Does the recycling of waste streams from drinking water treatment plants worsen the quality of finished water? A case assessment in China
Zhiquan Liu, Yongpeng Xu, Xuewei Yang, Rui Huang, Qihao Zhou and Fuyi Cui

ABSTRACT
The overall purpose was to assess the feasibilities of recycling filter backwash water (FBWW) and combined filter backwash water (CFBWW) in a drinking water treatment plant in south China. The variations of regular water-quality indexes, metal indexes (Al, Mn and Cd), polyacrylamide and disinfection by-product indexes (trihalomethanes and their formation potentials) along with the treatment and the recycling processes were monitored. Results showed the recycling procedure caused increases of turbidity, total solids, ammonia nitrogen (NH₃-N), permanganate index (CODMn), and dissolved organic carbon, Al, Mn and Cd concentrations in a mixture of raw water and FBWW or CFBWW compared to those in raw water. However, the recycling procedure had negligible impacts on the qualities of settled water and filtered water because most of the contaminants could be effectively removed by the conventional water treatment process. Although recycling did cause slight increases of NH₃-N and CODMn levels in settled water and filtered water, the quality of finished water always conformed to Chinese standards for drinking water quality according to the surveyed indexes in the present study. Thus, it is appropriate to recycle waste streams in water-stressed areas if the source water is well managed and the water treatment processes are carefully conducted.

Key words | combined filter backwash water (CFBWW), filter backwash water (FBWW), wastewater recycle, water quality

INTRODUCTION
Drinking water treatment plants (DWTPs) generate waste streams in large quantities, reaching up to 10% of the plant production (Cornwell & Lee 1994; Loret et al. 2015). This waste stream is composed mainly of filter backwash water (FBWW), sludge thickener overflow and dewatering liquid wastes. It is usually discharged directly into nearby rivers or lakes or into the waste-water network for further treatment. In fact, it is quite worthwhile, from economic and environmental perspectives, to recycle water streams, as this can improve the utilized efficiency of water resources and reduce the discharged amount of waste water. However, solving drinking water challenges by recycling can only be envisaged if the quality of finished water and the safety of the recycling procedure can be guaranteed (Gottfried et al. 2008; Wang et al. 2012; Loret et al. 2013).

The benefits and risks of recycling have been seriously debated. It has been reported that recycling waste streams can save water, reduce polluted emissions, enhance coagulation performance and improve water quality (Anderson 2003; Walsh et al. 2008; Wang et al. 2012; Anderson et al. 2014). Although recycled FBWW may increase particle and cyst loadings and hydraulic surges to DWTPs, it is reported that recycling FBWW does not result in additional coagulant demand within the main treatment line due to the low
dissolved organic carbon (DOC) concentrations in FBWW relative to raw water and the presence of destabilized particles in the recycled waste streams (Cornwell & Lee 1994; Cornwell & MacPhee 2001; Tobiason et al. 2003; Zhou et al. 2014a, 2014b, 2015). Some bench-scale experiments demonstrate that recycling FBWW may enhance the removal efficiencies of oocytes, humic-like substances, DOC, trihalomethane (THM) concentrations, ultraviolet absorbance at 254 nanometres (UV254) and toxicity equivalency concentrations of finished water (Bourgeois 2004; Bratby 2006; McCormick et al. 2010; Macova et al. 2011). However, some other researchers believe problems of recycling waste streams persist, such as deteriorating water quality and increased public health risk (Bourgeois et al. 2004; Wang et al. 2012; Lorent et al. 2013). It is reported that recycling untreated waste streams can increase concentrations of iron, Mn, NH3-N and disinfection by-products (DBPs) of filter effluent (Wang et al. 2012; Zhou et al. 2014b). Lorent et al. (2013) find that recycling untreated water without a sedimentation step can generate an unacceptable excess of risk for the consumer. The published results are contradictory and there is no consensus viewpoint on this topic to date.

Furthermore, most previous studies were bench- or pilot-scale experiments, each focused on a specific recycling process (FBWW or combined filter backwash water (CFBWW)). A comprehensive full-scale investigation is rarely reported. It remains uncertain whether wastewater stream recycling in DWTPs is safe or not. It is urgent that we assess the risks of recycling practices and specify safe recycling conditions and procedures, e.g., which type of water can be recycled (Xu et al. 2015).

The objectives of the present study were to evaluate the impacts of recycling FBWW and CFBWW on the effluent quality of the DWTP. Variations of several water-quality indexes, including regular water-quality indexes, metal indexes, polyacrylamide (PAM) and DBPs, were analyzed throughout the treatment and recycling processes. The results can aid water treatment researchers and engineers in evaluating the feasibility of wastewater recycling in DWTPs.

**METHODS**

**DWTP description and selection of sample sites**

The investigation was performed in Beijing DWTP (BJW) located in Guangdong Province, China. Figure 1 shows the water treatment and waste-water recycling processes performed by BJW. The main treatment processes of BJW were coagulation–sedimentation, filtration and disinfection. PAC was adopted as the coagulant at a dosage of 15 mg/L throughout the investigation period. The rate of inflow was 288,000 m3/d, and the recycled water stream was 3.2% of the total inflow. Three operational modes were used in daily experiments over a single experimental period. The first condition (C-I) operated without recycling waste water (solid
lines in Figure 1), and samples were collected from sites 1–4 (S1–S4). The second condition (C-II) recycled FBWW only (dashed and solid lines in Figure 1), and samples were collected from sites 1–6 (S1–S6). The last condition (C-III) recycled CFBWW (dot-dash, dashed and solid lines in Figure 1), and samples were collected from sites 1–11 (S1–S11). Details of the operation of BJW can be found in the Supplementary Materials (available with the online version of this paper).

Analytical method

Water quality indexes, including turbidity, total solids (TS), NH$_3$-N, COD$_{Mn}$, UV$_{254}$, Al, Mn, Cd, DOC, PAM and THMs, were analyzed by National Water Quality Monitoring Net of City Water Supply Foshan Monitoring Station and BJW laboratory according to the standard methods (Water Environmental Federation & American Public Health Association 2005). THM formation potential (THMFP) tests were conducted according to the method proposed by McCormick et al. (2010) under defined conditions of 5d incubation time, 25 ± 0.5°C incubation temperature, 7.0 ± 0.2 incubation pH and 3–5 mg/L free residual chlorine after the incubation.

RESULTS AND DISCUSSION

Turbidity variations during a single experimental period

To thoroughly examine the recycling practices of BJW and confirm the appropriate sampling method, turbidity variations with (or without) the performance of waste-stream recycling were studied. Figure 2 shows the turbidity variations observed in recycled water (S5), plant influent (S2), settled water (S3) and filtered water (S4).

The turbidity of the recycled water depended on the proportion of FBWW and sludge water, because the latter contained more destabilized particles and solids. In C-II, the recycling of FBWW with a small amount of residual CFBWW from the last run caused an initial peak in the turbidity of the recycled water (1,660 NTU). The value decreased significantly with the continuous dilution by FBWW (20–80 minutes, Figure 2), and reached an approximately constant value of 200 NTU after a 130-minute recycling operation. The recycling of sludge water (at 230 minutes), which contained high concentrations of solids and suspended matter, elevated the turbidity of the recycled water, reaching a maximum value of 1,080 NTU at 410 minutes. When the FBWW water with low turbidity was discharged into the wastewater basin, the turbidity of the recycled water began to decrease at 410 minutes.

The turbidity variations observed for plant influent mirrored the turbidity variations observed for recycled water, with an increase from 10 NTU to a peak of approximately 53 NTU. This indicated that the recycling procedure was the predominant factor affecting the turbidity variations observed in plant influent (linearly dependent, R$^2 = 0.96$). The turbidities of settled water and filtered water were compared between C-I and C-II and C-I and C-III, noting that the recycling procedure cannot affect the turbidities observed for settled water and filtered water (dual tails t-Test, p > 0.80). In addition, the filter blockage percentage did not show abnormal rises during the experimental period.
Generally, recycling waste streams had no significant impact on the turbidity of settled water and filtered water. However, it was unclear whether recycling waste streams would adversely impact other water-quality indexes. A long-term investigation was performed. Based on the observed results in this section, samples of recycled FBWW were collected after 150 minutes, and samples of recycled CFBWW were collected after 410 minutes. Samples of settled water and filtered water were collected after a delay time of 170 minutes (the hydraulic retention time from the plant influent to the effluent of the sedimentation tank), i.e., 300 minutes for recycled FBWW samples and 580 minutes for recycled CFBWW samples.

Variations of water-quality indexes during long-term investigations

Variations of regular water-quality indexes

A summary of observations regarding the turbidity, TS, NH₃-N, UV₂₅₄, COD and DOC of raw water, recycled water, plant influent, settled water and filtered water is presented in Table 1.

As discussed above, recycling FBWW or CFBWW could increase the turbidity of plant influent significantly, but it would not affect the turbidity of finished water. Dual tails t-Tests showed no differences in the turbidities of settled water and filtered water between C-I and C-II or C-I and C-III (p = 0.22 and 0.08 for C-I and C-II, respectively, and p = 0.92 and 0.47 for C-I and C-III, respectively). Recycling the waste streams likely promoted their flocculation efficiency. This conclusion was supported by the high residual alum found in recycled waste streams, as previous studies indicated that increasing residual alum increased collision cores and enhanced the performance of coagulation (Cornwell & Lee 1994; Xu et al. 2015). The TS results were in accordance with observed turbidity variations, confirming the finding that recycling FBWW or CFBWW cannot increase solid-particle concentrations in finished water.

Similar to the impacts on solid-particle concentrations in the finished water, the recycling procedure did not elevate dissolved organic concentrations, based on DOC and UV₂₅₄ variations. These results agreed with findings reported by Zhou et al. (2015), who investigated the effects of recycling FBWW (using a recycling ratio of 5%) on the organic concentration of finished water. The removal efficiencies of DOC and UV₂₅₄ may likely be enhanced by the recycling procedure because of the enriched destabilized particles in the influent, which increase the probability of collision sites available during the flocculation process.

Despite the above observations, waste-stream recycling may also adversely affect the quality of plant effluent. Average concentrations of NH₃-N in recycled water were similar for C-II and C-III (0.31 mg/L and 0.34 mg/L, respectively) but were higher than that in raw water (0.18 mg/L). The average COD Mn concentrations in C-II recycled water (33.8 mg/L) and in C-III (61.2 mg/L) were also much higher than that in raw water (2.5 mg/L). Therefore, the waste-stream recycling process increased NH₃-N and COD Mn concentrations in plant influent. Due to the limited removal efficiencies of NH₃-N and COD Mn, the recycling procedure increased the concentrations of NH₃-N and COD Mn in settled water; NH₃-N increased from 0.11 mg/L to 0.16 mg/L (dual tails t-Test, p = 0.04), and COD Mn increased from 2.0 mg/L to 2.4 mg/L (dual tails t-Test, p = 0.03). A similar situation was observed for filtered water, in which NH₃-N increased from 0.06 to 0.08 mg/L (dual tails t-Test, p = 0.01) and COD Mn increased from 1.6 mg/L to 1.7 mg/L (dual tails t-Test, p = 0.01). Previous studies also reported that recycling untreated FBWW increased NH₃-N and COD Mn concentrations in filtered water (Cornwell & Lee 1994; Wang et al. 2012; Zhou et al. 2014a). It is likely that conventional treatment processes cannot remove NH₃-N and COD Mn efficiently, such that the elevated NH₃-N and COD Mn levels caused by recycling FBWW or CFBWW increase the treating load, thereby increasing NH₃-N and COD Mn concentrations in associated settled and filtered water.

Generally, recycling FBWW or CFBWW had negligible effects on the variations observed in regular water-quality indexes. The recycling procedure did not affect turbidity, TS, DOC and UV₂₅₄, though recycling did cause slight increases in NH₃-N and COD Mn. Regardless, all these indexes still conformed to Chinese standards for drinking water quality (Ministry of Health of the People’s Republic of China & Standardization Administration of the People’s Republic of China 2006).
Table 1 | Variations of turbidity, TS, NH$_3$-N, COD$_{Mn}$, UV$_{254}$ and DOC with different treatment and recycling processes

<table>
<thead>
<tr>
<th>Indexes</th>
<th>Processes*</th>
<th>Units</th>
<th>Raw water</th>
<th>Recycled water</th>
<th>Plant influent</th>
<th>Settled water</th>
<th>Filtered water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Range</td>
<td>Average</td>
<td>Range</td>
<td>Average</td>
<td>Range</td>
</tr>
<tr>
<td>Turbidity</td>
<td>C-I</td>
<td>NTU</td>
<td>2.24–28.6</td>
<td>11.7</td>
<td>–</td>
<td>–</td>
<td>2.18–6.15</td>
</tr>
<tr>
<td></td>
<td>C-II</td>
<td></td>
<td>2.25–26.6</td>
<td>11.1</td>
<td>65.9–778</td>
<td>442</td>
<td>6.68–78.3</td>
</tr>
<tr>
<td></td>
<td>C-III</td>
<td></td>
<td>2.43–25.6</td>
<td>11.0</td>
<td>265–1,763</td>
<td>980</td>
<td>18.0–78.6</td>
</tr>
<tr>
<td>TS</td>
<td>C-I</td>
<td>mg/L</td>
<td>120–258</td>
<td>191</td>
<td>–</td>
<td>–</td>
<td>108–200</td>
</tr>
<tr>
<td></td>
<td>C-II</td>
<td></td>
<td>130–228</td>
<td>194</td>
<td>358–1,462</td>
<td>930</td>
<td>138–228</td>
</tr>
<tr>
<td></td>
<td>C-III</td>
<td></td>
<td>130–246</td>
<td>180</td>
<td>568–2,438</td>
<td>1,577</td>
<td>124–232</td>
</tr>
<tr>
<td>NH$_3$-N</td>
<td>C-I</td>
<td>mg/L</td>
<td>0.13–0.37</td>
<td>0.18</td>
<td>–</td>
<td>–</td>
<td>0.07–0.20</td>
</tr>
<tr>
<td></td>
<td>C-II</td>
<td></td>
<td>0.14–0.32</td>
<td>0.18</td>
<td>0.26–0.45</td>
<td>0.31</td>
<td>0.16–0.26</td>
</tr>
<tr>
<td></td>
<td>C-III</td>
<td></td>
<td>0.14–0.34</td>
<td>0.19</td>
<td>0.28–0.49</td>
<td>0.34</td>
<td>0.18–0.31</td>
</tr>
<tr>
<td>COD$_{Mn}$</td>
<td>C-I</td>
<td>mg/L</td>
<td>2.2–3.3</td>
<td>2.5</td>
<td>–</td>
<td>–</td>
<td>1.9–2.1</td>
</tr>
<tr>
<td></td>
<td>C-II</td>
<td></td>
<td>1.8–3.3</td>
<td>2.4</td>
<td>15.2–51.8</td>
<td>33.8</td>
<td>2.1–2.8</td>
</tr>
<tr>
<td></td>
<td>C-III</td>
<td></td>
<td>2.1–3.2</td>
<td>2.3</td>
<td>54.7–119.7</td>
<td>61.2</td>
<td>2.0–2.5</td>
</tr>
<tr>
<td>UV$_{254}$</td>
<td>C-I</td>
<td>cm$^{-1}$</td>
<td>0.031–0.067</td>
<td>0.045</td>
<td>–</td>
<td>–</td>
<td>0.028–0.054</td>
</tr>
<tr>
<td></td>
<td>C-II</td>
<td></td>
<td>0.028–0.058</td>
<td>0.041</td>
<td>0.043–0.112</td>
<td>0.061</td>
<td>0.032–0.060</td>
</tr>
<tr>
<td></td>
<td>C-III</td>
<td></td>
<td>0.052–0.073</td>
<td>0.043</td>
<td>0.034–0.425</td>
<td>0.099</td>
<td>0.031–0.063</td>
</tr>
<tr>
<td>DOC</td>
<td>C-I</td>
<td>mg/L</td>
<td>0.68–2.50</td>
<td>1.64</td>
<td>–</td>
<td>–</td>
<td>0.68–2.24</td>
</tr>
<tr>
<td></td>
<td>C-II</td>
<td></td>
<td>0.70–2.34</td>
<td>1.49</td>
<td>2.33–6.62</td>
<td>3.82</td>
<td>1.47–2.28</td>
</tr>
<tr>
<td></td>
<td>C-III</td>
<td></td>
<td>0.70–2.51</td>
<td>1.51</td>
<td>1.74–4.68</td>
<td>2.91</td>
<td>1.33–2.37</td>
</tr>
</tbody>
</table>

TS: total solids.

*C-I – conventional water treatment processes without recycling procedure; C-II – conventional water treatment processes with recycling FBWW; C-III – conventional water treatment processes with recycling CFBWW.
Variations of metal indexes and polyacrylamide

The effluent of BJW exhibited high-detection frequencies for Al, Mn and Cd, based on annual water-quality reports of BJW over the last 3 years (data not shown). Therefore, we assessed the impacts of waste-water recycling on these metal concentrations at BJW (Supplementary Material, Table S1, available with the online version of this paper). Obviously, recycled water contained high concentrations of Al, Mn and Cd, but most of the metal ions could be removed well by the treatment processes. In filtered water, the concentrations of Al, Mn and Cd were similar with different treatment and recycling processes, and no significant differences were observed, regardless of whether recycling was performed, according to dual tails t-Test results (p > 0.11). Thus, the recycling procedure cannot affect the concentrations of metal in finished water.

Similar to the metal index, PAM, which was used to improve sludge dewatering performance at BJW, did not accumulate in the treatment processes. The PAM concentration was 0.08–0.23 μg/L in the plant and no changes in PAM concentrations were observed for finished water obtained by recycling FBWW or CFBWW (dual tails t-Test, p = 0.28 and 0.68).

Variations of THMFPs

THMFPs were selected to investigate the impacts of the recycling procedure on the risk of disinfection in finished water. Figure 3 shows the range of concentrations of THMFP at various sites. Recycled streams contained lower concentrations of THMFPs compared to raw water. When recycled water is mixed with raw water, the net THMFP concentration in plant influent will decrease via the dilution effect. Concentrations of THMFPs also decreased in finished water after the treatment. However, no significant differences were observed in the concentrations of THMFPs in settled and filtered water between C-II (or C-III) and C-I (dual tails t-Test, p > 0.05). It is likely that the treatment processes have poor removal efficiencies for THMFPs and that, therefore, THMFPs cannot accumulate in waste streams. Thus, it appears that waste-stream
recycling does not cause a disinfection problem. Similar results have been reported by McCormick et al. (2010), who employed a bench-scale experiment to investigate the effects of recycling 10% untreated FBWW with raw water prior to coagulation on finished water quality.

**Variations of microbiological index**

The data of total coliform and total bacteria of the finished water were obtained from the annual water-quality reports of BJW over the last 3 years. The index always conformed to Chinese standards for drinking water quality (total coliform, undetectable; total bacteria, less than 100 CFU/mL), and no statistical difference was found between C-II (or C-III) and C-I (p > 0.52). The result indicated the recycling may not cause microbial risks after treatment by disinfection.

However, some pathogenic microorganisms, such as cryptosporidium, can resist treatment by oxidants. It is still uncertain whether the recycling of wastewater streams will cause the accumulation of some pathogenic microorganism as well as some toxic compounds within DWTPs and bring about some health risks. Further relevant study is important and necessary.

**Evaluation of the effects of recycling on DWTPs**

The manner in which recycled FBWW or CFBWW affected the quality of finished water was complex. The recycling procedure did not increase the turbidity, TS, NH\(_3\)-N, DOC, PAM, Al, Cd and THMFP concentrations of finished water, while it did increase NH\(_3\)-N and COD\(_{Mn}\) concentrations. However, according to the comparisons of indexes obtained for finished water with and without recycling to standard measurements (Figure 4), all investigated water-quality indexes, excepting UV\(_{254}\) and THMFP measurements (there is as yet no Chinese standard for UV\(_{254}\) and THMFP in finished water), conformed to Chinese standards for drinking water quality (Ministry of Health of the People’s Republic of China & Standardization Administration of the People’s Republic of China 2006). Furthermore, most of the indexes for the finished water with recycling processes were less than 30% of the upper limits of the standards except COD\(_{Mn}\), which was approximately 60% of the upper limits.

The running cost of recycling was also calculated (Table 2). Comparing the saved water resource cost and the increased energy consumption, adopting the recycling procedure of wastewater streams can save some running cost of BJW, and the benefits increased with the expansion of recycled water amount. Thus, the recycling procedure can not only save water resources but also provide economic profits.

In this case, recycling FBWW and CFBWW will not cause non-conformity in finished water quality to drinking water standards.
water standards. However, the increased tendency of NH$_3$-N and COD$_{Mn}$ would be concerning if there were serious NH$_3$-N and COD problems in the raw water of other DWTPs. For good management, it is appropriate to adopt waste-stream recycling for some DWTPs if the source water is limited or waste-stream discharge into waste networks is prohibited.

**CONCLUSIONS**

The goal of this study was to assess the safety of waste-stream recycling practices via a case investigation at BJW. The key findings of this study are outlined as follows:

- Untreated, nonhomogeneous FBWW and CFBWW contained high concentrations of particulate matter but contained low concentrations of dissolved organic matter.
- Recycling FBWW and CFBWW increased turbidity, TS, NH$_3$-N, COD$_{Mn}$, DOC, Al, Mn and Cd concentrations in plant influent. However, recycling had no significant impact on the quality of settled water and filtered water except in the case of NH$_3$-N and COD$_{Mn}$ levels, which increased slightly.
- Finished water obtained via treatment using conventional processes with recycling FBWW or CFBWW conformed to Chinese standards for drinking water quality.
- It is appropriate to set up waste-water treatment lines, as used herein, for some DWTPs if the source water is limited or waste-stream discharge into waste networks is prohibited.
- Close attention must be given to NH$_3$-N and COD$_{Mn}$ indexes if a recycling procedure is adopted and the raw water exhibits NH$_3$-N and COD$_{Mn}$ problems.

**ACKNOWLEDGEMENTS**

The work was supported by Major Science and Technology Program for Water Pollution Control and Treatment (No. 2012ZX07408001, 2014ZX07405002), Open Project of State Key Laboratory of Urban Water Resource and Environment, Harbin Institute of Technology (No. ES201511) and the Fundamental Research Funds for the Central Universities (Grant No. HIT. NSRIF. 201673).

**REFERENCES**

Walsh, M., Lake, C. & Gagnon, G. A. 2008 Strategic pathways for the sustainable management of water treatment plant


First received 23 December 2015; accepted in revised form 5 September 2016. Available online 28 September 2016