Comparison of invertebrate removal by traditional-BAC and pre-BAC treatment processes: verification in a full-scale drinking water treatment plant
Zhiling Wu and Hongbin Chen

ABSTRACT
Invertebrate removal by traditional biological activated carbon (tra-BAC) and pre-BAC treatment processes was investigated in a full-scale water treatment plant. The results showed that invertebrate reproduction occurred in both BAC filters, but the invertebrate abundance in the finished water processed by tra-BAC was about 15 times greater than that processed using the pre-BAC process. In the pre-BAC process, the sand filter was placed after the BAC filter, and sand filtration removed most of the invertebrates, with an average removal efficiency of 91.1%. However, the pre-BAC filter, which was positioned behind the sedimentation tank, needed to be backwashed more frequently than the tra-BAC filter because of the high turbidity of the inlet water. The frequent backwashing reduced the biomass on the activated carbon and decreased the invertebrate reproductive rate. The results of this study are helpful for evaluating the pre-BAC treatment process in drinking water treatment plants.

Key words | drinking water, invertebrate removal, pre-BAC treatment process, traditional BAC treatment process

INTRODUCTION
Due to the ongoing deterioration in raw water quality and increasing concerns regarding drinking water safety, the conventional water treatment process (coagulation, sedimentation, filtration, and disinfection) can barely meet the demand for drinking water in many regions of China (Gao et al. 2010; Guo et al. 2016). The biological activated carbon (BAC) treatment process has been increasingly used as an advanced water treatment process in China since 1985 (Dong et al. 2015).

In a traditional-BAC (tra-BAC) treatment process, a combination of ozonation and BAC filtration is normally conducted near the end of the conventional treatment process, between sand filtration and disinfection (Han et al. 2013). Utilizing adsorption and biodegradation, ozonation and BAC filtration have been shown to be efficient at removing tastes and odors, biodegradable dissolved organic carbon, microcystin-LR, and disinfection by-products (DBPs) precursors (Yapsakli & Cecen 2010; Yang et al. 2011; Kim et al. 2014; Zhang et al. 2015). However, disadvantages of the tra-BAC treatment process have been discovered through operational experience. One of the major disadvantages of tra-BAC is invertebrate leakage through the BAC filter (Schreiber et al. 1997). The porous structure of the activated carbon provides an ideal habitat for the growth of microorganisms, including bacteria and lower invertebrates (Van Lieverloo et al. 2012). The invertebrates that grow on the activated carbon can penetrate the carbon layer. As previous research has shown, the invertebrate abundance in the BAC filtrate can be more than 10 times that of the inflow (Li et al. 2010; Wang et al. 2014). Existing disinfection processes can inactivate bacteria efficiently (Voukkali & Zorpas 2014). However, based on our previous research, existing
disinfection measures cannot inactivate invertebrates completely (Zhu 2014). In addition, because the BAC filter is the last filtration barrier in the tra-BAC treatment process, some living invertebrates can enter the water supply. There is no direct evidence that these invertebrates cause harm to human health. However, large invertebrates may cause panic among consumers if they appear in drinking water (Lin et al. 2007, 2010, 2012). Moreover, some invertebrates may act as vectors and hosts of waterborne pathogens (Locas et al. 2007; Bichai et al. 2010, 2014).

To optimize the tra-BAC treatment process, the pre-BAC treatment process was developed and applied. In pre-BAC treatment processes, the ozonation and BAC filtration section is placed between sedimentation and sand filtration. Sand filtration was used in a pilot-scale process to remove invertebrates in our previous study (Chen 2012). The results showed that sand filtration removed 48.3–82.1% of invertebrates. Granular activated carbon (GAC) with the added sand beds was also shown to be an efficient approach (Yin et al. 2012). Therefore, in the pre-BAC process, invertebrates that pass through the BAC filter may be removed by the downstream sand filter. However, the current literature lacks studies comparing invertebrate removal in the tra-BAC and pre-BAC treatment processes under the same operational conditions.

In the present study, both the tra-BAC and pre-BAC processes were used at full scale in Drinking Water Treatment Plant A (DWTP A), located in the lower reaches of the Yangtze River. The objective of this study was to evaluate the invertebrate removal of the tra-BAC and pre-BAC treatment processes under the same operational conditions. The results of this study will be meaningful for invertebrate control in DWTPs and the comprehensive evaluation of the tra-BAC and pre-BAC processes.

METHODS AND MATERIALS

Drinking water treatment plant A

DWTP A uses polluted river water as source water. The raw water quality is Class IV or worse, per the Environmental Quality Standards for Surface Water (GB 3838-2002). During this study, the turbidity ranged from 10 to 56 NTU. The raw water had high chroma and a pronounced earthy taste. The ammonia nitrogen level fluctuated greatly, with high concentrations occurring in winter and relatively low concentrations in summer. The chemical oxygen content was constant, at around 5.5 mg/L.

A flow diagram showing the tra-BAC and pre-BAC processes is shown in Figure 1. Most of the operating parameters were the same in both processes. The main parameters are summarized in Table 1.

Sampling and analysis

Water samples were collected monthly at DWTP A from May 2015 to April 2016, from the following locations: inlet water of BAC filter 1 (site 1), filtrate of BAC filter 1 (site 2), finished water 1 (site 3), inlet water of BAC filter 2 (site 4), filtrate of BAC filter 2 (site 5), filtrate of sand filter 2 (site 6), and finished water 2 (site 7) (Figure 1). To avoid the effect of backwashing, the sampling time was set at the
middle of the operation cycle of the BAC filters. Water samples were taken through a plankton net (10 μm mesh size; Hydro-Bios GmbH, Kiel, Germany), and approximately 300 L water was filtered to collect invertebrates (Zhu et al. 2014). Activated carbon particles were sampled from the BAC filters using a stainless steel sampler, and preserved in sterile plastic pipes (Wang et al. 2014).

**Invertebrate analysis**

For invertebrate enumeration, samples were transferred to a counting plate and allowed to settle for 10 min. The entire counting chamber was scanned, and the invertebrates were counted under a microscope (BX-51, Olympus, Japan).

**Scanning electron microscopy (SEM)**

The activated carbon samples from the BAC filters were photographed with an FEI Nova Nano SEM 450 to observe the attached microorganisms. The samples were fixed overnight in 2.5% glutaraldehyde solution. After fixation, the samples were passed through an alcohol series for dehydration. They were then dried in a vacuum freeze drier (TF-FD-1).

**Water quality parameters**

Levels of turbidity were directly determined by a portable turbidimeter (2100N, HACH, USA). Chroma, odor, ammonia nitrogen and chemical oxygen demand by manganese (CODMn) were analyzed according to the state standard method (Ministry of Environmental Protection of the People’s Republic of China 2002).

**Statistical analyses**

The annual mean abundance of invertebrates in the inlet water and filtrate of the tra-BAC and pre-BAC filters were calculated as arithmetic means with standard deviation (SD). All the figures were drawn with Origin 8.1.

**RESULTS AND DISCUSSION**

**Comparison of invertebrate composition in the inlet water and filtrate of BAC filters**

The BAC filter is important for invertebrate reproduction (Wang et al. 2014). To check for invertebrate growth in the BAC filters, samples were taken for comparison (Figure 2). The invertebrate abundance in a year was averaged and is indicated by error bars. In the tra-BAC treatment process, the average invertebrate abundance found in the inlet water was 2,846 ± 2,297 ind/m³. The average invertebrate abundance in the tra-BAC filtrate was 3.4 times higher (9,624 ± 6,534 ind/m³). In the pre-BAC treatment process, the average invertebrate abundance in the inlet water was 5,086 ± 2,573 ind/m³, and the average abundance in the

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### Table 1 | Operating parameters of the tra-BAC/pre-BAC treatment process

<table>
<thead>
<tr>
<th>Operating parameter</th>
<th>Units</th>
<th>Pre-BAC</th>
<th>Tra-BAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-oxidation dosage</td>
<td>mg/L</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Sand size</td>
<td>mm</td>
<td>0.8–1.2</td>
<td>0.8–1.2</td>
</tr>
<tr>
<td>Height of sand</td>
<td>m</td>
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<td>1.2</td>
</tr>
<tr>
<td>Filtering velocity of sand filter</td>
<td>m/h</td>
<td>7</td>
<td>7.9</td>
</tr>
<tr>
<td>Main ozone</td>
<td>mg/L</td>
<td>0.5–0.8</td>
<td>0.5–0.8</td>
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<tr>
<td>GAC effective size (d₁₀)</td>
<td>mm</td>
<td>0.86</td>
<td>0.63</td>
</tr>
<tr>
<td>GAC depth</td>
<td>m</td>
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</tr>
<tr>
<td>Empty bed contact time of GAC filter</td>
<td>min</td>
<td>16.9</td>
<td>16.9</td>
</tr>
<tr>
<td>Filtering velocity of GAC filter</td>
<td>m/h</td>
<td>8.3</td>
<td>8.3</td>
</tr>
<tr>
<td>GAC operation cycle</td>
<td>h</td>
<td>72–84</td>
<td>108–120</td>
</tr>
<tr>
<td>Residual chlorine</td>
<td>mg/L</td>
<td>1.6–1.7</td>
<td>1.6–1.7</td>
</tr>
</tbody>
</table>

GAC, granular activated carbon.

**Figure 2 | Comparison of mean abundances of invertebrates in the inlet waters and filtrates of the BAC filters from May 2015 to April 2016.**
filtrate was 1.5 times higher (7,669 ± 5,282 ind/m³). The invertebrate abundances in both BAC filtrates were greater than those of their respective inlet waters, confirming that invertebrate growth occurred in both BAC filters. In addition, the average invertebrate abundance in the inlet water of the pre-BAC filter was higher than that of tra-BAC, but in the filtrates, the average invertebrate abundance in the pre-BAC filter was lower than that of tra-BAC. This indicates that the invertebrate reproductive rate in the pre-BAC filter was lower than that in the tra-BAC filter. In the pre-BAC treatment process, the BAC filter was installed after the sedimentation step. The turbidity of the settling pond effluent was no less than 0.4–0.5 NTU, whereas the turbidity of the inlet water of the tra-BAC filter was only around 0.1 NTU. Thus, the pre-BAC filter was more easily clogged. Consequently, backwashing every 72–84 h is necessary for the stable operation of the pre-BAC filter. The tra-BAC filter requires backwashing every 108–120 h. Previous research done by our team has shown that the invertebrate abundance increased with operating time after 24 h running of the BAC filter (Zhu et al. 2014). Therefore, the reduced period between backwashes may reduce invertebrate multiplication. A 46% reduction in invertebrate abundance was recorded after backwashing. Hence, increased backwashing frequency may increase invertebrate runoff.

The overall changes in the invertebrate output with water temperature were investigated in the two inlet and filtrate waters (Figure 3). During sampling, the water temperature ranged between 7 °C and 29.8 °C. Most samples were taken at temperatures above 15 °C. The annual mean temperature was 18.2 °C. The seasonal changes in the invertebrate abundance of the BAC filtrates were considerably larger than those of the inlet waters. In the tra-BAC process, the invertebrate abundance was higher when the water temperature was above 15 °C, reaching a maximum of 8,450 ind/m³ and 20,705 ind/m³ in the inlet water and BAC filtrate, respectively. At lower water temperatures, the invertebrate abundance ranged from 500–1,150 ind/m³ and 1,161–4,313 ind/m³ in the inlet water and BAC filtrate, respectively. At low temperatures, the concentrations of organic species were comparatively low, and the biomass decreased; so food for the invertebrates was limited; Meanwhile, the growth and reproduction of most invertebrates were also limited (Zhu et al. 2014). In the pre-BAC process, the invertebrate abundance exhibited the same variation as that in the tra-BAC process. At temperatures above 15 °C the invertebrate abundance was 2,583–9,565 ind/m³ and 3,710–15,067 ind/m³ in the inlet water and BAC filtrate, respectively. At lower temperatures, the invertebrate abundance was 2,382–3,083 ind/m³ and 896–3,070 ind/m³, respectively.

Figure 3 | Seasonal changes in invertebrate abundances in the inlet waters and BAC filtrates from May 2015 to April 2016.
During the survey period, seven kinds of invertebrates were observed in the BAC filters. These included rotifers, nematodes, crustaceans, oligochaetes, gastrotricha, turbellarians and tardigrades. The dominant groups were rotifers, nematodes, and crustaceans in both the tra-BAC and pre-BAC filters, accounting for more than 98% of the total invertebrates. Zhu (2014) provided some descriptions of the characteristics of these invertebrates. Changes in the frequency of the dominant groups were detected during the study period (Figure 4). In the tra-BAC filter, rotifers accounted for 48.6–88.9% and 82.0–99.7%, nematodes for 4.3–38.9% and 0.17–12.9%, and crustaceans for 0–27.1% and 0–8.9%, in the inlet water and the filtrate, respectively. In the pre-BAC filter, rotifers were also the dominant group, accounting for 36.6–85.7% and 63.3–93.1% in the inlet water and the filtrate, respectively. However, crustaceans were the second most prevalent group (7.1–58.5% and 2.5–31.6%), followed by nematodes (4.5–29.0% and 2.7–8.7%). There was a relatively large difference between the proportions of crustacea in the tra-BAC and pre-BAC filters. The inlet water of the pre-BAC filter was the effluent of the sedimentation tank. Based on previous research (Liu et al. 2007), the removal efficiency of crustaceans by coagulation and sedimentation was limited, because crustaceans are planktonic microorganisms and their bodies do not adhere well to alum grains. However, because of their relatively large bodies, crustaceans can be removed effectively by sand filtration (Zhu 2014). Hence, the proportion of crustaceans was greater in the pre-BAC filter than in the tra-BAC filter.

**Biomass formed in the tra-BAC and pre-BAC filters**

The number of invertebrates present in the BAC filters was an expression of the accumulation of biomass within the BAC filters. Previous research concerning a down-flow BAC process (Han et al. 2013) found that the biomass on the activated carbon decreased with increasing BAC filter depth, and the highest quantity of biomass was usually found in the upper layer of the BAC filter. In this research, down-flow BAC filters were used, so activated carbon from the upper layers was collected to analyze the biomass.

SEM was used to observe the microorganisms on the activated carbon, and to evaluate the morphological characteristics of the biofilm to intuitively compare the amount of the biomass. Figure 5 shows the SEM images of the activated carbon. The results show colonies of microorganisms in both BAC filters. The biofilm in the tra-BAC filter was very thick, and the microorganisms covered almost the entire area of the activated carbon. However, in
the pre-BAC filter the biofilm was sporadically distributed on the activated carbon, and there were many regions on the surface of the activated carbon devoid of microorganisms. More microorganisms were observed in the tra-BAC filter than in the pre-BAC filter, which suggested that the biomass of the tra-BAC filter was greater than that of the pre-BAC filter. The difference in the quantity of microorganisms was attributed to the frequent backwashing of the pre-BAC filter. This backwashing destroyed the biofilm, and increased the runoff of the microorganisms.

The SEM results showed that the tra-BAC filter contained more microorganisms than the pre-BAC filter. These microorganisms included various bacteria, algae, and fungi (Yang et al. 2011). All of these microorganisms can be food for invertebrates. A larger biomass meant more food for the invertebrates. Hence, this may also explain why the invertebrate reproductive rate in the pre-BAC filter was lower than that in the tra-BAC filter.

Comparison of invertebrate compositions in the finished water of the BAC treatment processes

To determine the invertebrate compositions in the finished water, samples were taken for comparison (Figure 6). In the tra-BAC process, the invertebrate abundance in the finished water was 1,523–38,442 ind/m³, with an annual average abundance of 14,648 ind/m³. In the pre-BAC process, the invertebrate abundance in the finished water was 180–2,200 ind/m³, with an annual average abundance of 952 ind/m³. The invertebrate abundance in the finished water of the tra-BAC process was around 15 times higher than that of the pre-BAC process. In the tra-BAC process, the BAC filter was the last filtration barrier, so the invertebrates on the filter pass directly into the finished water. However, in the pre-BAC process, a sand filter was placed after the BAC filter, which removed a significant proportion of the invertebrates.

During the survey period, rotifers, nematodes, crustaceans, and tardigrades were observed in the finished water of the two BAC processes. The dominant groups were rotifers, nematodes, and crustaceans, accounting for more than 99% of the total invertebrates. Changes in the frequency of the dominant groups were detected (Figure 7). In
the tra-BAC process, rotifers were the most common group, averaging 87.8% of the total invertebrates, followed by nematodes (7.9%) and crustaceans (4.3%). However, in the pre-BAC process, nematodes were the most common, averaging 54.7%, followed by rotifers (41.9%) and crustaceans (3.3%). Comparing Figure 4(b) and 4(d), the invertebrate composition in the finished water of the tra-BAC process was similar to that of the BAC filtrate. However, in the pre-BAC process, nematodes became the dominant species in the finished water. This difference arose because of the different removal efficiencies of the sand filtration in the pre-BAC process for rotifers and nematodes, which is briefly discussed in the next section.

Removal efficiency of invertebrates by sand filtration in pre-BAC processes

As shown in Figure 8(a), the total invertebrate abundance was 896–15,067 ind/m³ in the inlet water of the sand filter, which was consistently reduced to <1,000 ind/m³ in the filtrate. Thus, the total invertebrate removal efficiency of the sand filter was found to be at least 75.0%, with an annual average removal rate of 91.1 ± 6.5%. These results show that, in the pre-BAC process, the sand filter demonstrated the efficient and reliable removal of invertebrates.

The removal efficiency of rotifers by sand filtration showed a similar variation to that of total invertebrates, 78.3–98.8% with an annual average removal efficiency of 93.4%. The rotifer abundance in the inlet water of the sand filter was 644–13,493 ind/m³, while that in the filtrate was 24–519 ind/m³. However, the removal efficiency of nematodes was −33.1–74.3%, with an annual average removal efficiency of 21.8%. The removal efficiencies of nematodes fluctuated greatly during the study period. In some samples, the nematode abundance in the sand filtrate was higher than that in the inlet water. The nematode abundance in the inlet water was 69–790 ind/m³, while that in the filter was 81–494 ind/m³. The sand filter could not efficiently remove nematodes, which may be because of their slender body shape and strong penetration ability.

Comparison of COD$_{\text{Mn}}$ in the finished water of the BAC treatment processes

In this study, COD$_{\text{Mn}}$ was chosen to indicate the organic matter removal of the processes, because COD$_{\text{Mn}}$ is the surrogate parameter of organic matter in drinking water in the latest national standard (GB5749-2006) of China (Han et al. 2015). Figure 9 shows the changes of COD$_{\text{Mn}}$ in the finished water of the BAC treatment processes from May 2015 to April 2016.
In the tra-BAC process, the COD\textsubscript{Mn} concentration in the finished water was 1.72–2.26 mg/L, with an annual average concentration of 1.96 mg/L. In the pre-BAC process, the COD\textsubscript{Mn} concentration in the finished water was 1.92–2.40 mg/L, with an annual average concentration of 2.13 mg/L. The COD\textsubscript{Mn} concentration in the finished water of the tra-BAC process was lower than that of the pre-BAC process. The results implied that the tra-BAC process had better removal efficiency of organic matters than the pre-BAC process. As mentioned above, frequent backwashing of the pre-BAC filter reduced the biomass on the activated carbon, which affected the organic removal efficiency of the pre-BAC process.

CONCLUSIONS

In the tra-BAC process, the invertebrate abundance in the finished water was about 15 times higher than in the pre-BAC process. Sand filtration was placed after the BAC filter in the pre-BAC process, which removes most of the invertebrates with an average removal efficiency of 91.1%. It can be concluded that the pre-BAC process could effectively control the invertebrates entering the drinking water supply. However, frequent backwashing of the pre-BAC filter reduced the biomass on the activated carbon, which affected the organic removal efficiency of the pre-BAC process. As only the COD\textsubscript{Mn} concentrations in the finished water of the two processes were compared in this study, further comparison of the organics removal should be done, including the precursors of DBPs, taste-and-odor, and cyanotoxins, for the comprehensive evaluation of the tra-BAC and pre-BAC processes. And for the future application of the pre-BAC process, the up-flow BAC filter is suggested to replace the down-flow BAC filter, which may solve the clogging problem of the BAC filter in this study.

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