Experimental evaluations of water treatment systems using a pilot-scale plant for adaptations to a sharp increase in raw-water turbidity caused by climate change

Y. Kobayashi, M. Itoh, T. Yamada, M. Akiba and Y. Matsui

ABSTRACT

One effect of climate change on the water supply systems in Japan may be a sharp increase in the raw-water turbidity following heavy rain. The objective of this study was to evaluate water treatment performance with a sharp increase in raw-water turbidity. This evaluation was carried out from the perspective of turbidity response by a pilot-scale plant using sand filtration and membrane filtration with coagulation–sedimentation pretreatment. Two coagulants were used; namely, polyaluminum chloride with a basicity of either 72% (PACl-72%) or 51% (PACl-51%). Raw-water turbidity was increased from 5 to 300 TU by adding kaolin suspension. In the case of sand filtration, the filtered-water turbidity increased during the filter stabilization period. An increase in the coagulant dosage produced a more rapid decrease in the filtered-water turbidity and shortened the filter stabilizing period. Filtered-water turbidity decreased more rapidly for PACl-72% than for PACl-51%. In the case of membrane filtration, an increase in raw-water turbidity caused no significant increase in filtered-water turbidity or transmembrane pressure. These results demonstrated that, although neither filtration technique completely failed, membrane filtration was more robust than sand filtration against a sharp increase in raw-water turbidity.

Key words | climate change, coagulant, membrane filtration, pilot-scale plant, sand filtration, turbidity

INTRODUCTION

It is essential for a water supply system to supply safe water continuously, which is indispensable for comfortable civil life and urban activity (Water Supply Division, Ministry of Health, Labour and Welfare, Japan, 2008). In its Fourth Assessment Report, the Intergovernmental Panel on Climate Change described how ‘warming of the climate system is unequivocal’ and concluded that ‘even the most stringent mitigation efforts cannot avoid further impacts of climate change in the next few decades, which makes adaptation essential, particularly in addressing near-term impacts’ (IPCC 2007). The scenarios in ‘Climate Change and Its Impacts in Japan’ project that the average temperature increase between the end of the 20th century (1980–1999) and the end of the 21st century (2090–2099) will be in the range from 2.1 to 4.0°C (Ministry of Education, Culture, Sports, Science and Technology et al., Japan 2009). Therefore, it is essential to study adaptation measures for climate change.

The influences of climate change on the water environment and resources in Japan are predicted to consist of increases in: drought risk; frequency of short-term heavy rainfall; rivers, lakes, and groundwater temperatures; and probabilities of blue-green algae events and saline groundwater due to sea level rise (Ministry of the Environment, Japan 2008). Heavy rainfall of more than 50 mm/h has occurred 1.5 times as often in recent years (1998–2007) as compared to 30 years ago (1976–1987) and that of more than 100 mm/h has occurred 2.1 times as often (River Bureau, Ministry of Land, Infrastructure, Transport and...
Tourism, Japan 2008). Since 73.2% of the raw water in 2006 was dependent on surface water in the water supply system (Japan Water Works Association 2008), an increase in river water turbidity caused by heavy rainfall is a concern in Japan. After one heavy rainfall in 2007, the raw-water turbidity in the city of Kitami reached nearly 15,000 kaolin turbidity units (TU), which resulted in a stoppage of the water supply in the area for 4 days (Ebie et al. 2007), while the average raw-water turbidity in Japan was approximately 4.4 TU. Treated-water turbidity is one of the most important indices used to evaluate the performance of any water treatment system. Filtered-water turbidity must be kept at less than 0.1 TU in Japan to prevent contamination of treated water by Cryptosporidium oocysts (Water Supply Division, Ministry of Health, Labour and Welfare, Japan 2007). The filtered-water turbidity should be carefully controlled by discarding the filtered water over a filter stabilizing period after backwashing for example in rapid filtration, or installing of membrane filtration. While rapid filtration systems are commonly used for water treatment in Japan, the number of membrane filtration systems has increased in recent years. Therefore, it is necessary to consider adaptation measures in the water treatment system to protect against any sharp increase in raw-water turbidity.

Studies have shown that evaluation of treatment under high turbidity raw water in drinking water including coagulation–sedimentation process (Li & John 1991; Lin et al. 2008), two-stage filtration system (Dantas & Di Bernardo 2006), coagulation–microfiltration system (Wittmann et al. 2002; Choi & Kweon 2010), coagulation–ultrafiltration system (Xiangia et al. 2008) and coagulation–nanofiltration and reverse osmosis membrane system (Lin et al. 2012). However, to our knowledge, each one of these evaluations was based on their own single system and experiment with one or more different system parallely has not yet conducted.

Polyaluminum chloride (PACl), which is an aluminum-based coagulant, makes up approximately 90% of the coagulant used in the country (Japan Water Works Association 2008). A limit of 0.1 mg/L was set in 2009 for aluminum, which became a new Complementary Item under the quality standards for drinking water in Japan, and there is a tendency to require even lower aluminum concentrations in drinking water. Because of these backgrounds, 72%-basicity PACl is produced experimentally to reduce residual aluminum concentration of finished water, while the basicity of conventional PACl is around 51%. It was reported that the basicity of PACl could vary with aluminum speciation and had an effect to reduce the residual aluminum concentration of the treated water (Yan et al. 2008). Lin et al. (2008) has reported by jar tests that high basicity PACl (PACl-E), whose concentration of $A_\alpha$ was lower than lower basicity PACl (PACl-I) on Al (III) speciation, was superior to PACl-I in turbidity removal on coagulation for natural highly turbid water up to 5,000 NTU. However, there has been little reference to report about performance of high basicity PACl using pilot-scale plant which has sand-filtration and membrane filtration.

The objective of this study is to evaluate the turbidity removal performance comparing a rapid filtration system and membrane filtration system using a pilot-scale plant and deals with a sharp increase in raw-water turbidity. Additionally, we evaluate turbidity removal performance not only for water treated with conventional 51%-basicity PACl, but also for water treated with 72%-basicity PACl in the turbidity conditions using this pilot-scale plant.

**METHODS**

Outline of pilot-scale plant and operating conditions

Experimental tests were performed in the National Institute of Public Health (NIPH), Japan, using a pilot-scale plant that has sand filtration and membrane filtration with coagulation–sedimentation pretreatment. Figure 1 shows the experimental flow through the pilot-scale plant. Table 1 lists the specifications and operating conditions of the experimental plant, which has two lines of the same specifications. Each line has a capacity of 15 m$^3$/day, owing to a raw-water adjustment tank, a coagulation–sedimentation tank, two sand filtration towers, and a membrane filtration device. After the sedimentation process, the water is divided and fed separately into the sand filtration towers and the membrane filtration device. Groundwater from a deep well was used as experimental raw water. We added a high-concentration (20,000 TU) kaolin suspension to the raw water, via a tubing pump, to control the raw-water turbidity. The undiluted coagulant and pH adjuster (sulfuric acid) were added in a pipe between the raw-water mixing tank and the
coagulation tank. The coagulation pH was set at 7.0 and was automatically controlled with feedback from a pH meter in the rapid mixing tank. The G-value of the rapid mixing was set at 450 s$^{-1}$ and that of the slow mixing was set at 12 s$^{-1}$, based on the results from preliminary jar tests. Settled water was pumped to both the sand filtration process and the membrane filtration process. The sand filtration rate was set at 120 m/day, as Guidelines for Waterworks Operation and Management 2006 edition (Japan Water Works Association 2006) which was widely used in the country mentioned that filtration rate between 120 and 150 m/day is recommended for a conventional rapid sand filtration system in Japan. In this study, the backwash interval of the sand filtration units was 24 h. The backwash process included air-washing for 330 s, air-washing and water backwashing in parallel for 70 s, and water backwashing for 400 s. The backwashed water of the sand filtration in this study was the groundwater from the deep well to reset the sand bed condition from former filtration. The membrane filtration device was operated by dead-end ultrafiltration, with a filtration flux of 75 L/m$^2$/h. The membrane material was cellulose acetate (CA), which is one of the major membrane materials including polyvinylidene difluoride (PVDF), polysulfone (PS) or polyether sulfone (PES) and CA that are used in Japan. Recently the share of PVDF membrane is growing but CA membrane is still in use or newly installed in some cases. The molecular weight cut-off was at 150,000. After each 179 min of filtering operation, the membrane was backwashed by membrane filtrated water for 1 min, with a backwashing flux of

**Table 1 | Specifications and operating conditions of the pilot-scale plant**

<table>
<thead>
<tr>
<th>Treatment process</th>
<th>Specifications</th>
<th>Operating conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coagulation-sedimentation</td>
<td>Rapid mixing tank: Effective capacity: 0.055 m$^3$</td>
<td>Residence time: 5.5 min; Coagulation pH: 7.0; G-value: 450 s$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>Slow mixing tank: Effective capacity: 0.338 m$^3$</td>
<td>Residence time: 33.8 min; GT-value: 24,000</td>
</tr>
<tr>
<td></td>
<td>Sedimentation tank: Effective capacity: 0.900 m$^3$</td>
<td>Residence time: 90 min</td>
</tr>
<tr>
<td>Sand filtration</td>
<td>Thickness of sand layer: 60 cm; Effective diameter: 0.6 mm; Uniformity coefficient: 1.5</td>
<td>Filtration rate: 120 m/day; Backwash interval: 24 hour</td>
</tr>
<tr>
<td>Membrane filtration</td>
<td>Cellulose acetate ultrafiltration membrane (hollow fiber membrane); Molecular weight cut-off: 150,000; Membrane filtration area: 2.5 m$^2$</td>
<td>Flux:75 litres/m$^2$/hour; System: dead-end filtration Backwash interval: 179 min</td>
</tr>
</tbody>
</table>
358 L/m²/h. We set the 179 min of backwash interval, which is longer than a normal interval in treatment operation, so as to observe transmembrane pressure (TMP) trends during our experimental period. No chemical, such as sodium hypochlorite, was used for backwashing.

**Conditions**

The raw-water turbidity was pre-set at three levels: low turbidity of 5 TU, medium turbidity of 30 TU, and high turbidity of 300 TU. According to the results from The Japan Research Centre (2005) that included research on raw-water quality of 36 Japanese water purification plants over 5 years, the 5 TU level was at the 50th percentile of the cumulative frequency of all turbidity data and the 30 TU level was at the 95th percentile. Further, the 300 TU level was at the 95th percentile of the cumulative frequency of turbidity data in which 30 TU was exceeded for 5 days. Based on these results, it was assumed that 5 TU was the usual turbidity of the surface water, 30 TU was the usual turbidity in rainfall, and 300 TU was the peak turbidity in heavy rainfall. A popular PACl with 51% basicity (51%-PACl) and a high-basicity variant (72%-PACl) were used as coagulants. The basicity of PACl can be shown to obey the following equation:

$$\text{Basicity of PACl} = \frac{(n/6) \times 100\%}{(n/6) \times 100\%}$$ (1)

It has been reported that the basicity of PACl can vary with aluminum speciation (Yan et al. 2008): the PACl of higher basicity has less of the monomeric species (Al₈) but more of the medium polymeric species (Al₅) and colloidal species (Al₃). Moreover, it has been shown that PACl with higher Al₈ content has a tendency to increase the residual aluminum concentration of the treated water (Yan et al. 2007). The coagulant dosage in the experiments using raw water of 5 or 30 TU was 36 mg/L and that for 300 TU was 36 or 72 mg/L as PACl. These dosages were set on the basis of results from preliminary jar tests (not shown).

**Analytical methods**

Turbidity, pH, and TMP were continuously monitored by instruments installed within the pilot-scale plant. The turbidity of the raw water at the raw-water mixing tanks and that of the settled water in the sedimentation tanks were monitored using surface scatter turbidity meters (HACH SS6). The surface scatter turbidity meters were calibrated by 100 TU kaolin standard suspension before the experimental test, generally said that 1 TU was about 1.4 Nephelometric Turbidity Units (NTU) (Magara et al. 2002). The turbidity of water treated by sand filtration or membrane filtration was monitored using a super-sensitive laser turbidity meter (NIPPON DENSHOJU NP500T) which could detect from 0.0000 to 2.0000 TU. The pH was monitored at both the raw-water mixing tanks and the rapid mixing tanks. The TMP, which is the difference in pressure before and after the membrane, was monitored with pressure meters. Dissolved organic carbon (DOC) concentration of raw water was analyzed after experiment using Total organic carbon analyzer (SHIMADZU TOC-V CPH) in filtered water by glass microfiber filters whose pore size was 1.0 μm. Metals were analyzed using an inductively coupled plasma mass spectrometer (ICP-MS Agilent 7500 Ce) after the addition of nitric acid to samples as 1%. Dissolved metals were analyzed in the filtered water by using a membrane filter with a pore size of 0.45 μm. Electrical conductivity (EC) was measured using meters (HIROBA, ES-14). Alkalinity was calculated from the consumption of sulfuric acid to reach pH 4.8 using an automatic titration instrument.

**Raw-water quality**

Table 2 lists the average quality of raw water after the addition of kaolin suspension for each turbidity level. DOC, which was analyzed after the experiment, is shown as a reference because it is not average quality. Total Al and Total Fe concentrations in both 30 TU water and 300 TU water were higher than those in 5 TU water due to the addition of kaolin as an artificial turbidity.

**RESULTS AND DISCUSSION**

Figure 2 shows the turbidity trends for raw water, settled water (after using 51%-PACl), sand filtered water, and membrane filtered water. Average of the measured raw-water...
turbidity was higher than its setting value, with a setting value of raw-water turbidity of 5, 30, or 300 TU measured average value were 7.9, 36, or 360 TU, respectively, as shown in Table 2. For a coagulant dosage of 36 mg/L, and with the same three pre-set values of raw-water turbidity, the settled-water turbidity was approximately 1.0, 3, or 10 TU, respectively. Because the settled-water turbidity reached 10 TU when the pre-set raw-water turbidity was 300 TU, a coagulant dosage of 72 mg/L was applied, resulting in a settled-water turbidity decrease to about 6 TU. Hence, larger settled-water turbidity values appear to correlate to higher turbidity in raw-water, but decreased by the increase in coagulant dosage.

The rise in raw-water turbidity tended to produce a rise in the turbidity of the sand-filtered water after each backwash. This results was caused by a rise in the turbidity of the influent water to sand filtration, that was the settled-water, and passage of more particles through the sand filtration bed, because the condition of sand filtration bed was reset by backwashed water, namely, groundwater from deep well. With a 36 mg/L coagulant dosage, filtered effluent turbidities produced readings ranging from 0.01 to 0.05 TU, demonstrating that even at 0.05 TU levels neither the 2 TU limit required by the Japanese drinking water quality standard nor the 0.1 TU limit required by the ‘guidelines for Cryptosporidium treatment in waterworks’ will be exceeded. The authorities can be reassured that sand filtration with adequate control, such as through coagulant dosage, is effective for turbidity removal even under the condition of a high raw-water turbidity, such as 300 TU.

The increase of raw-water turbidity resulted in slower reduction of the filtered-water turbidity and extension of the filter developing period. Conversely, the increase of coagulant dosage both accelerated the filtered-water

Table 2 | Average quality of raw water under the turbidity conditions

<table>
<thead>
<tr>
<th>Pre-set raw-water turbidity</th>
<th>Unit</th>
<th>5 TU</th>
<th>30 TU</th>
<th>300 TU</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>(−)</td>
<td>6.9</td>
<td>6.8</td>
<td>6.8</td>
</tr>
<tr>
<td>Turbidity</td>
<td>(TU)a</td>
<td>7.9</td>
<td>36</td>
<td>360</td>
</tr>
<tr>
<td>Water temperature</td>
<td>(°C)</td>
<td>17.5</td>
<td>17.2</td>
<td>17.3</td>
</tr>
<tr>
<td>DOCb</td>
<td>(mg/L)</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>(mg/L)</td>
<td>91.0</td>
<td>90.8</td>
<td>90.9</td>
</tr>
<tr>
<td>Electrical conductivity</td>
<td>(μS/cm)</td>
<td>379</td>
<td>379</td>
<td>379</td>
</tr>
<tr>
<td>Total Al</td>
<td>(μg/L)</td>
<td>35.0</td>
<td>202</td>
<td>1,070</td>
</tr>
<tr>
<td>Dissolved Al</td>
<td>(μg/L)</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Total Mn</td>
<td>(μg/L)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Dissolved Mn</td>
<td>(μg/L)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Total Fe</td>
<td>(μg/L)</td>
<td>3.0</td>
<td>7.1</td>
<td>42.4</td>
</tr>
<tr>
<td>Dissolved Fe</td>
<td>(μg/L)</td>
<td>&lt;1.0</td>
<td>&lt;1.0</td>
<td>&lt;1.0</td>
</tr>
</tbody>
</table>

*aThe traditional Japanese turbidity unit is the kaolin turbidity unit.
*bDOC was analyzed after experiment, not average.

Figure 2 | Turbidity of water in the pilot-scale plant when raw, after coagulation–sedimentation with 51%-PACl, after sand filtration, and after membrane filtration. (While turbidity after membrane filtration was not detected by 0.0001 TU through the experiment, they were showed as 0.0001 TU.)
turbidity decreased and shortened the filter stabilizing period. A result which Tambo et al. (1975) had reported in experimental study using aluminum sulfate as coagulant was similar to this result. For a rapid filtration system, these results indicate that it is essential to minimize an effect on quality of finished water by extension of the drain time of the filtering-start-up water which had relatively high turbidity during a filter stabilizing period after backwashing of the sand-filter bed, or adequate operation in the coagulation–sedimentation process such as dosing coagulant adaptively in order to adapt a sharp rise in raw-water turbidity.

In the case of membrane filtration, the turbidity of the filtered water was under the minimum (0.0001 TU) detection limit of the super-sensitive laser turbidity meter (Figure 2) and not influenced by changes of conditions, such as raw-water turbidity, coagulant dosage and type of PACI. Xianglia et al. (2008) reported similar results, although using FeCl3 as a coagulant.

Figure 3 shows a comparison of the turbidity trends for 51%-PACI and 72%-PACI. No significant difference between the pair of coagulants was observed in the turbidity of the raw water or settled water. While Lin et al. (2008) reported high basicity PACI (PACI-E) was superior to low basicity PACI (PACI-L) in turbidity removal for highly turbid water up to 5,000 NTU by jar-tests, it is considered to result from difference of pH condition (Lin et al. controlled the pH at 7 for PACI-L and at 8 for PACI-E). In the case of sand
filtration, the filtered-water turbidity decrease was quicker and the filter stabilization period was shorter when using 72%-PACl. These results appear to be the response of floc characteristics, i.e. greater particle size and higher zeta potential for 72%-PACl than for 51%-PACl (Kobayashi et al. 2011). This suggested that using 72%-PACl as coagulant would shorten the drain time of start-up water and would be a useful option to help manage a sudden rise in raw-water turbidity.

Figure 4 shows the trends in TMP (normalized to 25 °C) when using 51%-PACl as the coagulant. In this experiment, neither the raw-water turbidity nor the 51%-PACl coagulant dosage affected the TMP significantly. Moreover, there was no considerable difference between the pair of coagulants. Previous studies (Lee et al. 2006; Choi & Kweon 2010) reported that the difference of the turbidity from kaolin particles had little effect on the flux decline, but natural particles were found to be detrimental to the membrane performance. In our experiment, raw water was prepared by adding kaolin suspension to groundwater from deep well so that there would be no significant difference between conditions. With the membrane filtration system, it became clear that the sharp rise in raw-water turbidity would little affect the turbidity removal or the TMP in thus short-term such as our experiment period of 5 days. These results indicated that the membrane filtration system would be safer and more stable than the rapid filtration system in the event of a rise in raw-water turbidity. In contrast, we would need to validate TMP over the longer term.

CONCLUSIONS

Adequate control of coagulant dosage would be needed to diminish influences such as the extended drain time of start-up water due to the slower decrease of filtered-water turbidity. Using high-basicticity (72%) PACl as the coagulant reduced both the turbidity of sand-filtered water and the filter stabilizing period.

The membrane filtration system obtained lower turbidity in the finished water compared to conventional filtration, suggesting that rapid filtration systems, that are coagulation/sedimentation sand-filtration, are less robust against sharp increases in raw-water turbidity. However, under all the experimental conditions, the finished-water turbidity of both the membrane filtration and the rapid filtration satisfied the 2.0 TU limit of the drinking water quality standard in Japan.

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REFERENCES


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