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Effect of filter-feeding fish silver carp on phytoplankton species and size distribution in surface water: A field study in water works

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Abstract

Silver carp were introduced into the pre-sedimentation pond to control excessive phytoplankton in raw water. The effectiveness of the filter-feeding silver carp on phytoplankton control and the effect of silver carp on phytoplankton community were investigated. The results showed that *Microcystis* could be effectively removed by silver carp stocked in the pre-sedimentation pond, and simultaneously, the concentration of single-cell phytoplankton increased obviously. The difference in phytoplankton species and single-cell phytoplankton size between in the water and in the gut of silver carp indicated that phytoplankton smaller than 5 μm, such as *Chamydomonas* and *Platymonas*, were almost not be filtered by silver carp, phytoplankton with the size between 5 and 20 μm could be partly filtered, and large size phytoplankton, mainly colony-forming *Microcystis* could be filtered almost completely. These filter-feeding characteristics directly caused the phytoplankton size distribution biased toward miniaturization. Therefore, this biological treatment using silver carp could be applied only to deal with groups of *Microcystis*-dominated eutrophic water, and was not appropriate in water bodies where single-cell micro phytoplankton were dominant. Especially when silver carp are used in water treatment, a cautious attitude should be taken based on the evaluation of phytoplankton biomass and species structure features in raw water.

Key words: phytoplankton control; silver carp; *Microcystis*; single-cell micro phytoplankton
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Introduction

The omnipresence of excessive growth of phytoplankton caused by continuing eutrophication in surface source water poses increasing problems to drinking water works. The direct algae-related problems in such waters are unpleasant tastes, odors and high treatment cost (Hu and Chiang, 1996; Sugiura et al., 1998; Chow et al., 1999). In addition, the bio-toxins released by some species of cyanobacteria (Codd, 2000; Hoeger et al., 2005; Huang et al., 2007) and some disinfection byproducts formed through the oxidation of phytoplankton cells (Oliver and Shindler, 1980; Graham et al., 1998) also threaten public health.

Besides chemical method (Ma and Liu, 2002; Chen and Yeh, 2005) and physical method (Bare et al., 1975; Borchardt and Omelia, 1961; Babel et al., 2002) for phytoplankton removal in water treatment processes, biological treatment for phytoplankton control in large water body, such as lakes and reservoirs, are also effective (Laws and Weisburd, 1990; Carpenter et al., 1995). The biological treatment of stocking filter-feeding silver carp in eutrophic water body has been widely applied to control excessive phytoplankton and improve water quality in the world (Starling and Rocha, 1990; Domaizon and Dévaux, 1999; Radke and Kahl, 2002; Lu et al., 2002; Ma et al., 2009). Although silver carp can not completely control phytoplankton smaller than 10 μm (Smith, 1989, Vörös et al., 1997), it shows effectiveness in dealing with phytoplankton larger than 10 μm, especially colony-forming cyanobacteria (Starling and Rocha, 1990; Xie and Liu, 2001; Radke and Kahl, 2002). However, the efficiencies of silver carp filtering process for different phytoplankton species, and the dynamic change process of phytoplankton cell size distribution are rarely reported.

In order to control excessive phytoplankton in raw water, silver carp were introduced into the pre-sedimentation pond in a water works, in which the water flow detention time was 5 days. In this study, the effectiveness of the filter-feeding fish silver carp on phytoplankton control and the effect of silver carp on the phytoplankton community were evaluated in a pre-sedimentation pond. The phytoplankton size distributions along the pre-sedimentation pond were also determined.

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1 Materials and methods

1.1 Field site and full-scale facility

The full-scale study was conducted in the pre-sedimentation pond in a water works in Tianjin, China. Source water applied in our test was from Yuqiao Reservoir, the main water source of drinking water works in Tianjin. In the reservoir cyanobacterial bloom was a growing problem due to increasing eutrophication resulting from agricultural and industrial pollution. The reservoir was characterized by summer cyanobacteria blooms (*Microcystis flos-aquae*) from June to October. Besides *Microcystic flos-aquae*, some single cell species such as *Synechocystis*, *Merismopedia*, *Scenedesmus*, and *Cyclotella* were also observed by microscopy in the reservoir water. The characteristics of raw water are listed in Table 1.

Table 1 Raw water quality in summer and autumn

Parameter	Value
Turbidity (NTU)	4–21
pH	7.4–8.4
Total phosphorus (mg/L)	0.02–0.07
COD_{Mn} (mg/L)	2.6–4.6
Phytoplankton (cells/L)	7.2×10^5–6.4×10^7
Chlorophyll *a* (mg/m^3)	2.5–32.5

The pre-sedimentation pond was 200 m × 86 m × 3.5 m (length × width × depth). There were guide walls in the pond (Fig. 1). The inflow was 12,000 m^3/day, and the hydraulic retention time (HRT) was 5 days. The outflow was pumped into the conventional coagulation-sedimentation-filtration treatment unit. Approximately 9000 silver carp were stocked in the pond in May 2005. The average weight was (120 ± 21.8) g, with stocking density 22 g/m^3. In April 2007 the average weight was (355 ± 34.2) g and the density was 67 g/m^3. Very few fish was dead in the experimental period.

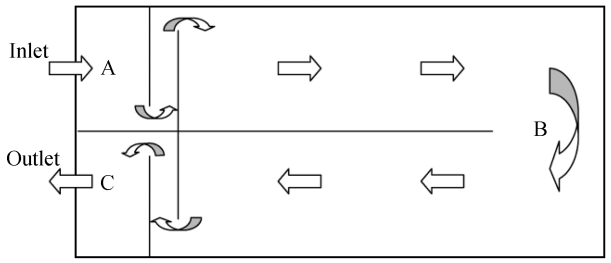

Fig. 1 Sketch of the pre-sedimentation pond. A, B, and C are sampling points.

1.2 Analysis methods

Phytoplankton concentration was determined according to the Chinese standard method (SEPAC, 2002). The size of phytoplankton cell was determined by micro-size device in the microscope (Olympus BX21). The girth of the maximum part was divided to obtain the size of cells. Chlorophyll *a* (Chl-*a*) was analyzed by visible spectrophotometry (754, Shanghai Spectrum Instruments Co., Ltd., China).

Contents in the gut of silver carp were washed into a specimen bottle by 300 mL distilled water. Lugols solution 4 mL (40 g iodine dissolved in 1000 mL aqueous solution containing 60 g potassium iodide) was added. Then the amount and species of phytoplankton were determined. The proportions of various species were obtained.

Permanganate consumption (COD_{Mn}) was determined use acid method according to Chinese standard method (SEPAC, 2002). Turbidity was measured using turbidimeter (2100N, Hach, USA).

2 Results and discussion

2.1 Phytoplankton concentration in inflow and outflow

As shown in Fig. 2, the period of high phytoplankton concentration (> 2.00×10^7 cells/L) was mainly in July and August in 2007, and a small peak emerged at the end of September. The maximum was 6.42×10^7 cells/L on 18 August. It was also found that during the period of high phytoplankton concentration, *Microcystis* was preponderant in the phytoplankton species with the highest ratio 93% (August 15).

The total phytoplankton concentration in outflow was relatively stable (always below 2.60×10^7 cells/L). The phytoplankton in outflow mainly consisted of diatoms and green algae, and *Microcystis* was very few. The dominant species in outflow were *Chlamydomonas*, *Platymonas*, *Scenedesmus*, and *Cyclotella*. This phenomenon was still obvious even when *Microcystis* become the dominant species in inflow in July and August.

2.2 Chlorophyll *a* in inflow and outflow

Chlorophyll is a major photosynthetic pigment in photosynthesis in plants. The primary productive forces can be evaluated by determining the concentration of phytoplankton chlorophyll. Chl-*a* is a photosynthetic pigment that can be found in most of phytoplankton species, therefore, the Chl-*a* concentration can be used to assess phytoplankton biomass (Schlueter et al., 2000), especially when *Microcystis* comprised high proportion of the phytoplankton biomass (Itayama et al., 2008). It was also observed that the high Chl-*a* concentration (> 15 mg/m^3) occurred in July and August in 2007 (Fig. 3). In July and August the water temperature and light intensity increased, that is, environmental conditions became suitable to the growth of cyanbacteria, therefore, the Chl-*a* concentration in inflow had a rapid increase and reached the highest value of 32.55 mg/m^3 on 10 August.

Concentrations of Chl-*a* in outflow were relatively stable, but on the whole, there was an increasing trend from May to September. It was noted that because of the rapid increase of phytoplankton concentration in inflow between 24 July and 15 August, Chl-*a* concentrations in inflow were higher than that in outflow by 30%–40%, while in other periods Chl-*a* concentrations in outflow were always higher than that in inflow. In fact, we found high concentration of green algae and diatoms in outflow

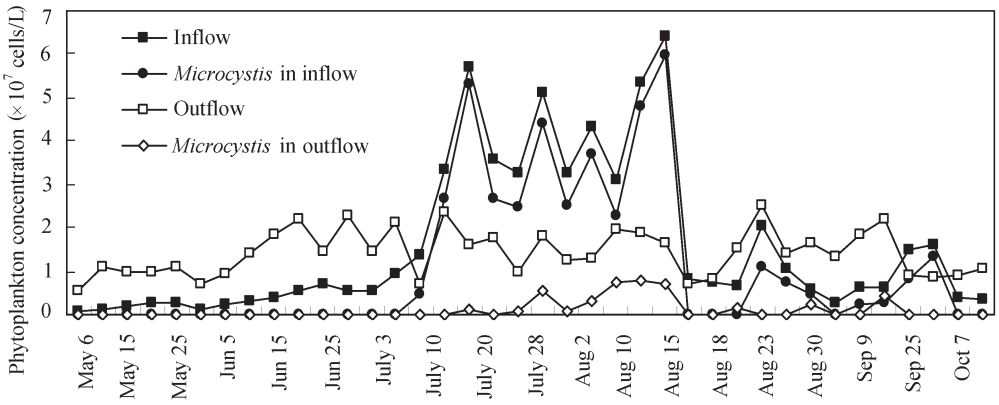

Fig. 2 Concentrations of total phytoplankton and *Microcystis* in inflow and outflow of the pre-sedimentation pond in 2007.

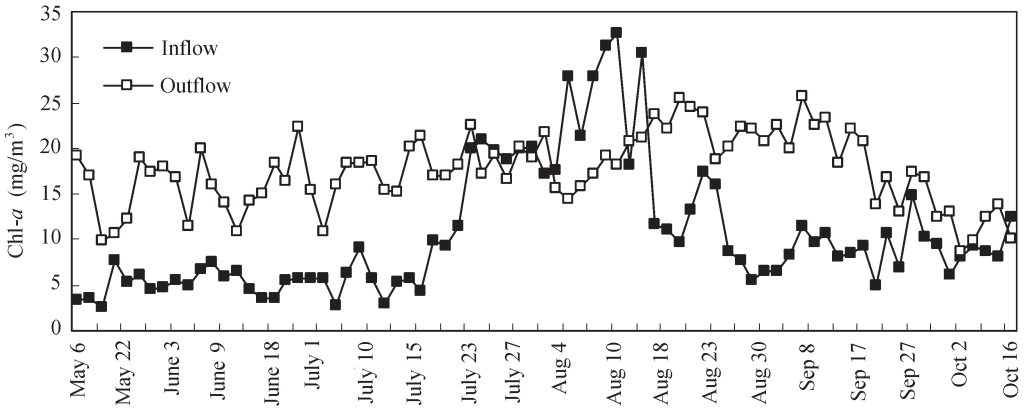

Fig. 3 Concentrations of Chl-*a* in inflow and outflow of the pre-sedimentation pond in 2007.

through microscope determination, which might account for the higher Chl-*a* concentration in outflow. In May and June Chl-*a* had obvious volatility, which may be due to the species alternation between green algae and diatoms in outflow. The respond factor of Chl-*a* for green algae was much higher than it for diatoms and cyanobacteria, thus the relative low density of green algae can result in a higher value of Chl-*a*.

Due to the rapid decrease of *Microcystis* concentration, Chl-*a* concentration in inflow had a dramatic decrease in late August, but the environmental conditions such as water temperature and light intensity were still suitable for the growth of green algae and diatoms.

2.3 Phytoplankton in pre-sedimentation and in gut of silver carp

At stated time fishing with cast net was conducted for the phytoplankton analysis in the gut of silver carp. The proportions of major algae species in inflow, outflow and the gut of silver carp, and the removal percentage of major phytoplankton species during June to September are shown in Table 2.

In June, the dominant species in inflow were mainly *Platymonas*, *Chamydomonas*, *Staurastrum*, *Cyclotella*. In outflow, the proportions of other advantages phytoplankton such as *Platymonas*, *Staurastrum*, *Cyclotella*, were reduced, but the proportion of *Chamydomonas* rose to 55.5%. The proportion of *Chamydomonas* in the gut of silver carp was 0.40%, which indicated that silver carp can not effectively filter *Chamydomonas* (removal percentage was –141.67%), consequently, the increase of *Chamydomonas* may result in a significant increase of Chl-*a* in outflow.

In July and August, *Microcystis* appeared in inflow, and became the absolute dominant species, with a very high proportion of 76.68% and 52.41% for the samples collected on 17 July, and 23 August, respectively. Most of green algae and diatoms had very low concentrations, and their proportions in water dropped significantly. It was noteworthy that in outflow very low concentrations of *Microcystis* were detected, and the removal percentage were as high as 100% and 94.00% for the samples collected on 20 July, and 23 August, respectively. Meanwhile the majority of diatoms and green algae, such as *Staurastrum*, *Platymonas*, *Achnanthes* and *Synedra*, were increased significantly, and corresponding removals were also negative. For the sampls collected on 20 July and 24 August, the proportions of *Microcystis* in the gut of silver carp also had remarkable increase to 83.2% and 61.41%, respectively, which were slightly higher than the proportion of water, while the proportion of green algae in the gut of silver carp was very low. This result indicates that *Microcystis* can be filtered effectively by silver carp, and it has a contribution to the high *Microcystis* removal in the pound. Similar conclusion has been also reported previously (Xie and Liu, 2001; Radke and Kahl, 2002; Starling and Rocha, 1990; Starling, 1993), but those studies were conducted in lakes, reservoirs or enclosures, which have long HRT and

Table 2 Proportions, concentrations and removal percentage of major algae species in inflow, outflow, and in the gut of silver carp in four months

Algae	27 Jun					21 Jun	17 Jul					20 Jul
	Inflow		Outflow		Removal (%)	Prop in gut (%)	Inflow		Outflow		Removal (%)	Prop in gut (%)
	Prop (%)	Conc ($\times 10^4$ cells/L)	Prop (%)	Conc ($\times 10^4$ cells/L)			Prop (%)	Conc ($\times 10^4$ cells/L)	Prop (%)	Conc ($\times 10^4$ cells/L)		
Chlorophyta												
Chamydomonas	22.80	208.87	55.50	504.76	–141.67	0.40	4.55	54.39	14.29	115.31	–112	0.08
Staurastrum	13.78	126.19	12.44	113.14	+10.34	13.89	0.73	8.70	36.66	295.90	>–1000	1.81
Scenedesmus	5.46	50.04	2.39	21.76	+56.52	7.94	2.37	28.28	4.31	34.81	–23.08	2.15
Platymonas	27.79	254.56	13.16	119.66	+52.99	–	1.82	21.76	15.90	128.37	–490	–
Cyanophyta												
Microcystis	–	–	–	–	–	–	76.68	915.97	–	–	+100	83.2
Bacillariophyta												
Cyclotella	10.69	97.91	2.39	21.76	+77.78	11.90	3.64	43.51	2.96	23.93	+45.00	0.50
Achnanthes	1.19	10.88	2.39	21.76	–100	16.27	0.18	2.18	3.50	28.28	>–1000	0.37
Synedra	1.66	15.23	0.96	8.70	+42.86	3.57	0.36	4.35	5.93	47.87	>–1000	0.27

Algae	23 Aug					24 Aug	23 Sep					26 Sep
	Inflow		Outflow		Removal (%)	Prop in gut (%)	Inflow		Outflow		Removal (%)	Prop in gut (%)
	Prop (%)	Conc ($\times 10^4$ cells/L)	Prop (%)	Conc ($\times 10^4$ cells/L)			Prop (%)	Conc ($\times 10^4$ cells/L)	Prop (%)	Conc ($\times 10^4$ cells/L)		
Chlorophyta												
Chamydomonas	1.68	34.81	5.92	115.31	–231.25	0.07	2.08	6.53	35.69	439.49	>–1000	–
Staurastrum	0.10	2.18	11.51	224.10	>–1000	6.00	1.39	4.35	7.77	95.73	>–1000	1.06
Scenedesmus	6.71	139.25	3.35	65.27	+53.13	16.31	13.19	41.34	4.42	54.39	–31.58	1.62
Platymonas	–	–	10.17	197.99	> –1000	–	0.69	2.18	20.85	256.73	>–1000	–
Cyanophyta												
Microcystis	52.41	1087.85	3.35	65.27	+94.00	61.41	27.08	84.85	5.3	65.27	+23.08	47.87
Bacillariophyta												
Cyclotella	0.94	19.58	1.01	19.58	0	5.37	20.83	65.27	2.12	26.11	+60	2.94
Achnanthes	0.94	19.58	1.34	26.11	–33.33	1.27	0.69	2.18	7.60	93.56	>–1000	0.89
Synedra	15.93	330.71	55.42	1079.15	–226.32	1.92	1.39	4.35	7.42	91.38	>–1000	0.21

Prop: proportion; Conc: concentration; –: not calculated because values were below detection limit.

relative high nutrients concentrations, so that the micro phytoplankton biomass cannot be effectively filtered by silver carp and have a relative high growth potential, except colony-forming *Microcystis*. However, *Microcystis* mainly exists in colony-forming mode, and its size is 50–300 μm, which is much bigger than the silver carp gill rakers aperture. It means that *Microcystis* can be easily filtered by silver carp. The low and negative removal of green algae and diatoms can be explained by the size-selective filtering and taxon-specific digestion of phytoplankton by silver carp (Vörös et al., 1997) and the competition of plankton algae (Titman, 1976). During 20 July and 20 August, the significant reduce of the total phytoplankton concentration was mainly due to the decrease of *Microcystis*, while the obvious increase in the concentrations of green algae and diatoms was probably caused by the relatively steady increase of Chl-*a* in outflow.

After 20 August, phytoplankton concentrations in inflow were always below 2.0×10^7 cells/L, and the dominant species were *Microcystis*, *Cyclotella*, and *Scenedesmus*. But their concentrations were much lower in September than in August. However, the dominant species in outflow had changed to *Chamydomonas* and *Platymonas*, with proportions of 35.69% and 20.85%, respectively. In fact, environmental conditions were still suitable for the growth of the two micro phytoplankton, and silver carp could not filter these smaller cells (< 5 μm). Therefore, even they had relatively low proportions in inflow, they could easily become dominant species in outflow.

Figure 4 shows the percentage of single-cell phytoplankton with different size scopes in inflow and the gut of silver carp. It can be found that the proportion of the phytoplankton with size < 5 μm in the gut of silver carp is less than that in inflow; there is a obvious increase for the phytoplankton with size scale 10–20 μm in the gut of silver carp, and the proportions of the phytoplankton with size scale 5–10 μm are relatively stable both in water and in the gut of silver carp. These phenomena indicate that phytoplankton smaller than 5 μm can not be filtered by silver carp, and phytoplankton with the size between 5 and 20 μm can be partly filtered.

2.4 Single-cell algae size distribution in pre-sedimentation pond

Figure 5 shows the size distribution of single-cell phytoplankton in water samples collected at points A, B, and C (underwater 0.7 m depth) in the pre-sedimentation pond during June to September. The single-cell algae mainly included green algae, diatoms, and some single-cell cyanobacteria. It was found that in point A (the inflow) the proportions of cells with size 5.0–7.5 μm had the highest value, which were over 40% in four months. In point B, the proportions of cells with size 2.5–5.0 μm had obvious increase. In point C (the outflow) the proportions of cells with size 2.5–5.0 μm had increased more than 50%, and the phytoplankton with size 2.5–5.0

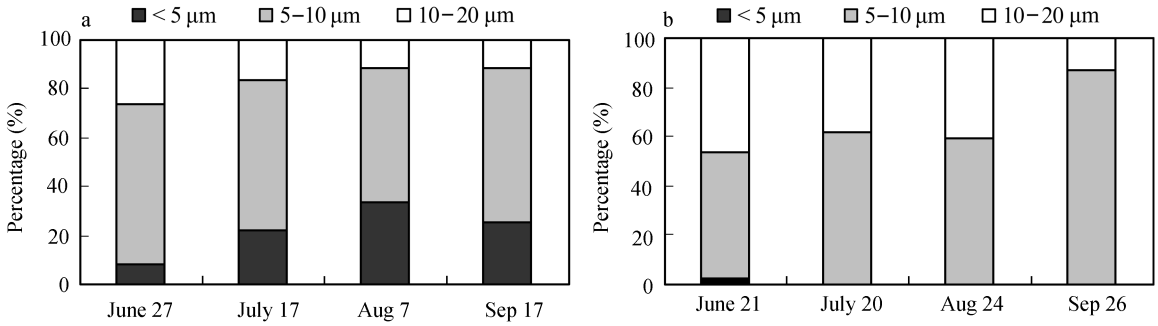

Fig. 4 Percentages of single-cell phytoplankton with different size scopes in inflow (a) and the gut of silver carp (b).

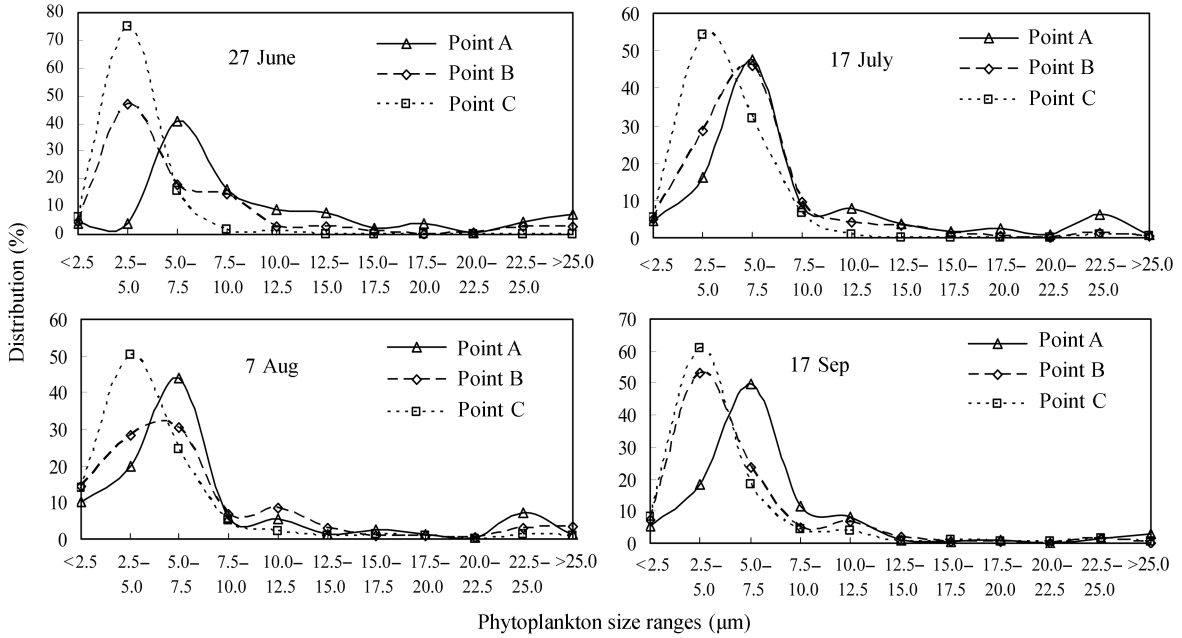

Fig. 5 Single-cell phytoplankton size distribution and simulating curve in sampling points A, B, and C of the pre-sedimentation pond.

μm also became the dominant species in the outflow of pre-sedimentation pond. In order to obtain an intuitionistic and comprehensive evaluation, we made a simulating curve distribution (Fig. 5). It indicated that through the pre-sedimentation pond the dominant phytoplankton size scale in raw water had changed from 5.0–7.5 μm to 2.5–5.0 μm, and the proportion of the phytoplankton with size scale 2.5–5.0 μm in outflow was more dominant. At the same time the proportions of the phytoplankton larger than 5.0 μm decreased. Overall, the phytoplankton size distribution had a trend biased toward miniaturization.

The changes in phytoplankton community and amount can be explained using the ecological knowledge. Large size scale phytoplankton, such as colony-forming *Microcystis*, can be filtered effectively by silver carp, but single-cell micro phytoplankton can avoid to be filtered; at the same time, due to the lack of large size scale phytoplankton and colony-forming *Microcystis*, nutrition in water can be utilized further by single-cell micro phytoplankton, thereby single-cell micro phytoplankton obtain greater growth potential. It can be conducted that the filter-feeding characteristics of silver carp may directly cause the phytoplankton size distribution biased toward miniaturization. This conclusion well proves that silver carp can reduce the phytoplankton biomass greater than 5.0 μm (Starling, 1993; Ma et al., 2009), but increase the phytoplankton biomass less than 5.0 μm, which results in an increase of the Chl-*a* concentration. This conclusion has a little difference from the conventional view that zooplankton biomass are reduced by silver carp grazing, and thus silver carp stocking indirectly accelerate the increase of nanoplankton biomass (Spataru and Gophen, 1985; Smith, 1985).

2.5 Turbidity and COD_{Mn} in inflow and outflow

Turbidity and COD_{Mn} were determined to evaluate the potential effect of the behavior and metabolism of silver carp on water quality. Figure 6a shows that turbidity in inflow has an obvious change due to the fluctuant density of suspended substance such as phytoplankton and inorganic particulate matter in inflow. The turbidity of outflow was relative stable, with the scale of 2–7 NTU, and in summer and autumn had much higher value due to the increase of phytoplankton biomass. It means that the behavior of the filter-feeding fish such as stirring the substrate sludge has little influence on the turbidity of outflow. There may be two reasons: (1) silver carp is a filter-feeding fish that acts in upper water layer in most of time; (2)

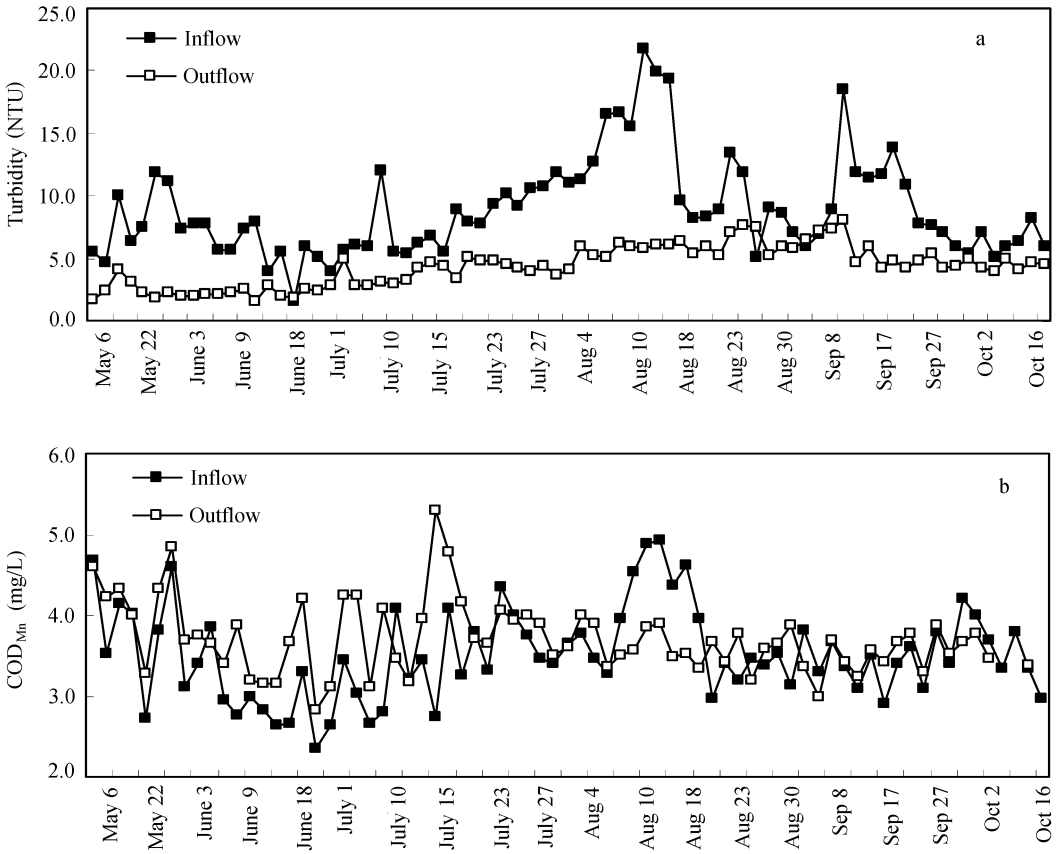

Fig. 6 Variation of turbidity (a) and COD_{Mn} (b) in the inflow and outflow of pre-sedimentation pond in 2007.

the pre-sedimentation pond also acts as a horizontal flow sedimentation tank, thereby suspended particulate matter and fecal pellets can be easily removed by sedimentation. Considering that silver carp in the pre-sedimentation pond may increase the concentration of dissolved matter due to metabolism, COD_{Mn} is used to assess the potential effect on water quality (Fig. 6b). It was found that the stocking of silver carp in the pre-sedimentation pond can not lead a remarkable increase in COD_{Mn} of outflow. Although noticeable changes of water quality caused by silver carp have not been observed in this study, we should still pay more attention to some potential problems, including long-term effect on water quality.

According to the above mentioned problems, the toxicology is also another key issue. When aquatic organism, silver carp, is used in raw water, its metabolites may affect water quality. Moreover, the inorganic or organic pollutants in raw water and some bio-toxin released from *Microcystic* are harm to silver carp and then affect the effectiveness of this biological treatment. Therefore, the further study in the toxicology and the security of water quality is needed.

The removal of phytoplankton particles removal is one of the main objectives in drinking water treatment, especially in area where eutrophic water is used as source water. Due to its high removal efficiency for colony-forming *Microcystis*, low cost, and environmental friendly manner, silver carp shows a great prospect in pre-treating *Microcystis*-dominated eutrophic water. However, it will lead to an increase of single-cell micro phytoplankton. Therefore, a cautious attitude should be taken when it is used as a phytoplankton control medium in eutrophic water body, especially when silver carp are used as raw water pre-treating measure in water works. Further research is needed on the effect of this alteration of phytoplankton community and size distribution on the following conventional coagulation-sedimentation-filtration treatment processes.

3 Conclusions

Silver carp have a significant effect on the phytoplankton species and size distribution in raw water. The effect mainly depends on silver carp filter-feeding characteristic. Silver carp can effectively filer large size scale phytoplankton and colony-forming *Microcystis*, but cannot effectively filter single-cell micro phytoplankton (mainly *Chamydomonas* and *Platymonas*). As a result, single-cell micro phytoplankton obtains greater growth potential which directly causes the phytoplankton size distribution biased toward miniaturization. Therefore, this biological treatment using silver carp shows a great prospect in pre-treating *Microcystis* dominated eutrophic water, but is not appropriate in some water bodies where single-cell micro phytoplankton is dominant.

Acknowledgments

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