of about 700–1000 mm (Chen et al., 2007). Our research focused on the lower-middle reaches of the Hanjiang River, where diatom blooms frequently occur. The studied reaches along which 13

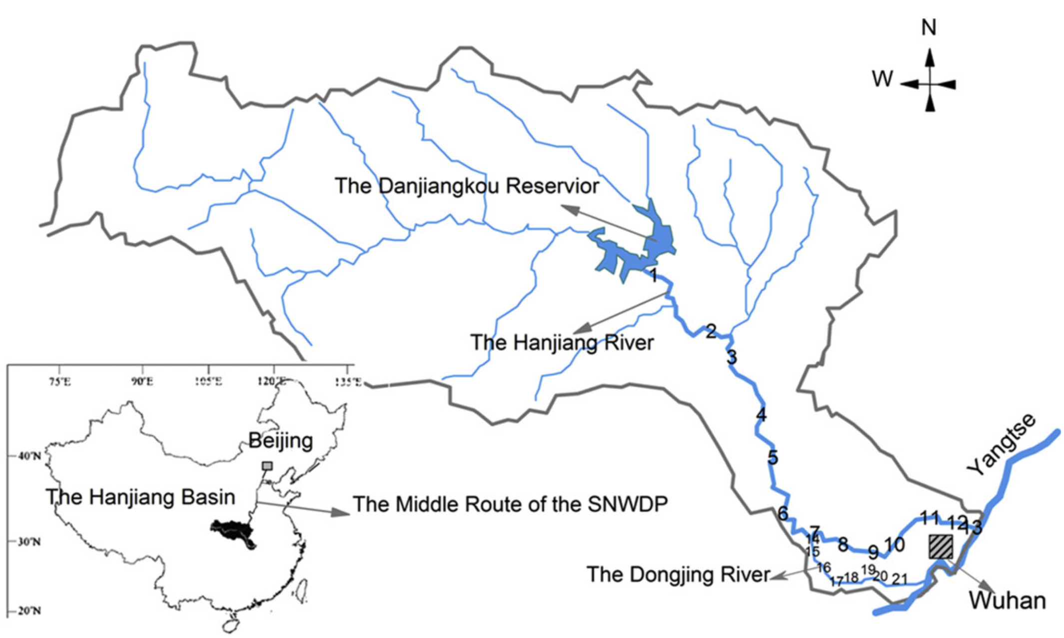

Fig. 1 – Sampling sites on the Hanjiang River.

sampling sites (1–13) were set, have a length of 652 km, extending from site-1, next to the dam of the Danjiangkou Reservoir, to site-13, the confluence of the Hanjiang River and the Yangtze River.

The Dongjing River, one distributary of the Hanjiang River, was also investigated. It has a length of 140 km, and a basin area of 417.5 km^2. The investigated reaches, where 8 sampling sites (14–21) were set, have a length of 60 km.

2.2. Data collection

To investigate the roles of environmental factors in phytoplankton dynamics both in different months and during the diatom bloom period respectively, two sampling frequencies were adopted. A monthly sampling program was conducted at all sites from December in 2008 to September in 2010. A more intensive sampling program was conducted at four sites (7, 15, 16, 17) during the diatom bloom period from December 29 in 2009 to March 7 in 2010. We selected these sites for the following reasons: a new river regulation project, Yangtze–Han Water Diversion, has been approved and is expected to operate in 2013. This project will divert water from Yangtze River to the lower Hanjiang River to abate the potential environmental sequences of the low-flow conditions caused by SNWDP. The water of this project will flow into the Hanjiang River between the site-7 and site-8. The velocity of flow in the water section from the site-8 to site-13 will be guaranteed above 0.3 m s^{-1}, when the project comes into operation (Zhu et al., 2008). This velocity is above the maximum velocity observed during the bloom period in all years, and we assumed that diatom blooms would not occur in this river section. Therefore, the Site-7 and the Dongjing River become the most distant river sections where blooms can break out.

Water samples were acquired from just below the surface, mid-depth and just above the bottom using a 5-L Schindler sampler, and then made into a mixed sample. 1000 ml raw water, 500 ml filtrates and filter papers (whatman GF/C, 47 mm) after in-situ filtration of 1000 ml water were preserved in the icebox, and taken back to the laboratory immediately for the following analysis.

2.3. Environmental parameters

DO, pH, turbidity, and conductivity were measured in-situ using automatic meters (Eutech Instruments Pte Ltd/Oakton Instruments, USA): pH, Ecoscan pH6; DO, Cyberscan DO110; turbidity, TN-100; Conductivity, Cyberscan CON11. Chemical parameters, including total nitrogen (TN), total phosphorus (TP), soluble reactive silicon (SRSi), and Chl *a* were all measured using standard methods (APHA et al., 1995). Hydrological data of the Hanjiang River were obtained from Hubei Academy of Environmental Sciences. Meteorological data, including air temperature, precipitation and photo synthetically active radiation (PAR) were acquired from the Donghu Experimental Station of Lake Ecosystem, Chinese Academy of Sciences. Environmental data for water released from the Danjiangkou Reservoir were obtained from the routine monitoring and related literature (Table 1) (Li et al., 2009; Kong et al., 2010).

Table 1 – Comparison between water quality of the reservoir release and the lower Hanjiang River.

	Reservoir release	Lower Hanjiang River
Water temperature (°C)	8.00 ± 1.90	7.50 ± 1.45
PH	8.24 ± 0.10	8.01 ± 0.45
DO (mg L^{-1})	9.58 ± 0.66	11.06 ± 0.081
Turbidity (NTU)	6.00	26.00 ± 11.00
NH_4^+–N (mg L^{-1})	0.07 ± 0.05	0.25 ± 0.09
TN (mg L^{-1})	1.12 ± 0.09	1.74 ± 0.44
TP (mg L^{-1})	0.01 ± 0.006	0.08 ± 0.04
SRSi (mg L^{-1})	2.26	2.01 ± 1.13
COD_{Mn} (mg L^{-1})	1.83 ± 0.40	2.74 ± 0.64
Chl *a* (mg L^{-1})	2.20 ± 1.24	22.68 ± 15.59

Notes: Turbidity and SRSi values were acquired from related literature. Values of other parameters were obtained from the routine monitoring for water quality of the release from the Danjiangkou Reservoir conducted by Hubei Academy of Environmental Sciences. All the data for these parameters are mean values of measured data in each February of 2005, 2006, 2007, 2008, 2009 and 2010. Data of the lower Hanjiang River are the mean values of all sampling sites in February, 2010.

2.4. Phytoplankton identification and biovolume

Most of the phytoplankton species were identified and counted with a Palmer-Maloney counting chamber using a Nikon CX41 microscope. Accurate taxon identification of species of small size was conducted, using a JEM-1230 Transmission electron microscope (JEOL, Japan). The identification was according to Hu and Wei (2006). The biovolumes of phytoplankton were calculated according to their morphometric characters (Zhang and Huang, 1991).

2.5. GAM model construction and prediction

Cross correlation analysis was conducted using Matlab 7.0 (MathWorks, Natick, MA, USA), to calculate the possible time lags between two environmental factors, dam release and air temperature, and the biovolume of *Stephanodiscus hantzschii*.

After correcting the time lags, we set up a GAM model using measured data, to study the nonlinear relationships between the biovolume of *S. hantzschii* and environmental factors (GAM, ln(biovolume) $\sim \sum$s(environmental factor i), d$f = 4$). Then, we further applied this model to a new predictive dataset consisting of environmental factors, of which the values were simulated based on the assumed variation in the dam release and air temperature. The pH values in the new dataset were simulated according to its linear correlation with the air temperature. Turbidity, PAR and SRSi were set to fixed values, at which the maximum enhancements of biovolume were observed in the GAM model. This operation could make sure that the effects of these factors would not be underestimated in the prediction, so the estimated minimum dam release would be sufficient for bloom prevention. Values of TN and TP in the new dataset were computed according to the assumed dam release based on Equation (1) and Equation (2). The construction, statistic test and prediction of the GAM were all conducted using R version 2.13.0 with the 'gam' package (Hastie, 2011).

$$C_{TN} = \frac{C_{DamTN} \times D_{dam} + C_{rivTN} \times D_{riv}}{D_{dam} + D_{riv}} \quad (1)$$

$$C_{TP} = \frac{C_{DamTP} \times D_{dam} + C_{rivTP} \times D_{riv}}{D_{dam} + D_{riv}} \quad (2)$$

C_{TN}, C_{TP}: the simulated concentrations of TN and TP; C_{DamTN} and C_{DamTP}: concentrations of TN and TP in the Danjiangkou Reservoir; C_{rivTN} and C_{rivTP}: concentrations of TN and TP of the sites for predicting; D_{riv}: river discharge of the sites for predicting during the 2010-bloom period (from January 1 to March 31); D_{dam}: assumed dam release.

3. Results

3.1. Temporal and spatial patterns of limnological conditions

All limnological parameters in the Hanjiang River showed a marked seasonal variation (Fig. 2). There was a close relationship between DO and pH, and the maximum values of both DO and pH were observed in early spring. High concentrations of TP and Chl *a* were also observed during this low-flow period (Fig. 2(B) and (D)). COD_{Mn} was much higher in the winter and summer than in the spring and fall (Fig. 2(D)). The concentrations of TN, NH_4^+–N, TP, COD and Chl *a* in the lower reaches were obviously higher than the concentrations in the upper reaches (Fig. 3(B–D)). The concentration of SRSi presented a gradual decline along the flow direction (Fig. 3(C)).

3.2. Meteorological and hydrological characters of the Hanjiang River

All meteorological and hydrological parameters of the Hanjiang basin showed strong seasonal variations (Fig. 4). Air temperature, PAR, precipitation and river discharge were much higher in the rainy season (May–November), than those in the dry season (December–April). The highest air temperature is roughly 35° higher than the lowest air temperature, and the maximum difference between the daily average PAR is about 40 mol photons m^{-2} d^{-1}. The air temperature ranged from 5 °C to 15 °C, and PAR ranged from 5 mol photons m^{-2} d^{-1}–20 mol photons m^{-2} d^{-1} during the bloom period (the diagonal area in Fig. 4(A)). Precipitation in 2010 was higher than that in 2009 (Fig. 4(B)). The low-flow period lasted about 5 months, from November to March in both years (Fig. 4(C)).

3.3. Time lags between the biovolume and environmental factors

We performed the cross correlation analysis only on the air temperature and the dam release, because it is normally manageable to conduct temperature forecast and dam release regulation, but considerably more difficult to control other environmental parameters in a short time. The time lags estimated by cross-correlation were given in Table 2. There was no time lag between the air temperature and the biovolume of *S. hantzschii*, indicating that the biovolume of *S.*

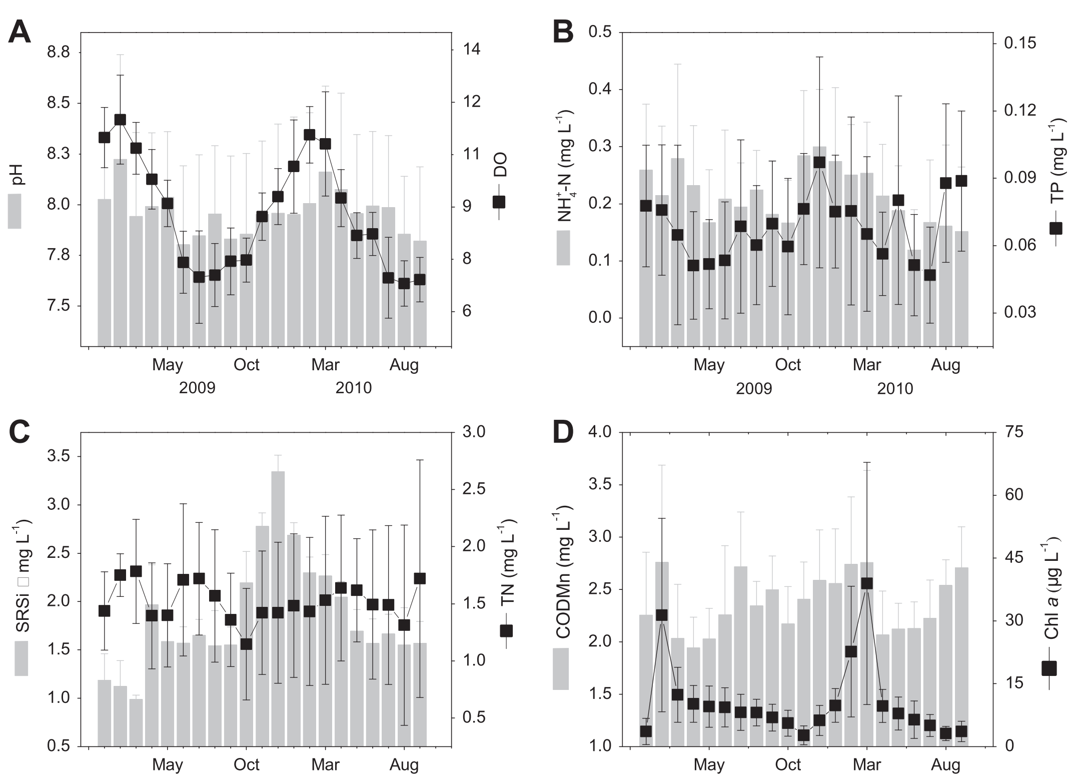

Fig. 2 – Temporal limnological variations in the lower-middle Hanjiang River. Bars and points indicate mean values of all sampling sites in the Hanjiang River. Error estimates are expressed as 1 standard deviation of the mean values. (A) pH, DO; (B) NH_4^+ and TP; (C) SRSi and TN; (D) COD_{Mn} and Ch *a*.

hantzschii is synchronous with the changes in air temperature or that the time lag between them is not more than a day. A time lag of 8–9 days was estimated between the biovolume of *S. hantzschii* and the dam release.

3.4. *Predictive parameters of the biovolume of* S. hantzschii

We set up a GAM model to study the nonlinear relationships between the biovolume of *S. hantzschii* and the environmental variations (Table 3). The results of the statistical test for the model indicated that seven parameters (air temperature, SRSi, turbidity, TP, dam release, PAR, pH) made statistically significant contributions to the variance in the biovolume. Although TN had no statistical meaning in explaining biovolume variance, we still included it in the GAM, because it indeed improved the explained percentage of the model. The model revealed that among the environmental factors, air temperature explained most of the variance in the biovolume, followed by SRSi, turbidity, TP, dam release, PAR, pH and TN. The biovolume of *S. hantzschii* and the air temperature changed as a curve with a single peak, with the peak value of about 10 °C (Fig. 5). The single-peak relationships between the biovolume of *S. hantzschii* and PAR, TN, TP and turbidity were also observed, with peak values of 18 mol photons m^{-2} d^{-1}, 2.2 mg L^{-1}, 0.1 mg L^{-1} and 32 NTU, respectively. The biovolume of *S. hantzschii* exhibited negative relationships with SRSi concentration and dam release at low discharge. Especially, when the discharge was less than 2000 m^3 s^{-1}, there was a nearly linear relationship between the biovolume and dam release.

3.5. *Estimation of the optimal flushing strategy*

We further applied the GAM to the simulated dataset and drew a contour map (Fig. 6) to show how the variations in air temperature and dam release can affect the biovolume of *S. hantzschii*. The biovolume of *S. hantzschii* was largely determined by air temperature, and reached its maximum value within the range of 12 °C–17 °C. The highest biovolume appeared at the point of 15 °C and 750 m^3 s^{-1}. We defined the contour lines as bloom standards. The regulation of dam release is based on the predicted air temperature in the following few days. If we wish the biovolume of *S. hantzschii* to stay below certain values, first we should get the information of the air temperature in the future. Fortunately, in our research, the time lags were 8–9 days, which were close to the time limit of the weather forecast. That means we can obtain temperature information from the weather forecast and regulate the dam release above the contour lines of certain biovolume values based on the future air temperature. To sum up, in order to suppress the blooms in the Hanjiang River, we suggest adjusting the dam release above the release value in the contour line representing the bloom standard, according to the future air temperature forecasted by the weather report.

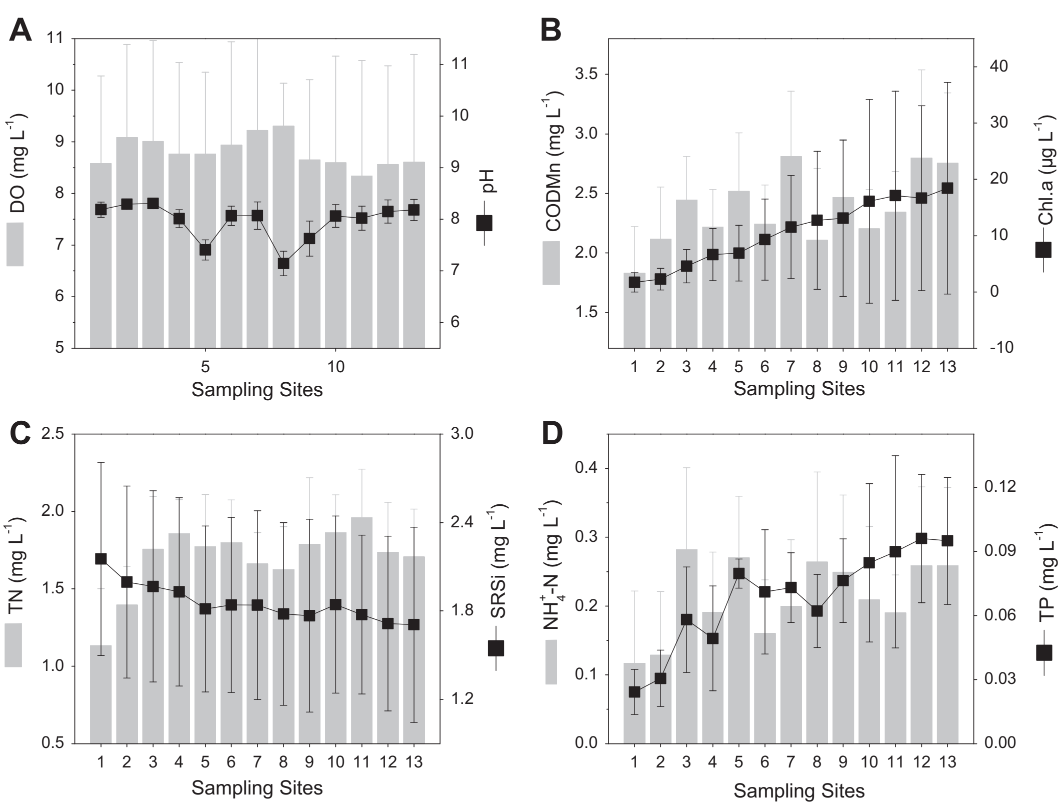

Fig. 3 – Spatial limnological variations in the lower-middle Hanjiang River. Bars and points indicate mean values during the whole sampling period in the Hanjiang River. Error estimates are expressed as 1 standard deviation of the mean values. (A) pH, DO; (B) COD_{Mn} and Chl *a*; (C) SRSi and TN; (D) NH_4^+ and TP.

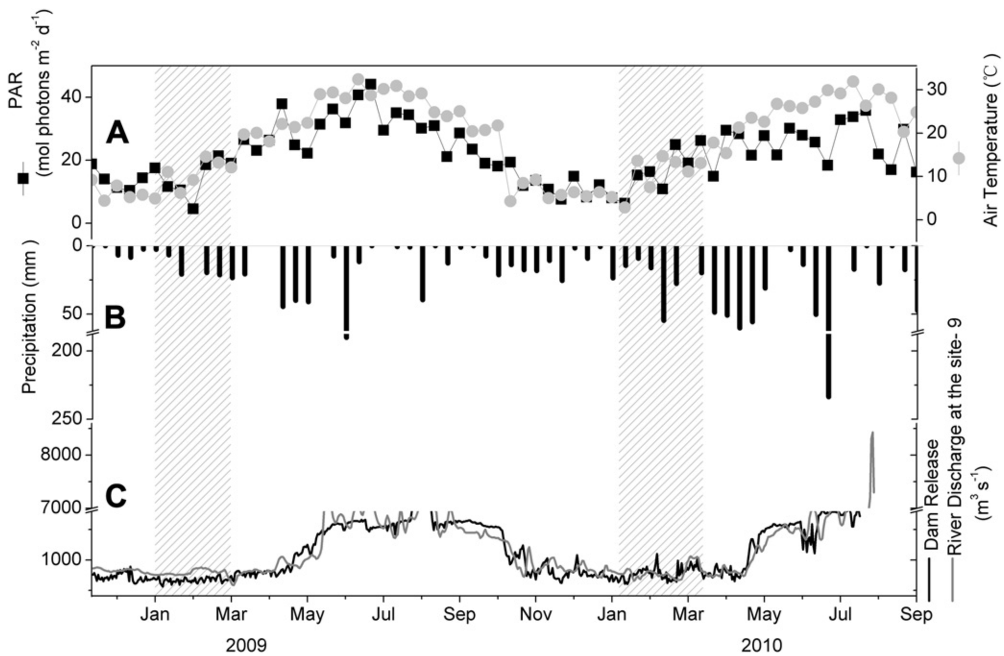

Fig. 4 – Meteorological and hydrological variation of the Hanjiang River. (A) air temperature and PAR; (B) precipitation; (C) dam release and river discharge. Release and discharge data were at the 1-day scale; air temperature and PAR were at half-month scale; precipitation was the accumulation of half a month).

4. Discussion

4.1. *Predictive parameters of the biovolume of* S. hantzschii

According to the GAM model, air temperature, SRSi, turbidity, TP and dam release explained most of the variance in the biovolume of *S. hantzschii*. The biovolume was largely explained by air temperature, especially when the air temperature was below the optimum temperature for the proliferation of *S. hantzschii*. Within this range, the biovolume of *S. hantzschii* exhibited a significantly upward trend with the increasing air temperature. However, the "optimum value" might be underestimated. The upstream of the Hanjiang River flows across several high mountains and receives high amounts of melting snow from these mountains in early spring. The river flow became very high when the air temperature is above 15 °C in the spring during our sampling period, and thus substantially diluted the concentration of *S. hantzschii*. In fact, laboratory incubation experiments showed that the optimum growth of *S. hantzschii* took place at 20 °C (Vandonk and Kilham, 1990; Swale, 1963), thus more severe blooms are expected to occur when the low flow and the higher temperature overlap.

Low flow is essential in the formation of diatom blooms in rivers (Fabbro and Duivenvoorden, 1996; Mitrovic et al., 2008; Kiss and Genkal, 1993), and the biovolume of *S. hantzschii* showed an evident negative correlation with the dam release under the value of 2000 $m^3\ s^{-1}$ in the present study. It is likely that the low-flow decreases loss of phytoplankton caused by flushing, and provides phytoplankton more retention time to enlarge their biovolumes (Allan and Maria, 2007). Although low-flow plays a significant role in the formation of diatom blooms, extremely low flow can suppress the population enhancement of diatom species, as the settlement rate of the diatom species increases in the low-flow conditions (Bormans and Webster, 1999). Sometimes low-flow conditions can lead to thermal stratification in some regulated rivers, and thus give rise to cyanobacteria blooms while diatom blooms collapse (Bormans and Condie, 1998).

The deficiency of underwater light has often been considered to be the cause of low primary productivity in turbulent rivers (Reynolds and Descy, 1996). Besides the high-flow conditions, deficient underwater light caused by high turbidity might account for the low biomass of phytoplankton in the Hanjiang River in wet seasons. However, it was not the case in the early spring. There was indeed a weak positive correlation between the biovolume and PAR. However, a strong positive correlation between the biovolume and turbidity was observed, indicating that the proliferation of *S. hantzschii* was not exhibited by low underwater radiation. The former experiment in the laboratory showed that increasing light did not substantially improve the growth rate of S.

Table 2 – Time lags between the biovolume of *S. hantzschii* and environmental factors.

Site	7	15	16	17
Air temperature-phytoplankton	0 (0.70)	0 (0.74)	−1 (0.73)	0 (0.70)
Dam release-phytoplankton	9 (0.51)	8 (0.45)	8 (0.42)	9 (0.43)

Notes: Values out of brackets indicate the estimated time lag; Values within brackets indicate the cross-correlation coefficient.

Table 3 – Statistical test for the GAM model.

Model factors	Residual degree of freedom	Residual deviance	Deviance variation	Cumulation of deviance explained (%)	Pr (F)
Initial	157	87.11			
Air temperature	153	44.32	42.79	49.12	<0.000
SRSi	149	34.16	10.16	60.79	<0.000
Turbidity	145	29.34	4.82	66.32	<0.000
TP	141	26.85	2.49	69.18	0.006
Dam release	137	24.64	2.21	71.71	0.009
PAR	133	22.84	1.8	73.78	0.012
pH	129	21.82	1.02	74.95	0.035
TN	125	21.04	0.78	75.85	0.069

hantzschii under low temperature conditions (Swale, 1963). And recent experiment in our laboratory also revealed that the *S. hantzschii* could grow well under the shade environment (Wang, 2010).

Previous studies proved that *S. hantzschii* can grow successfully in low Si and high P concentrations (Mechling and Kilham, 1982; Kilham, 1984; Kilham et al., 1986). In this study, the GAM revealed that biovolume of *S. hantzschii* presented a negative relationship with SRSi. The proliferation of *S. hantzschii* actively assimilated SRSi, consequently causing a substantial decline of SRSi in the lower Hanjiang River. Similar phenomena of low SRSi were also found in many other rivers during diatom blooms (Ha et al., 2003; Mitrovic et al., 2008). On the other hand, proliferation of diatoms requires high amounts of dissolved phosphors (DP). Unfortunately, however, no previous study has measured DP in the Danjiangkou Reservoir and the Hanjiang River. As TP data were available, we used TP as an alternative index of P, and TP indeed explained part of the biomass variance in the GAM model (Table 3). A weak positive relationship between *S. hantzschii* biomass and TP was observed within the range of 0.04–0.09 mg L^{-1}. The weak relationship indicated that although the proliferation of this species could result in higher TP concentrations, TP level in the lower Hanjiang River was so high that it was not greatly affected by the diatom bloom. A previous research has indicated that the growth rate of *S. hantzschii* is higher than those of other common diatom species in the range of low temperature (Vandonk and Kilham, 1990). Therefore, the concurrence of low temperature and low Si/P ratio might suppress the population enhancement of

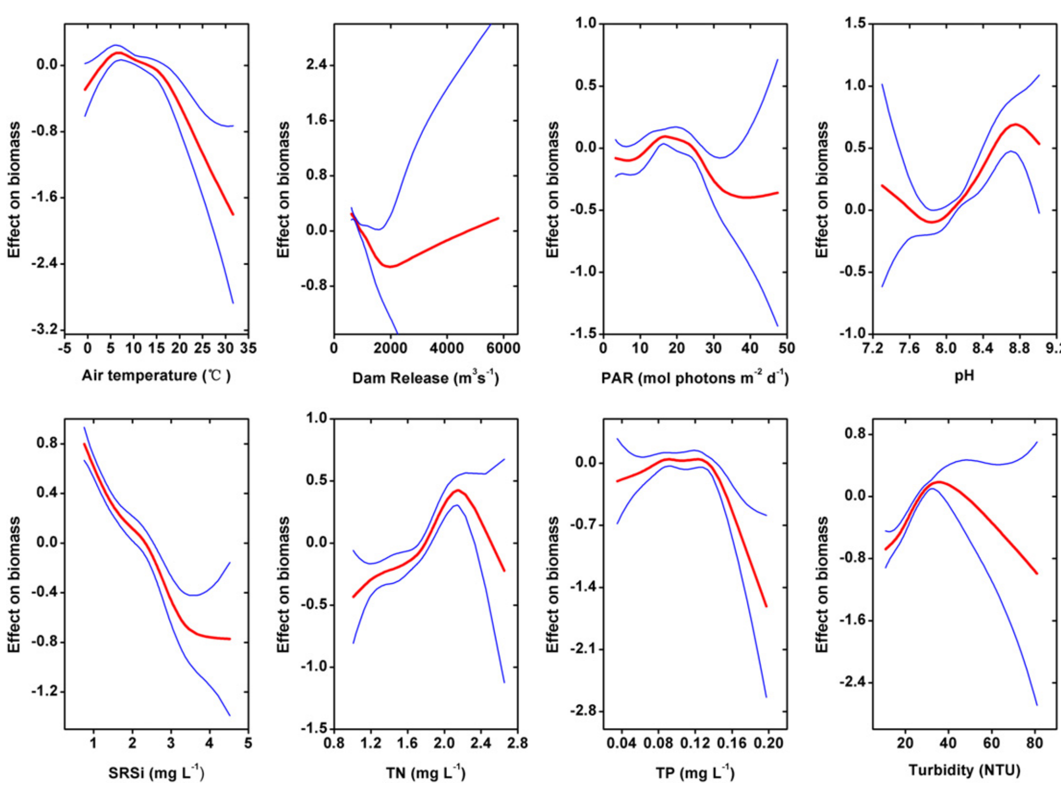

Fig. 5 – Enviromental effect curves from a GAM model with 4 df fitted to Stephanodischus hantzschii population data of the Hanjiang River (Red line), with two 95% confidence bands (blue lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

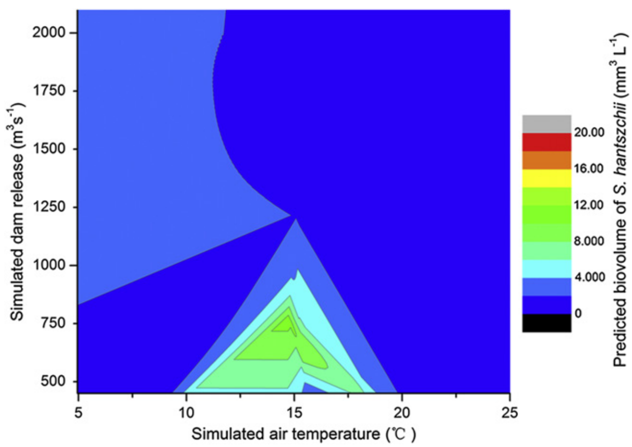

Fig. 6 – The prediction of the biovolume of *S. hantzschii* by simulated air temperature and dam release.

other diatom species. As *S. hantzschii* can adapt well to these conditions and there are no competitors, it has the enormous potential for proliferation.

The relationship between diatom species and pH could be very complex. Many benthic diatom species are sensitive to variations in pH and usually selected as indicators of pH in aquatic ecosystems (Weckstrom et al., 1997; Birks et al., 1990). On the other hand, like other algae, proliferation of diatoms reduces the CO_2 in the water body and thus causes an increase in the pH value. A positive relationship between *S. hantzschii* biomass and TN was observed within the range of 1.0–2.2 mg L^{-1}. Although TN had no statistical significance in explaining the variance in the biovolume of *S. hantzschii*, it indeed improved the accumulation of deviance explained. Therefore, we still included TN in the GAM model.

4.2. *The flushing strategy for the prevention of diatom blooms*

After we constructed the GAM model using measured data, we further applied it to the new simulated dataset. The reason we did not simply use the constructed GAM to optimize the release for flushing is that the regulation of the dam release will cause changes of other environmental factors in the lower river, and therefore, the optimal release needed for flushing will change. As the water quality of the Danjiangkou Reservoir is much better than that of the downstream section (Table 1), increasing dam release will definitely dilute the concentrations of downstream pollutants. As predicted by the GAM using the new dataset, the release for flushing was far less than the release revealed by the GAM using measured data, and thus we could save some considerable amount of water. The air temperature played a significant role in determining the quantity of the dam release. Special attention should be paid to the air temperature in the range from 12 °C to 17 °C, within which the biovolume of *S. hantzschii* is relatively high. During this period, the release should be regulated to a reasonably high level according to the air temperature. The most exciting point in this study is that the time lag between the dam release and biovolume of *S. hantzschii* was about 8–9 days, near the limit of a reliable weather forecast. This means we can pay attention to the air temperature in the following several days and conduct a flexible regulation of the dam release. When the release increased, it will take less time for the reservoir water to arrive at the bloom section, and the time lag between the dam release and the biovolume will be shorter. However, as the dam release estimated to flush blooms is not too much, the time lags between the dam release and the biovolume would not change a lot. Thus, we suggest using the time lags estimated in this study to prevent diatom blooms in the lower Hanjiang River throughout the whole bloom-sensitive period. Such a flushing strategy considering the time lags will be quite feasible in similar large regulated rivers, where dams or reservoirs have already been located. A recent survey (Nilsson et al., 2005) showed that, there are about 45,000 dams above 15 m high in the world, and 300 giant dams above 150 m high, such as the Danjiangkou Dam and the Three Gorges Dam. This reveals a prospect of applying dam storage to the prevention of downstream blooms. Therefore, of particular interest to river managers is calculating the time lags between the dam release and the biovolume of the bloom-forming species and computing the proper dam release according to future air temperature. Our study can be seen as a supplement to the former studies in the Murray River in Australia and the Nakdong River in South Korea (Webster et al., 2000; Jeong et al., 2007). Webster et al. (2000) suggested four strategies for preventing blooms in rivers (setting a minimum discharge, pulsing the discharge, changing the discharge height, and altering the depth of water withdrawal), and all these strategies are largely related to river discharge and stratification. We adopted the strategy of increasing river discharge, and further explored the possibility of using the upstream reservoir in bloom prevention. Jeong et al. (2007) studied the relationship between dam hydrology and phytoplankton proliferations, and estimated a yearly time lag between the hydrological environments and the population dynamics of two bloom-forming species, *Microcystis aeruginosa* and *S. hantzschii*. Although we studied the dynamics of the same diatom species, we focused more attention on the short-term effects of dam release on biovolume of *S. hantzschii* presented. We put forward a flexible and practical strategy at a scale of a few days. With this strategy, decision makers would know the proper start time and the water quantity for flushing downstream bloom.

We used different simplifications to estimate the environmental parameters in the new dataset. These simplifications ignored the changes of these factors along the river channel. Thus, the proposed flushing strategy is only indicative. Some hydrological and water quality models such as the CE-QUAL-W2 model have proven effective in predicting the limnological variations along the river channel. Therefore, using these models might improve the precision of these predictive parameters, and thus enhance the quality of the prediction of the proposed strategy in this study.

5. Conclusions

In this study, a novel and practically feasible flushing strategy was developed to prevent the downstream diatom blooms in the lower Hanjiang River. The flushing strategy estimated the optimal time and flushing water quantity for bloom prevention. Several steps were taken when using this flushing strategy:

- Calculating time lags between the biovolume of bloom-formation species and the main environmental factors, especially air temperature and the dam release.
- Constructing the GAM model to relate the environmental factors to the biovolume of the bloom-formation species.
- Using the GAM model to predict the biovolume of algae with the air temperature and the assumed dam release.
- Setting the dam release discharge above a critical value dependent on the forecasted air temperatures over the following few days.

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REFERENCES

Allan, J.D., Maria, M.C., 2007. Stream Ecology-Structure and Function of Running Waters. Springer, Dordrecht, pp. 130–132.

APHA, AWWA, WPCE, 1995. Standard Methods for the Examination of Water and Waste Water. American Public Health Association, Washington, DC.

Atkins, R., Rose, T., Brown, R.S., Robb, M., 2001. The Microcystis cyanobacteria bloom in the Swan river – February 2000. Water Science and Technology 43 (9), 107–114.

Birks, H.J.B., Line, J.M., Juggins, S., Stevenson, A.C., Ter Braak, C.J.F., 1990. Diatoms and pH Reconstruction. Philosophical Transactions of the Royal Society B: Biological Sciences 327, 263–278.

Bormans, M., Condie, S.A., 1998. Modelling the distribution of Anabena and Melosira in a stratified river weir pool. Hydrobiologia 364 (1), 3–13.

Bormans, M., Webster, I.T., 1998. Dynamics of temperature stratification in lowland rivers. Journal of Hydraulic Engineering 124 (10), 1059–1063.

Bormans, M., Webster, I.T., 1999. Modelling the spatial and temporal variability of diatoms in the River Murray. Journal of Plankton Research 21 (3), 581–598.

Chen, H., Guo, S.L., Xu, C.Y., Singh, V.P., 2007. Historical temporal trends of hydro-climatic variables and runoff response to climate variability and their relevance in water resource management in the Hanjiang basin. Journal of Hydrology 344 (3–4), 171–184.

Fabbro, L.D., Duivenvoorden, L.J., 1996. Profile of a bloom of the cyanobacterium Cylindrospermopsis raciborskii (Woloszynska) Seenaya and Subba Raju in the Fitzroy River in tropical central Queensland. Marine and Freshwater Research 47 (5), 685–694.

Ha, K., Jang, M.H., Joo, G.J., 2003. Winter Stephanodiscus bloom development in the Nakdong River regulated by an estuary dam and tributaries. Hydrobiologia 506 (1–3), 221–227.

Hastie, T., 2011. GAM: Generalized Additive Models. R Package Version 1.04.1. http://CRAN.R-project.org/package=gam.

Hu, H.J., Wei, Y.X., 2006. The Freshwater Algae of China: Systematics, Taxonomy and Ecology. Science Press, Beijing.

Jeong, K.S., Kim, D.K., Joo, G.J., 2007. Delayed influence of dam storage and discharge on the determination of seasonal proliferations of Microcystis aeruginosa and Stephanodiscus hantzschii in a regulated river system of the lower Nakdong River (South Korea). Water Research 41 (6), 1269–1279.

Jones, G.J., Korth, W., 1995. In-situ production of volatile odor compounds by river and reservoir phytoplankton populations in Australia. Water Science and Technology 31 (11), 145–151.

Kilham, S.S., 1984. Silicon and phosphorus growth kinetics and competitive interactions between *Stephanodiscus minutus* and *Synedra* sp. Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie 22, 435–439.

Kilham, P., Kilham, S.S., Hecky, R.E., 1986. Hypothesized resource relationships among African planktonic diatoms. Limnology and Oceanography 31, 1169–1181.

Kiss, K.T., Genkal, S.I., 1993. Winter blooms of centric diatoms in the River Danube and in its side-arms near Budapest (Hungary). Hydrobiologia 269/270, 317–325.

Kong, L., Cai, Q., Xu, Y., Wang, L., Wang, M., 2010. Seasonal change features of rotifer community and its correlation with environmental factors in Danjiangkou Reservoir. Journal of Lake Science 22 (6), 941–949.

Li, S.Y., Cheng, X., Xu, Z., Han, H., Zhang, Q., 2009. Spatial and temporal patterns of the water quality in the Danjiangkou Reservoir, China. Journal of Hydrology Science 54 (1), 124–134.

Maier, H.R., Burch, M.D., Bormans, M., 2001. Flow management strategies to control blooms of the cyanobacterium, Anabaena circinalis, in the River Murray at Morgan, South Australia. River Research and Applications 17 (6), 637–650.

Maier, H.R., Kingston, G.B., Clark, T.F., Sanderson, A., 2004. Risk-based approach for assessing the effectiveness of flow management in controlling cyanobacterial blooms in rivers. River Research and Applications 20 (4), 459–471.

Mechling, J.A., Kilham, S.S., 1982. Temperature effects on silicon limited growth of the Lake Michigan diatom Stephanodiscus minutus (Bacillariophyceae). Journal of Phycology 18, 199–205.

Mitrovic, S.M., Chessman, B.C., Davie, A., Avery, E.L., Ryan, N., 2008. Development of blooms of Cyclotella meneghiniana and Nitzschia spp. (Bacillariophyceae) in a shallow river and estimation of effective suppression flows. Hydrobiologia 596 (1), 173–185.

Nilsson, C., Reidy, C.A., Dynesius, M., Revenga, C., 2005. Fragmentation and flow regulation of the World's large River Systems. Science 308 (5720), 405–408.

Phlips, E.J., Hendrickson, J., Quinlan, E.L., Cichra, M., 2007. Meteorological influences on algal bloom potential in a nutrient-rich blackwater river. Freshwater Biology 52 (11), 2141–2155.

Reynolds, C.S., 1992. Algae. In: Calow, P., Petts, G.E. (Eds.), The River's Handbook: Hydrological and Ecological Principles. Blackwell Scientific publication, Oxford, pp. 195–215.

Reynolds, C.S., Descy, J.P., 1996. The production, biomass and structure of phytoplankton in large rivers. Archiv für Hydrobiologie – Supplement 113 (1–4), 161–187.

Stone, R., 2008. Three Gorges dam: into the unknown. Science 321 (5889), 628–632.

Swale, E.M.F., 1963. Notes on Stephanodiscus hantzschii Grun. in culture. Archives of Microbiology 45 (2), 210–216.

Thebault, J.M., Qotbi, A., 1999. A model of phytoplankton development in the Lot River (France)- Simulations of scenarios. Water Research 33 (4), 1065–1079.

Vandonk, E., Kilham, S.S., 1990. Temperature effects on silicon-limited and phosphorus-limited growth and competitive interactions among three diatoms. Journal of Phycology 26 (1), 40–50.
Wang P, 2010. Studies on the Formation Mechanism of Diatom Blooms in Hanjiang River from Hydrodynamics and Nutrition (Master's dissertation). Wuhan, China: Huazhong Agricultural University.
Webster, I.T., Sherman, B.S., Bormans, M., Jones, G., 2000. Management strategies for cyanobacterial blooms in an impounded lowland river. River Research and Applications 16 (5), 513–525.
Weckstrom, J., Korhola, A., Blom, T., 1997. Diatoms as quantitative indicators of pH and water temperature in subarctic Fennoscandian lakes. Hydrobiologia 347, 171–184.
Xie, P., 2003. Three-Gorges dam: risk to ancient fish. Science 300 (5623), 1149.
Zhang, Z.S., Huang, X.F., 1991. Research Methods of Freshwater Plankton. Science Press, Beijing.
Zhu, Y.P., Zhang, H.P., Chen, L., Zhao, J.F., 2008. Influence of the South-North water diversion project and the mitigation projects on the water quality of Han river. Science of The Total Environment 406 (1–2), 57–68.