

## Water quality improvement by advanced treatment processes of GAC filtration and ozonation over an eight-year period

Seung-Hyun Kim and Jeyong Yoon

### ABSTRACT

Water quality improvement by the advanced GAC (granular activated carbon) treatment processes of filtration and ozonation was evaluated using one sample plant in this study. For the evaluation, the percentage removal performances of selected target contaminants were compared using a statistical technique. This evaluation showed that GAC filtration and ozonation were generally effective in improving the water quality with respect to alkylbenzene sulfonate (ABS),  $\text{KMnO}_4$  consumption and turbidity. Ozonation was effective in ABS removal, while GAC filtration was not. GAC filtration was mainly responsible for reduction of  $\text{KMnO}_4$  consumption, while the ozonation effect was minimal. Both GAC filtration and ozonation contributed to turbidity reduction. The study reports that pre-determination of a specific goal for a target contaminant is important for effective evaluation of advanced water treatment. Applying the same design conditions that have proved effective in pilot-scale experiments to an actual plant was also important for successful advanced treatment.

**Key words** | ABS, BAC, GAC,  $\text{KMnO}_4$  consumption, ozonation

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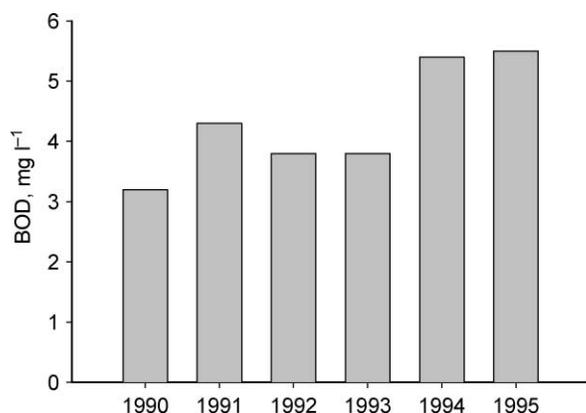
### INTRODUCTION

Economic development causes water pollution. Economic development leads to urbanization and industrialization, which then lead to the generation of massive amounts of sewage and industrial wastewater. Discharge of untreated sewage and industrial wastewater into water bodies results in contamination of water resources. Korea is no exception. Serious water pollution is undeniably associated with rapid economic development. Figure 1 shows this deterioration: annual average biochemical oxygen demand (BOD) concentration of the Nakdong-river has continued to increase (Ministry of Environment 1995). Nakdong-river, which is one of the four major rivers, supplies water to the southeastern part of Korea. This river is shown because of the extent of its pollution. Concentrated industrial development in the southeastern area has resulted in heavy pollution of the Nakdong-river.

The Korean government relied on reinforcement of water treatment as a solution to the pollution. They started

to introduce advanced treatment processes into the conventional process of coagulation–sedimentation–filtration at a number of water treatment plants. Granular activated carbon (GAC) filtration first appeared in 1986, followed by ozonation in 1988. However, it was not until 1994 that extensive installation of the advanced processes occurred. There are currently 16 water treatment plants that have adopted the advanced processes (Oh 1999).

Unfortunately preparation was not well planned in the introduction of the advanced process. Lack of preparation is conspicuous in the selection of target contaminants. They were decided without a specific goal. For example, if the advanced process was added for controlling organic contamination, a specific goal such as total organic carbon (TOC) reduction below  $2\text{mg l}^{-1}$  should be provided. A similar problem was noted in the operation of GAC filtration. It was operated without an accountable regeneration guideline. A specific goal for removing target



**Figure 1** | Variation of BOD level at Nakdong-river during the early 1990s.

contaminants or a guideline for GAC regeneration should first be established based on pilot-scale experiments. Unfortunately, this did not happen. Pilot-scale experiments and installation of the advanced process were often conducted simultaneously. It seems that the whole process of the implementation proceeded with an expectation that, once added, all the problems concerning water quality would somehow disappear, regardless of the quality of the preparation.

Lack of preparation would render optimization of the advanced water treatment processes difficult. Nonetheless, the process would bring in water quality improvement to some extent. This study aims to evaluate the water quality improvement by the advanced processes. An exact evaluation of water quality improvement will be helpful for future process optimization or improvements. A water treatment plant considering the addition of the advanced process can also benefit from this type of evaluation. There are many countries undergoing rapid economic development, especially in Asia. Sooner or later, these countries will experience significant water quality degradation and they will inevitably resort to advanced water treatment processes. The lessons from past experience could be valuable in the preparation for the introduction of advanced processes.

## MATERIALS AND METHODS

### Selection of sample plant

This study did not attempt to evaluate all 16 plants. Instead, one sample plant was selected. The criterion for the

selection was representativeness. The sample plant should be representative of the 16 plants in terms of location, size and process. Table 1 shows that Nakdong-river is the biggest beneficiary of the advanced water treatment processes in terms of location. Eleven out of the 16 plants use Nakdong-river as their raw water sources. The advanced process was preferably added to large-scale plants. Nine plants have a production capacity over  $100,000 \text{ m}^3 \text{ d}^{-1}$ , while four have a capacity of less than  $50,000 \text{ m}^3 \text{ d}^{-1}$ . Most processes were activated carbon filtration with ozonation. Some plants used GAC filtration alone, while others added ozonation. Two types of ozonation, pre-ozonation and intermediate ozonation, were employed. Pre-ozonation was primarily adopted to control taste and odour (T&O). Intermediate ozonation was usually adopted to encourage biological activity of the GAC filtration (Rittmann & Huck 1989), which was then called biological activated carbon (BAC) filtration. Five plants adopted GAC filtration, while the rest adopted BAC filtration.

Since Nakdong-river was the biggest beneficiary of the advanced processes, the selection was made in favour of a plant that used this river as the raw water source. Similarly, a large-scale plant ( $>100,000 \text{ m}^3 \text{ d}^{-1}$ ) adopting BAC filtration was given priority in the selection. Careful screening selected the 'N7' plant as the sample plant. This plant satisfied the condition of being representative. It is a large-scale plant ( $400,000 \text{ m}^3 \text{ d}^{-1}$ ), uses Nakdong-river water and employs BAC filtration with pre-ozonation.

### N7 plant

The N7 plant consisted of conventional processes (pre-sedimentation, coagulation, flocculation, sedimentation, filtration and disinfection). Backwash waste was returned to the pre-sedimentation basin, to which pre-chlorination was given. The advanced processes were introduced in two phases: GAC filtration in 1995 and ozonation in 1998. GAC filtration together with a low-pressure pumping station was added after dual-media filtration. Pre-ozonation was added before pre-sedimentation, while intermediate ozonation was added before GAC filtration. Pre-ozonation was added in order to remove Fe and Mn in the raw water as well as to improve coagulation efficiency, while intermediate ozonation was added in order to encourage biological

**Table 1** | Advanced process installation in Korea

Raw water	Plant	Capacity, m <sup>3</sup> day <sup>-1</sup>	Process	Year introduced
Han-river	H1	60,000	GAC	1998
	H2	85,000	GAC	1999
	H3	500,000	GAC	1986 <sup>1</sup>
Nakdong-river	N1	600,000	Pre-O <sub>3</sub> /BAC	1988/1994
	N2	1,555,000	Pre-O <sub>3</sub> /BAC	1996/2001
	N3	277,000	Pre-O <sub>3</sub> /BAC	1998
	N4	310,000	BAC	1997 <sup>2</sup>
	N5	800,000	BAC	1998 <sup>2</sup>
	N6	10,000	GAC	1995
	N7	400,000	Pre-O <sub>3</sub> /BAC	1995/1998
	N8	70,000	Pre-O <sub>3</sub> /BAC	1998 <sup>3</sup>
	N9	105,000	Pre-O <sub>3</sub> /BAC	2001
	N10	37,500	BAC	1998
	N11	270,000	BAC	1999
Kum-river	K1	28,000	BAC	1999 <sup>3</sup>
	K2	25,000	PAC/GAC	1998

<sup>1</sup>Addition of ozonation and GAC planned to be complete by 2006.

<sup>2</sup>Addition of pre-O<sub>3</sub> being planned.

<sup>3</sup>Pre-chlorination replaced pre-O<sub>3</sub>.

activity in the subsequent GAC filtration. **Figure 2** illustrates the treatment processes at the N7 plant. Two-phase installation allowed GAC filtration and ozonation to be evaluated separately.

**Table 2** provides the design information for the GAC filtration. Sixteen filters (12.0 m × 9.0 m × 8.0 m) were installed using coconut-based activated carbon (8 × 30 mesh-size). The apparent density of this carbon was 0.45 g cm<sup>-3</sup>, iodine number was 1,146 mg g<sup>-1</sup>, Brunauer-Emmett-Teller (BET) surface area was 1,086 m<sup>2</sup> g<sup>-1</sup>, and pore volume was 0.545 cm<sup>3</sup> g<sup>-1</sup>. The depth of the carbon layer was 2.2 m and EBCT (empty bed contact time) was 11 minutes. The filters were backwashed after 10 days

of operation using air-wash (1.0 m min<sup>-1</sup>) and water-wash (0.4 m min<sup>-1</sup>). As mentioned earlier, no information was given for regeneration timing of the GAC at the design stage. These are typical design values found in Korea (**Choi 2001**). About half of the plant with GAC filtration used charcoal-based activated carbon and the rest used coconut-based activated carbon. The carbon depth was typically 2.5 m, and most plants used slightly higher than 10 minutes of EBCT. Most plants backwashed their GAC filters weekly. Air-wash was typically given at 0.8 m min<sup>-1</sup> and water-wash was at 0.3–0.5 m min<sup>-1</sup>.

**Table 3** shows the design information for ozonation. The plant was equipped with three ozone generators

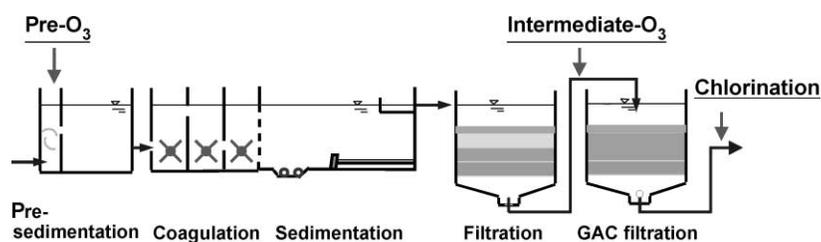


Figure 2 | Schematic diagram of N7 plant processes.

Table 2 | Design information for GAC filters at N7 plant

Carbon material	Carbon size	Height, m	EBCT <sup>a</sup> , min	Backwash		
				Air, m min <sup>-1</sup>	Water, m min <sup>-1</sup>	Frequency, day
Coconut	8 × 32	2.2	11	1.0	0.4	10

<sup>a</sup>EBCT, empty bed contact time.

Table 3 | Design information of ozone facilities at N7 plant

Capacity, kg h <sup>-1</sup>	Design dosage, mg l <sup>-1</sup>	Concentration, g Nm <sup>-3</sup>	Contactor			
			Volume, m <sup>3</sup>	Height, m	Contact time, min	Off-gas disposal
37.5 × 3	Pre: 1.5	26	Pre: 1,455	Pre: 6.1	Pre: 5.0	Heating
	Int: 3.0		Int: 3,861	Int: 6.3	Int: 12	

Pre, pre-ozone; Int, intermediate-ozone contactors.

(one for stand-by) of 37.5 kg h<sup>-1</sup>, which produced ozone from air. The design ozone dosage was 3.0 mg l<sup>-1</sup>. Two contactors were provided for both pre-ozonation (10.0 m × 15.5 m × 6.0 m) and intermediate ozonation (10.0 m × 26.0 m × 6.0 m). The contact times were 5 minutes (pre-ozonation) and 12 minutes (intermediate ozonation), respectively. Off-gas was disposed of using heating treatment. These are also typical design values found in Korea (Choi 2001). Most production facilities were designed with dosage of 2.5–3.0 mg l<sup>-1</sup>. Most contactors were designed with a water depth of 6–8 m and with a contact time of 5 minutes for pre-ozonation and 10 minutes for intermediate ozonation.

### Pilot-scale experiments

Two pilot-scale experiments of 1-year duration (1991 and 1995) were conducted at the N7 plant. The first pilot-scale experiment aimed to examine and compare water quality

improvement by GAC and BAC filtration (Masan 1992). Table 4 summarizes the results of the first experiment. The following water quality parameters were monitored: KMnO<sub>4</sub> consumption, UV-254, THMFP (trihalomethane formation potential), alkylbenzene sulfonate (ABS), NH<sub>3</sub>-N and turbidity. As shown in Table 4, BAC filtration was superior to GAC filtration in water quality improvement. The second pilot-scale experiment was aimed at finding the design information for pre-ozonation and BAC filtration (Masan 1995). Table 5 summarizes the results of the second experiment. While examining water quality improvement of such parameters as trace organics, T&O, THM and NH<sub>3</sub>-N, the superiority of BAC in water quality improvement was evident. The effects of pre-ozonation on coagulation efficiency were also examined. It was reported that pre-ozonation could improve turbidity removal by 5–10%. Both experiments agreed that these advanced processes would improve water quality.

**Table 4** | Comparison of contaminant percentage removal performances by GAC and BAC in the 1st pilot experiment

	KMnO <sub>4</sub> consumption	ABS	NH <sub>3</sub> -N	Turbidity	THMFP	UV-254
Influent level	1.9–11 mg l <sup>-1</sup>	0.05–1.03 mg l <sup>-1</sup>	0.1–2.0 mg l <sup>-1</sup>	–	20–100, µg l <sup>-1</sup>	0.03–0.10, 1/cm
GAC	15–85 (50)*	35–80 (60)	10–90 (85)	78	5–50	30–70 (50)
BAC	40–92 (65)	50–90 (80)	40–95 (90)		6–70	40–90 (75)

\*Figures in parentheses indicate average values.

### Target contaminants

Five target contaminants were selected based on the results of the pilot experiments: NH<sub>3</sub>-N, ABS, KMnO<sub>4</sub> consumption, turbidity and THM. T&O were excluded because Korean Drinking Water Standards (KDWS) regulated this parameter using sensory analysis (Ministry of Environment 1994). Since most of the volatile organics and pesticides regulated by KDWS were either not detected or detected at very low concentrations, trace organics were excluded from the evaluation.

**Table 5** | Summary of the second pilot experiment results

Process	Results
Pre-O <sub>3</sub>	UV-254 removal 10–30% Improved turbidity removal
Intermediate O <sub>3</sub>	UV-254 removal of 20–40% DOC (dissolved organic carbon) removal < 10% BDOC increase (15–20% to 32%)
BAC	Gradual decrease in organic removal; initial UV-254 removal of 50% dropped to 20% within 7 months BAC (40% of UV-254 removal) was superior to GAC (20% of UV-254 removal) in organic removal Low NH <sub>3</sub> -N removal at low temperature BAC's biological activity proved using aldehyde removal

Of these five contaminants, NH<sub>3</sub>-N and ABS have posed a problem to the N7 plant. The concentration of treated NH<sub>3</sub>-N frequently exceeded the KDWS's MCL (maximum contaminant level) of 0.5 mg l<sup>-1</sup>. Since conventional processes were not effective in ammonia removal, this plant needed an advanced treatment process to meet the MCL. The ABS situation was different. Although the incoming ABS concentration was often higher than 0.5 mg l<sup>-1</sup>, this plant satisfied the MCL with the conventional processes. However, it is expected that the ABS level will increase in the future. Similarly, this plant satisfied the MCLs of KMnO<sub>4</sub> consumption (10 mg l<sup>-1</sup>) and turbidity (1 NTU). Since KMnO<sub>4</sub> consumption is the only aggregate organic parameter being regulated by KDWS, it was selected as a target contaminant. Turbidity was selected to evaluate the effects of the advanced process on particle removal. THM was selected because it was a big concern in Korea when the advanced processes were installed.

### Grouping and analysis of water quality data

Water quality data measured and recorded at the N7 plant from 1994 to 2001 were used for the evaluation. Since the GAC filtration was installed at the end of 1995, data from 1994 and 1995 were designated as 'pre-AWT' and data from 1996 through 2001 were designated as 'post-AWT'. When necessary, 'post-AWT' was divided into 'post-GAC' and 'post-O<sub>3</sub>'. 'Post-GAC' corresponds to data from 1996 through 1998, while 'post-O<sub>3</sub>' corresponds to data from 1999 through 2001. Data were statistically analysed using the t-test and Duncan test. The t-test was employed to determine the difference between two groups of data. The Duncan test was employed for more than three data groups. These tests were conducted at a confidence level of 0.05.

## RESULTS AND DISCUSSION

### Comparison of treated water quality

Comparing the treated water qualities before and after the adoption of the advanced processes can reveal water quality improvement if raw water quality is identical. Table 6 shows that treated water quality has improved since the adoption of the advanced processes. Treated values of  $\text{NH}_3\text{-N}$ , ABS,  $\text{KMnO}_4$  consumption and turbidity decreased, but THM was an exception. TTHM concentration increased. The t-test found the difference statistically significant at a confidence level of 0.05, confirming the improvement.

However, the raw water quality changed. Contaminant loading gradually decreased, as shown in Figures 3, 4 and 6. The peak level of  $\text{NH}_3\text{-N}$  frequently exceeded  $3 \text{ mg l}^{-1}$  (six times the MCL), but it rarely exceeded  $0.5 \text{ mg l}^{-1}$  since 1998. ABS loading also decreased. The raw level of ABS

never exceeded the MCL of  $0.5 \text{ mg l}^{-1}$  from 1998 onwards. The incoming level of  $\text{KMnO}_4$  consumption fluctuated around  $15 \text{ mg l}^{-1}$  before 1998, but around  $10 \text{ mg l}^{-1}$  after 1998. These results clearly show a change in the raw water quality. The turning point was 1998 when raw water quality clearly improved. Enhanced wastewater treatment could be the reason. Many wastewater treatment plants have been built upstream of Nakdong-river in the late 1990s, as an effort to reduce the contaminant loading. The t-test found the difference significant, confirming the reduced loading in the raw water. Therefore, instead of the qualities of the treated water, the percentage removal performances were compared to examine water quality improvement.

### $\text{NH}_3\text{-N}$ removal

According to Table 6, the conventional process at the N7 plant removed 83% of incoming ammonia, and the removal

**Table 6** | Water quality comparison before and after addition of advanced processes at N7 plant

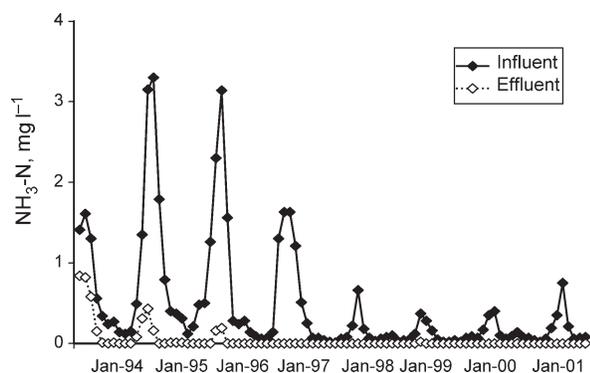
Contaminants	Description	Pre-AWT <sup>1</sup>	Post-AWT <sup>2</sup>	Post-GAC <sup>3</sup>	Post-O <sub>3</sub> <sup>4</sup>
$\text{NH}_3\text{-N}$	Raw, $\text{mg l}^{-1}$	$0.86 \pm 0.89$	$0.31 \pm 0.56$	$0.47 \pm 0.74$	$0.15 \pm 0.19$
	Treated, $\text{mg l}^{-1}$	$0.14 \pm 0.26$	$0.01 \pm 0.03$	$0.01 \pm 0.04$	ND
	% removal	$83 \pm 18$	$100 \pm 1.2$	$98 \pm 1.5$	$100 \pm 0.9$
ABS	Raw, $\text{mg l}^{-1}$	$0.36 \pm 0.15$	$0.20 \pm 0.17$	$0.27 \pm 0.18$	$0.14 \pm 0.15$
	Treated, $\text{mg l}^{-1}$	$0.18 \pm 0.13$	$0.08 \pm 0.12$	$0.13 \pm 0.14$	$0.02 \pm 0.04$
	% removal	$50 \pm 18$	$60 \pm 25$	$50 \pm 24$	$83 \pm 21$
$\text{KMnO}_4$ consumption	Raw, $\text{mg l}^{-1}$	$15.5 \pm 2.47$	$11.4 \pm 2.82$	$12.6 \pm 2.92$	$10.2 \pm 2.12$
	Treated, $\text{mg l}^{-1}$	$4.8 \pm 1.4$	$2.8 \pm 1.2$	$3.4 \pm 1.4$	$2.3 \pm 0.6$
	% removal	$69 \pm 8.9$	$75 \pm 7.2$	$73 \pm 8.3$	$77 \pm 5.5$
Turbidity	Raw, NTU	$8.7 \pm 3.2$	$17.4 \pm 17.8$	$17.5 \pm 21.4$	$17.2 \pm 13.7$
	Treated, NTU	$0.83 \pm 0.20$	$0.32 \pm 0.17$	$0.43 \pm 0.18$	$0.22 \pm 0.05$
	% removal	$90 \pm 4.7$	$98 \pm 2.5$	$96 \pm 2.9$	$99 \pm 1.2$
TTHM	Treated, $\mu\text{g l}^{-1}$	$18 \pm 10$	$29 \pm 13$	$32 \pm 12$	$27 \pm 14$

Pre-AWT, before addition of advanced water treatment.

Post-AWT, after addition of advanced water treatment.

Post-GAC, after addition of GAC filtration.

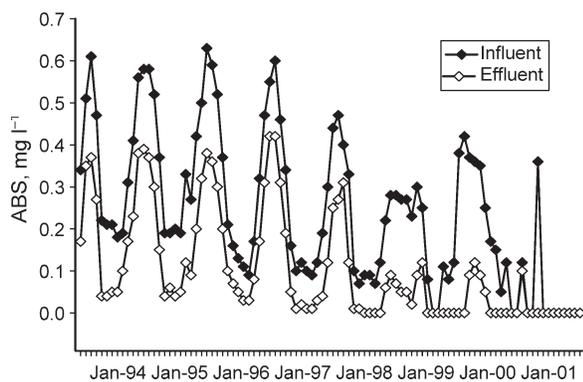
Post-O<sub>3</sub>, after addition of ozonation.



**Figure 3** | Monthly average values of  $\text{NH}_3\text{-N}$  for raw and treated waters at N7 plant during the study period.

performance improved to 100% after the advanced processes were adopted. The difference was statistically confirmed using the t-test. Ammonia removal performance was even better than expected from the pilot experiment (Tables 4 and 5). GAC and BAC filtrations were able to remove 10–90% and 40–95% of incoming ammonia depending upon temperature during the first pilot experiment. Even lower removal efficiency was observed during the second pilot experiment. Comparison was then extended to the ammonia removal performances of post-GAC and post- $\text{O}_3$ . The difference, which was minimal (98% vs. 100%), was found statistically insignificant. This result indicates that the advanced processes successfully improved the water quality in terms of ammonia reduction, and that GAC adsorption was mainly responsible for the reduction.

However, breakpoint chlorination rather than the advanced processes of GAC filtration and ozonation seemed to be responsible for complete ammonia reduction. Breakpoint chlorination was introduced into the N7 plant



**Figure 4** | Monthly average values of ABS for raw and treated waters at N7 plant during the study period.

to keep the treated ammonia level down to the MCL from early 1995. Breakpoint chlorination was practised at the pre-sedimentation basin. Addition of breakpoint chlorination complicated the evaluation. Both breakpoint chlorination and the advanced process could contribute to ammonia reduction. Nonetheless, breakpoint chlorination was more likely to drive the reduction. Seasonal variation was noted in Figure 3. The incoming level was lower than  $0.5 \text{ mg l}^{-1}$  most of the year, but it increased above  $0.5 \text{ mg l}^{-1}$  during the winter. The effect of seasonal variation was not noted because the amount of ammonia was completely reduced. This also suggests that breakpoint chlorination was actually responsible for ammonia reduction.

### ABS removal

The ABS removal performance improved from 50% to 60% after the advanced processes were adopted (Table 6). The t-test found the difference statistically significant. The magnitudes of the improvement by the advanced processes were then calculated. Assuming that the conventional process maintained a similar performance (50%), the contribution to ABS removal by the advanced processes was calculated to be 20%. This was short of the expectation from the pilot plant experiments. The first experiment showed that GAC and BAC filtrations were able to remove 35–80% and 50–90% of ABS according to the filtration time, respectively.

Figure 4 shows the effectiveness of ozonation on ABS removal. The treated level substantially decreased after 1999. As shown in Table 6, ABS removal performance improved from 50% to 83% after ozonation was added. On the other hand, the addition of GAC filtration failed to improve ABS removal. Both the t-test and the Duncan test found that the difference between ABS removal performances by GAC filtration and ozonation was statistically significant. This result indicates that ozonation was mainly responsible for ABS reduction.

The ineffectiveness of GAC filtration on ABS removal despite the results of the pilot experiments suggests a problem in the GAC filtration. As mentioned earlier, the pilot experiments (Masan 1992, 1995) showed that GAC filtration was effective in ABS removal, but such effectiveness was not repeated in the actual plant operation. Actual

plant operation may not be the same as that at the pilot plant, but results of the pilot experiments can still provide qualitative information. This lack of improvement could be caused by the wrong selection of activated carbon. The carbon employed in the actual plant operation was noted to be different from the one used in the pilot experiments. Another study confirmed the carbon problem (Osaka Department of Water 1991). According to the pilot experiments conducted at Osaka Department of Water, ozonation with GAC filtration was very effective in ABS removal. Ozonation achieved 80% of ABS removal, while GAC filtration following ozonation enabled complete reduction of ABS.

Figure 4 shows the temperature effect on ABS level. The influent level was high during the cold months and low during the warm months. Temperature also affected ABS removal. Better removal of ABS was observed during the warm months than during the cold months, as shown in Figure 5. Ozonation minimized the temperature effect and levelled out the seasonal variation. ABS removal became relatively constant following the addition of ozonation.

### KMnO<sub>4</sub> consumption removal

The addition of the advanced processes improved the removal performance of KMnO<sub>4</sub> consumption from 69% to 75%. The t-test confirmed that the difference was statistically significant. This result indicates that the

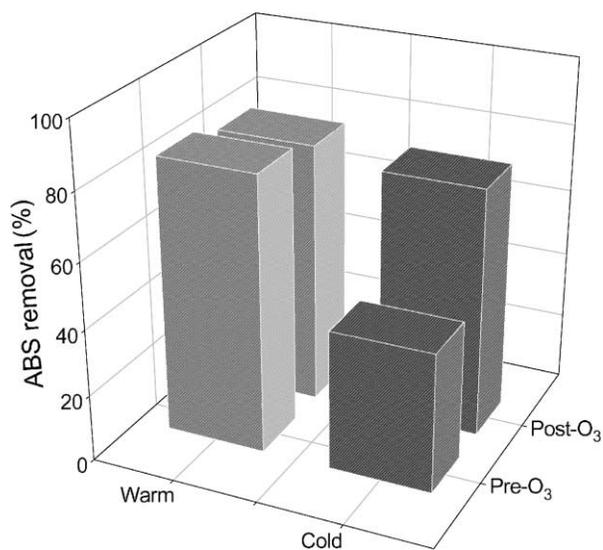


Figure 5 | Comparison of ABS removal performances between cold and warm months before and after ozonation.

advanced processes improved the removal of KMnO<sub>4</sub> consumption. The magnitude of the improvement (20%) by the advanced processes, which were calculated similarly to ABS, was short of the expectation from the pilot plant. The first pilot experiment showed that GAC and BAC filters could remove 15–85% and 40–92% of KMnO<sub>4</sub> consumption according to the filtration time, respectively. This could be due to the poor performance of GAC filtration. As mentioned earlier, the wrong selection of activated carbon resulted in poor performance of GAC filtration. Adsorption capacity generally decreases with time and the highest removal performance is obtained at the early stage. Such behaviour was not observed during the actual operation. Instead, relatively constant removal performance was maintained over the entire study period.

Contrary to the pilot experimental results (Masan 1992), ozonation did not help to improve the removal of KMnO<sub>4</sub> consumption. The pilot experiments showed that BAC filtration was superior to GAC filtration in the removal of KMnO<sub>4</sub> consumption. The removal performance slightly improved from 73% to 77% after addition of ozonation. However, the Duncan test found that this difference was statistically insignificant. This result indicates that GAC filtration was mainly responsible for reduction of KMnO<sub>4</sub> consumption. The level of KMnO<sub>4</sub> consumption varied somewhat with operation, as shown in Figure 6, but no definite pattern was found. The raw level of KMnO<sub>4</sub> consumption was generally high during spring or summer and low during winter, while the treated level was generally high during the first six months and low during the last six

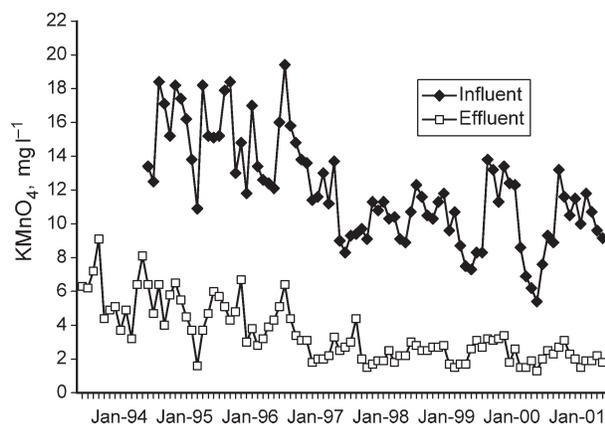


Figure 6 | Monthly average values of KmnO<sub>4</sub> consumption for raw and treated waters at N7 plant during the study period.

months. The seasonal effect was not noted on the removal of  $\text{KMnO}_4$  consumption.

### Turbidity removal

Figure 7 shows that addition of the advanced process improved turbidity removal. The t-test found the difference statistically significant. The reduction was obvious because GAC filtration is able to remove particles. Double stage filtration reduced the treated turbidity level further, but this was short of the pilot plant's expectation. The first pilot experiment showed that GAC and BAC filtrations reduced the influent level from 1.1 NTU to 0.24 NTU and to less than 0.19 NTU, respectively. The adoption of the advanced processes reduced the average treated level from 0.83 NTU to 0.32 NTU during the actual operation.

Besides GAC filtration, ozonation also helped to improve turbidity removal. The average treated level was 0.43 NTU after the adoption of GAC filtration and 0.22 NTU after adoption of ozonation. The Duncan test found that this difference was statistically significant. Once the beneficial effect of ozonation on particle removal was known, settled and filtered turbidity values before and after addition of ozonation were compared in order to examine the ozonation effect further. According to Figure 8, ozonation affected the sedimentation. After pre-ozonation, the average settled turbidity value reduced from 1.65 NTU to 1.27 NTU. This result indicates that pre-ozonation enhanced particle removal by sedimentation. The t-test found the difference statistically significant. Monthly

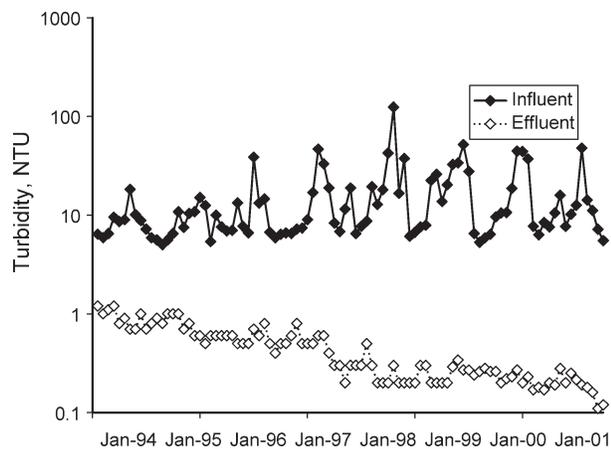


Figure 7 | Monthly average values of turbidity for raw and treated waters at N7 plant during the study period.

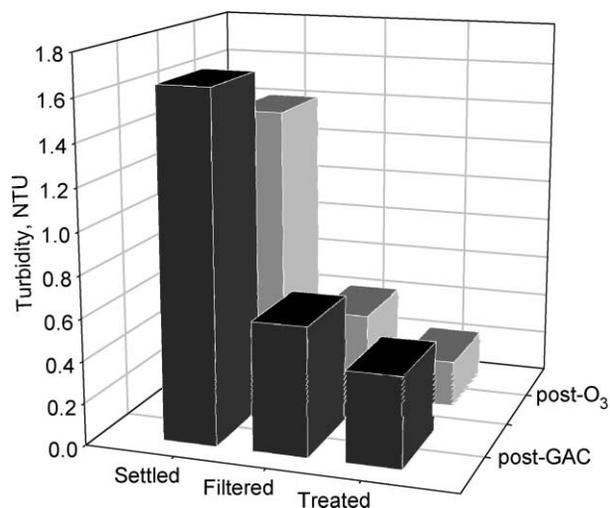


Figure 8 | Comparison of turbidity values at various processes after GAC filtration and ozonation.

average treated turbidity never exceeded 0.3 NTU from 1999 because of the addition of ozonation.

Figure 7 shows seasonal variation of turbidity. The raw level was high during the flooding season and low during winter, while the treated level was generally high during winter. This pattern was maintained after the adoption of the advanced processes, indicating that the seasonal variation did not affect particle removal performance of the advanced processes.

### THM removal

Figure 9 shows the monthly average values of TTHM for treated water during the study period. Seasonal variation was noted. The beneficial effect of the advanced process was not shown for TTHM. TTHM concentration rather increased from  $18 \mu\text{g l}^{-1}$  to  $29 \mu\text{g l}^{-1}$  after the adoption

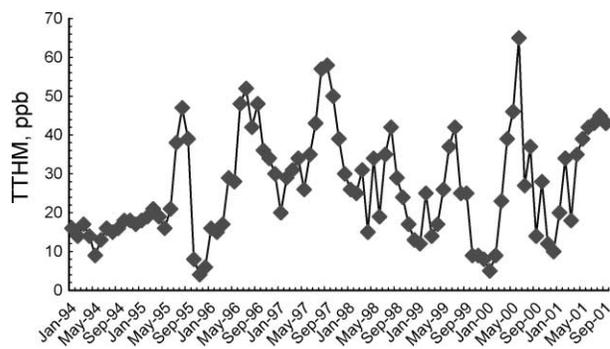


Figure 9 | Monthly average values of TTHM for treated water at N7 plant during the study period.

of the advanced process. The t-test confirmed that the difference was statistically significant. The reason for the increase was not clear.

Ozonation reduced TTHM concentration from  $32 \mu\text{g l}^{-1}$  to  $27 \mu\text{g l}^{-1}$  because pre-ozonation eliminated pre-chlorination. However, the difference was found statistically insignificant. Another effect of ozonation was a change in THM species. Chloroform and bromodichloromethane used to be the only THM species formed, but bromoform and chlorodibromomethane were also detected after ozonation.

## CONCLUSIONS

Water quality improvement by the advanced processes of GAC filtration and ozonation was evaluated by using one sample plant in this study. For this purpose, percentage removal performances of target contaminants were compared using a statistical technique. Evaluation of the sample plant showed that GAC filtration and ozonation were effective in water quality improvement of ABS,  $\text{KMnO}_4$  consumption and turbidity. The effect of the advanced process on ammonia removal could not be evaluated because breakpoint chlorination rather than the advanced processes induced complete reduction of ammonia. Ozonation was effective for ABS removal, while GAC filtration was not. GAC filtration was mainly responsible for reduction of  $\text{KMnO}_4$  consumption, while the ozonation effect was minimal.

The extent of the improvement for ABS and  $\text{KMnO}_4$  consumption was short of the expectation from the pilot plant because of the poor performance of GAC filtration. Use of poor-quality activated carbon could cause ineffective GAC performance. Both GAC filtration and ozonation

were able to reduce turbidity level. The GAC filter acted as a second filter, while pre-ozonation enhanced particle removal by sedimentation probably through microfloculation. Unlike these contaminants, the beneficial effect of THM reduction was not observed. ABS was the only contaminant that was important for seasonal variation. The advanced process flattened seasonal variation of ABS removal. Such an effect was not noted in the removal of other contaminants.

## ACKNOWLEDGEMENTS

This work was supported by Kyungnam University Foundation Grant.

## REFERENCES

- Choi, S. 2001 *Evaluation Report on Operation of Advanced Water Treatment Processes*, pp. 6–10 (Unpublished report).
- Masan 1992 *Report of pilot test using advanced water treatment*. Masan, Korea (in Korean).
- Masan 1995 *Report of pilot test using advanced water treatment*. Masan, Korea (in Korean).
- The Ministry of Environment at Republic of Korea 1994 *Drinking Water Regulation*. MOE, Korea (in Korean).
- The Ministry of Environment at Republic of Korea 1995 *Environment Report*. MOE, Korea (in Korean).
- Oh, H. 1999 Introduction and operation of advanced water treatment process using granular activated carbon and ozone/AOP. *Advanced Water Treatment Using Granular Activated Carbon*. Environment Research Institute, Kyungnam University, Korea, pp. 23–51.
- Osaka Department of Water 1991 *Water at 21 Century: Q&A for advanced water treatment at Osaka water*. Osaka, Japan (in Japanese).
- Rittmann, B. E. & Huck, P. M. 1989 Biological treatment of public water supplies. *Crit. Rev. Environ. Contr.* **19**(2), 119–194.

First received 4 November 2003; accepted in revised form 8 October 2004