Practical Paper

Using carbon dioxide to cope with fluctuations in raw water pH and maintain effective conventional treatment

Keith E. Dennett and Ryan T. Dixon

ABSTRACT

During the warmer months of the year, the Truckee River experiences dramatic diurnal fluctuations in pH from a low of about pH 7.5 to as high as pH 9.2. These pH fluctuations can significantly impact conventional surface water treatment, especially coagulation and filtration. The use of carbon dioxide (CO_2) to maintain the raw water pH was evaluated during bench-scale, pilot-scale, and full-scale testing using polyaluminium chloride (PACl) as the primary coagulant. The objectives were to minimize the required PACl dose and the concentration of residual aluminium as well as maintain low filter effluent particle counts. Results indicated that particle removal could be improved by either increasing the PACl dose or by reducing the raw water pH. For a fixed PACl dose, filter performance consistently improved as pH decreased. An increase in raw water pH required a corresponding increase in PACl dose to maintain filter performance. To minimize the PACl dose, the raw water pH must be maintained to ensure consistent filter performance. Full-scale tests demonstrated that using CO_2 to adjust the raw water pH to a target of 7.5 to 7.8 minimized overall chemical costs and eliminated the need to frequently adjust PACl dose to compensate for pH fluctuations.

Key words | carbon dioxide, coagulation, filtration, pH, polyaluminium chloride, particle destabilization

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INTRODUCTION

The multiple treatment processes that occur in series at conventional surface water treatment facilities are designed to remove contaminants like turbidity, natural organic matter (NOM), protozoan cysts and micro-organisms. Properly operated conventional treatment systems using coagulation, flocculation, sedimentation, filtration, and disinfection present a formidable barrier to the passage of these contaminants (Cleasby & Logsdon 1999).

Some objectives of coagulation are: (1) to maximize the removal of particles and turbidity by subsequent solid-liquid separation processes such as sedimentation, flotation, and filtration; (2) to maximize the removal of natural organic matter (NOM) and DBP precursors; (3) to

minimize the concentration of residual coagulant; (4) to minimize the production of sludge; and (5) to minimize operating costs (Edzwald & Tobiason 1999).

Increased significance has been placed on coagulation in order to maximize the removal of disinfection byproduct (DBP) precursors such as natural organic matter, and minimize DBP formation following the passage of the Disinfectants and Disinfection Byproducts Rule (USEPA 1998). The Surface Water Treatment Rule and the Interim Enhanced Surface Water Treatment Rule further emphasized the importance of carefully controlling coagulation and filtration to ensure the inactivation of *Giardia* cysts and *Cryptosporidium* oocysts during conventional water treatment (Edzwald & Kelley 1998; Cleasby & Logsdon

1999; Edzwald & Tobiason 1999; Kawamura 1999; Logsdon 2000; Dugan *et al.* 2001).

Changes in raw water quality such as increased turbidity and fluctuations in pH and alkalinity can pose challenges for water treatment plant operators. In order to ensure that coagulation is effective, Consonery *et al.* (1997) recommended that each conventional water treatment facility: (1) develop a coagulant control strategy to identify how to optimise the coagulant dose and pH conditions to respond to fluctuations in raw water quality; (2) provide adequate rapid mixing to quickly disperse chemicals; and (3) conduct proper process monitoring and sampling to ensure that treatment processes are optimised.

PROJECT BACKGROUND

The Truckee River is the primary source of drinking water for the metropolitan areas of Reno and Sparks in Nevada, USA. The Truckee Meadows Water Authority (TMWA) owns and operates two conventional surface water treatment plants (WTPs). The Glendale WTP has a design capacity of 0.12×10^6 m^3/d (32 mgd) and the Chalk Bluff WTP has a design capacity of 0.273×10^6 m^3/d (72 mgd). This region is an arid environment that receives an average of 190 mm (7.5 in) of precipitation each year. Typically, Glendale is only operated during the warmer months of the year when water demands are highest. During the remainder of the year, Chalk Bluff is capable of meeting the entire water demand. Both Glendale and Chalk Bluff are operated at design capacities during the summer months to satisfy greatly increased water demands, mainly due to residential irrigation.

The Truckee River is a relatively high quality surface water with fairly stable characteristics. Typical raw water quality parameters are included in Table 1. Most of the time, the turbidity of the raw water is between 2.5 and 5 NTU, except during infrequent storm events and during the early spring due to increased runoff from snowmelt. In addition, the concentration of total organic carbon (TOC) in the raw water is typically around 1.5 mg/l. Because the TOC is less than 2 mg/l, Chalk Bluff and Glendale meet the requirements of the Disinfectants and Disinfection

Table 1 | Typical raw water characteristics of the Truckee River

Parameter (units)	Typical range
Turbidity (NTU)	2–10
pH	7.6–9.0
Alkalinity (mg/l as $CaCO_3$)	44–51
Total organic carbon (mg/l)	1–2
UV 254 (cm^{-1})	0.028–0.030
Mn (mg/l)	< 0.01
Fe (mg/l)	0.05
Temperature (°C)	8–20
Particle counts (> 2 μm) (˙/ml)	24,500–31,000

Byproducts Rule (USEPA 1998) to control disinfection byproduct (DBP) formation. Thus, the primary treatment objective at these two WTPs is the removal of particles causing turbidity.

In order to respond to increases in turbidity during storm events, Chalk Bluff changed its primary coagulant from alum to a polyaluminium chloride (PACl) in January 1999. Based on preliminary testing, PACl appeared to be effective over a wide range of raw water turbidities. The flexibility of using PACl allowed plant operators to increase the dose during periods of high turbidity without concerns of 'overdosing' and loss of treatment. PACl consistently provided low turbidities and particle counts during sedimentation and filtration, extended filter run times without any noticeable deterioration in performance, and reduced solids production. The use of PACl appeared to satisfy several of the objectives of coagulation summarized by Edzwald & Tobiason (1999) including: (1) maximizing the removal of particles and turbidity through sedimentation and filtration; (2) minimizing the concentration of residual coagulant; (3) minimizing the production of sludge; and (4) minimizing operating costs.

Minimizing the quantity of solids generated during treatment is important since both Chalk Bluff and
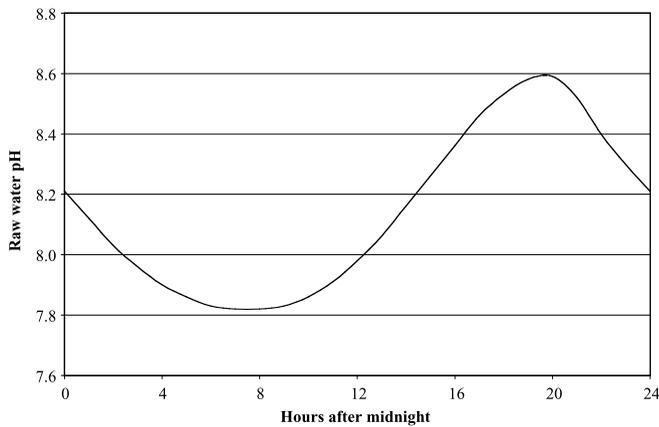
Figure 1 | Typical fluctuations in raw water pH.

Figure 2 | Variations in PACl dose and settled water turbidity during full-scale treatment due to fluctuations in raw water pH.

Glendale rely on evaporation ponds to dewater sludge from the sedimentation basins and solids in the spent filter backwash water. The change in primary coagulant from alum to PACl at Chalk Bluff was initiated because of the relatively large quantity of solids generated and the reduction in alkalinity associated with the use of alum. The expense of adding an additional water recovery basin at Chalk Bluff to handle solids was estimated to be $750,000 or more. In addition, in order to maintain adequate alkalinity in the raw water, the existing soda ash system would require capital improvements of approximately $500,000. To avoid these additional costs, the primary coagulant was switched to PACl. After switching to PACl, it was observed that the resulting solids dewatered more quickly than alum sludge and were also easier to handle and transport offsite.

Even though the quality of the raw water is fairly stable, one characteristic that exhibits some seasonal variability is the pH. During the warmer months of the year (i.e. March through October), the water in the Truckee River experiences dramatic diurnal fluctuations in pH caused by algal growth. The pH typically fluctuates from a low of about pH 7.5 during the morning hours to as high as pH 9.2 during the evening hours. Figure 1 shows typical daily fluctuations in raw water pH for the Truckee River.

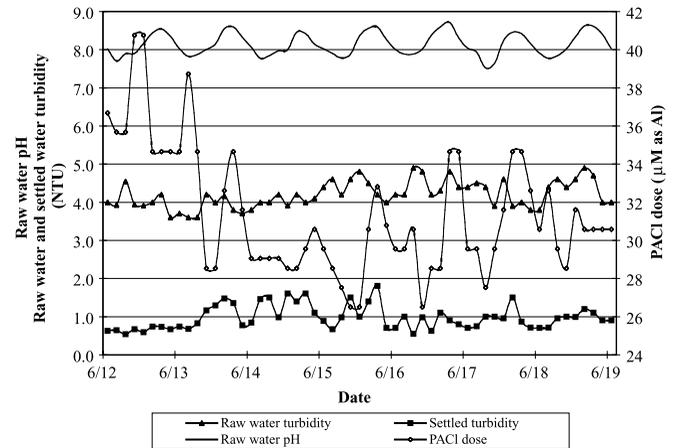Approximately half of the raw water for Chalk Bluff is obtained from the Highland Ditch, a gravity flow irrigation ditch that diverts flow from the Truckee River approximately 10 km upstream from Chalk Bluff. The remainder of the raw water is pumped directly from the river. The Highland Ditch experiences even more pronounced fluctuations in pH than the river because of the growth of algae and other aquatic plant life. As a result, the pH of the combined influent to Chalk Bluff from the Truckee River and the Highland Ditch may exceed pH 9 in the evening hours during the warmer months of the year.

At Chalk Bluff, fluctuations in raw water pH have resulted in: (1) an increase in the required coagulant dose; (2) a decrease in the efficiency and stability of conventional treatment; (3) an increase in the concentration of residual aluminium in the finished water; and (4) an increase in overall treatment costs. As shown in Figure 2, because of fluctuations in raw water pH, frequent adjustments in the PACl dose were required to maintain effective treatment. Since coagulant dosing is often determined from the results of infrequent jar testing or operator experience, fluctuations in raw water characteristics may frequently lead to either underdosing or overdosing.

Increases in particle counts in the filter effluent at both Glendale and Chalk Bluff provided evidence that filter performance deteriorated whenever the raw water pH was elevated. Proper coagulation that effectively

destabilizes particles in the water is recognized as the single most important factor influencing the removal of particles and microorganisms by granular media filtration (Amirtharajah 1988; Nieminski & Ongerth 1995; Hargesheimer *et al.* 1998; Cleasby & Logsdon 1999; Kawamura 1999; Logsdon 2000; Dugan *et al.* 2001). Filtration fails whenever chemical pretreatment is ineffective (Amirtharajah 1988; Logsdon 2000). Since the effectiveness of coagulation is dependent on both the pH of the coagulated water and the coagulant dose, optimum treatment requires careful control of pH conditions and coagulant dose.

Another major concern associated with the use of PACl also surfaced during the summer months. A notable increase in the concentration of residual aluminium was detected in the finished water from Chalk Bluff. In August 1999, the finished water from Chalk Bluff contained more than 0.10 mg/l of aluminium. Even though this concentration is within the USEPA secondary maximum contaminant level range of 0.05 to 0.20 mg/l, it was of significant concern because it was approximately three times higher than the concentration in the finished water from Glendale, which continues to use alum as its primary coagulant. It was uncertain whether the higher concentrations of residual aluminium were due to the use of PACl and/or the fluctuations in raw water pH that occur during the warmer months.

TMWA has considered switching from alum to PACl at Glendale to enable more consistent operations at both Chalk Bluff and Glendale. However, problems associated with fluctuations in raw water pH, frequent adjustment of coagulant doses, increased particle counts in the filter effluent, and elevated concentrations of residual aluminium in the finished water observed at Chalk Bluff need to be resolved. In order to identify the factors causing these problems, bench-scale, pilot-scale, and full-scale tests using carbon dioxide (CO_2) to adjust and maintain the pH of the raw water were conducted. CO_2 was selected as the acidifying agent due to its ability to reduce pH without changing alkalinity. The potential hazards associated with using sulphuric acid for full-scale treatment and the costs associated with upgrading the existing soda ash systems to maintain alkalinity made CO_2 an appropriate choice (Chowdhry *et al.* 1995).

RESEARCH OBJECTIVES

This research project was conducted in an effort to resolve problems with the stability and effectiveness of conventional surface water treatment resulting from fluctuations in the raw water pH. The main objectives of this research were to: (1) determine if CO_2 can be effectively and economically used to adjust and maintain the raw water pH; (2) optimise coagulation using PACl along with CO_2 to adjust the raw water pH and minimize the required PACl dose; (3) monitor the effects of pH adjustment using CO_2 on overall treatment effectiveness, especially particle removal during filtration; and (4) minimize the concentration of residual aluminium in the finished water.

MATERIALS AND METHODS

The first portion of this research involved bench-scale testing, which consisted mainly of jar testing. The second portion of this research consisted of pilot-scale testing to monitor the effects of raw water pH on overall treatment performance, especially filtration. The final portion of the research involved full-scale testing of the addition of CO_2 to control fluctuations in raw water pH and stabilize conventional treatment processes.

Bench-scale testing

Jar tests were conducted using raw water from the Truckee River in order to examine the influence of raw water pH on the coagulant dose required for turbidity removal, the zeta potential of floc particles, and the concentration of residual aluminium. The performance of SternPAC 70 (Sternson Limited, Brantford, Ontario), a high basicity PACl, was evaluated over a wide range of doses and pH conditions. It had a basicity of 70%, contained 5.5% of aluminium by weight, and was used in neat product form.

Raw water was pumped directly from the intake channel at Glendale. Typical characteristics of the raw water

prior to pH adjustment are summarized in Table 1. Water for jar testing was prepared in a 225-litre (50-gallon) high-density polyethylene tank. To reduce the pH, CO$_2$ was injected into the raw water supply line through a diffuser. To raise the pH, sodium hydroxide (NaOH) was added to the water.

Jar testing was conducted using a standard Phipps and Bird jar test apparatus (Richmond, Virginia, USA) with 2-litre square beakers. The mixing conditions used during jar testing attempted to simulate the conditions used for full-scale treatment at Chalk Bluff and Glendale. The jar test apparatus was operated at maximum speed (approximately 300 rpm, $G = 300$ s^{-1}) for 1 min to simulate rapid mixing. Three-stage tapered flocculation was simulated by operating the jar test apparatus at speeds of 60 rpm, 35 rpm, and 22 rpm during sequential 7-min intervals. This was followed by 10 min of settling time.

After rapid mixing, floc particles were withdrawn from selected samples. The zeta potential of these particles was analysed using a Zeta-Meter 3.0 Plus (Zeta-Meter Inc., Staunton, Virginia, USA). Platinum (anode) and molybdenum (cathode) electrodes were used to alleviate problems associated with air bubbles. A standard Min-U-Sil suspension was used to check the accuracy and precision of the instrument. The measurement of the zeta potential of floc particles can provide an indication of the effectiveness of particle destabilization (Licsko 1997; Letterman *et al.* 1999).

After settling, samples of supernatant were collected and analysed for turbidity, alkalinity, pH, temperature, and residual aluminium. Turbidity was measured using a Hach 2100N bench-top turbidimeter (Loveland, Colorado, USA). Alkalinity was measured according to Standard Methods 2320 B (APHA-AWWA-WEF 1998). Temperature and pH were measured using an Accumet pH meter (Fisher Scientific). Selected samples of the supernatant were filtered through either 0.8 micron (μm) or 0.45 μm filter papers (Millipore MF membranes). After filtration, the turbidity and residual aluminium of the samples were measured. Aluminum samples were acidified and the concentration of residual aluminium was determined using Method 200.8 (USEPA 1994) with a Perkin-Elmer Sciex ELAN 6100 ICP-MS (Wellesley, Massachusetts, USA).

Pilot-scale testing

Pilot-scale testing was conducted to evaluate the effectiveness of adjusting the pH of the raw water on the required coagulant dose while monitoring the efficiency of particle removal by dual media filtration. The performance of filtration was monitored using particle counters. Two consecutive pilot tests were conducted. The first test was conducted at lower raw water pH conditions (e.g. pH 7.5 to pH 8.0) and the second test was conducted at higher raw water pH conditions (e.g. pH 8.7 to pH 9.2). These two pH ranges were chosen in order to simulate the pH extremes that typically occur in the raw water from the Truckee River. The pH of the raw water was adjusted to the desired range prior to coagulant addition by injecting CO$_2$ gas into a pressurized pipe to decrease the pH or by adding a solution of NaOH to increase the pH.

The pilot system located at Glendale was designed to simulate the full-scale conventional surface water treatment processes used at both Glendale and Chalk Bluff. These processes include prechlorination, in-line rapid mix, three-stage tapered flocculation, sedimentation in Parkson Lamella® plate settlers (Fort Lauderdale, Florida, USA), and filtration through dual media filters containing anthracite coal and sand. A process schematic of the pilot system is shown in Figure 3. The pilot system was designed to treat a raw water flow rate of up to 34 l/min (9 gpm).

The raw water was pumped directly into the pilot system from the intake channel at Glendale. The raw water turbidity was monitored using a Hach 2100N turbidimeter (Loveland, Colorado, USA) and the raw water particle counts were monitored using a Met One A2500 WGS counter (Pacific Scientific, Grants Pass, Oregon, USA).

Prior to the rapid mix unit, CO$_2$ gas was injected from a gas cylinder through a diffuser into the raw water supply line. The flow then passed through a 25 mm (1 in) diameter in-line static mixer (Koflo Corporation, Cary, Illinois, USA). Following CO$_2$ addition, the water had a travel time of approximately 1.5 min before reaching the rapid mix unit where other chemicals were added. The CO$_2$ dose typically ranged between 0 and 3 mg/l, depending on the desired pH conditions and fluctuations of the raw water pH.
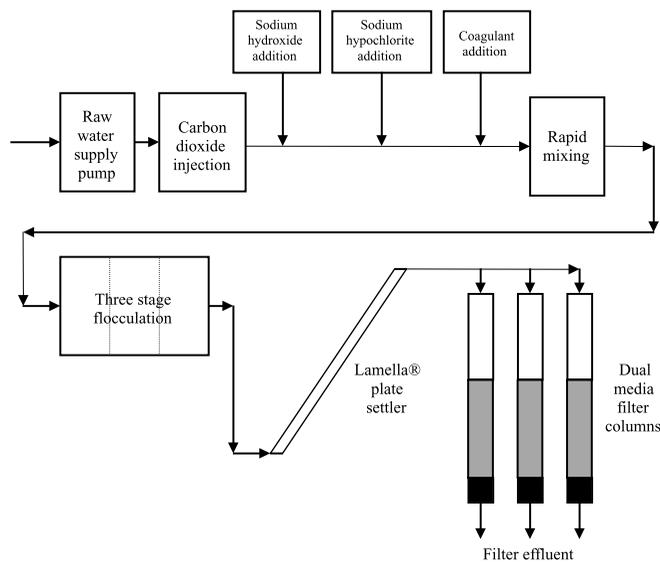
Figure 3 │ Process schematic for the pilot-scale system.

Immediately before rapid mixing, the raw water was chlorinated using a solution of sodium hypochlorite (NaOCl) to achieve a free chlorine concentration of 0.5 mg/l. Prechlorination is practised at both Chalk Bluff and Glendale for preoxidation and to control algal growth and microbiological growth in the raw water ponds and within the flocculation and sedimentation basins. During the pilot tests conducted at higher raw water pH conditions, a solution of NaOH was also added prior to rapid mixing. PACl was also fed immediately before the rapid mix unit. The PACl dose was measured using a stopwatch and a graduated cylinder.

The rapid mix unit had a detention time of approximately 15 s when the flow through the system was 24.6 l/min (6.5 gpm). The rapid mixer provided a mixing intensity with a G-value of approximately 600 s^{-1}. After rapid mixing, the water passed through a tapered, three-stage, variable speed flocculation basin. Approximate G-values for each stage were 70, 50 and 30 s^{-1}, respectively. The detention time in each stage of the flocculator was approximately 7 min when the flow through the system was 24.6 l/min (6.5 gpm).

The flow then entered a Lamella® plate settler that simulated the full-scale plate settlers used at both the Glendale and the Chalk Bluff. The design hydraulic load-

ing rate for the plate settler was 0.86 m/h (0.35 gpm/ft²) of projected horizontal plate area. The settled water turbidity was monitored using a Hach 1720 C turbidimeter (Loveland, Colorado, USA) and filter influent particle counts were monitored using a Met One Model PCX particle counter (Pacific Scientific, Grants Pass, Oregon, USA).

The water was then filtered through one of three identical dual media filter columns operating simultaneously in parallel. Each filter column had a diameter of 190 mm (7.5 in) and contained 1.37 m (54 in) of anthracite coal on top of 254 mm (10 in) of silica sand. The filter media specifications for the anthracite coal were an effective size (ES) of 1.00 to 1.10 mm, a uniformity coefficient (UC) of 1.5 or less, and a specific gravity (s.g.) greater than 1.6. The filter media specifications for the silica sand were an ES of 0.50 to 0.58 mm, a UC of 1.6 or less, and an s.g. greater than 2.5. A filter-loading rate of 15.9 m/h (6.5 gpm/ft²) was maintained throughout the duration of each pilot test. The turbidity and particle counts in the effluent from each filter column were monitored using a Hach 1720C turbidimeter and a Met One particle counter, respectively. After either particle breakthrough occurred or terminal head loss was reached, the filters were backwashed using air scour followed by a water wash. If the filter effluent particle counts exceeded 100 counts/ml, particle breakthrough was considered to have occurred. The terminal head loss for the filter columns was 3 m (10 ft).

The pilot system was operated at hydraulic loadings and detention times that simulated the operation of the full-scale treatment facilities as closely as possible. While each pilot test was in progress, the treatment conditions were systematically adjusted in order to evaluate the effects of the raw water pH, the coagulant dose, and the pH of the coagulated water on the particle counts in the filter influent and filter effluent.

The pilot system was operated in an attempt to identify the optimum treatment conditions (i.e. the minimum required coagulant dose for the pH conditions) while maintaining filter effluent particle counts of 20 counts per millilitre (counts/ml) or lower. Particle counts represented the cumulative number of particles greater than 2.0 μm. A particle count of 20 counts/ml was selected as a

'target' for filter performance based on typical operations criteria used at both Glendale and Chalk Bluff. Turbidity has traditionally been the primary water quality parameter used to assess particle removal during water treatment (Lusardi & Consonery 1999; Eisnor *et al.* 2001). However, particle counters are becoming increasingly popular for process optimisation in conventional water treatment plants because of their ability to more quickly detect decreases in filter performance resulting from changes in raw water quality or from equipment malfunction (Hatukai *et al.* 1997; Hargesheimer *et al.* 1998; Martin 1998; Eisnor *et al.* 2001; Bryant 2001).

Figure 4 | Variations in coagulated water pH and settled water turbidity with PACl dose.

Full-scale testing

For the full-scale testing, a 5.5 metric ton (6 ton) carbon dioxide receiver was temporarily installed at Chalk Bluff. CO_2 was stored as a liquid at approximately 20 atm (295 psig) and was piped from the receiver to a vaporizer. The vaporizer heated the liquid to approximately 20°C causing the liquid to undergo a phase change to a gas. The gas was fed through two parallel rotameters into two separate vaults located immediately after the raw water screening facility. Temperature and pressure gauges were placed after the rotameters to facilitate in the calculation of the CO_2 dose. The system was capable of delivering CO_2 doses of up to 3.6 mg/l. The CO_2 gas met all requirements specified by ANSI/AWWA (1995). The CO_2 was sparged into the raw water using 25 mm diameter, 1.2 m long diffusers having a pore size of approximately 30 μm (Interstate Specialty, Leicester, MA).

There was approximately 1 min of detention time within the pipes leading from the screening facility to the point of coagulant addition immediately upstream from the in-line blender rapid mixer. The in-line blender had a *G*-value of approximately 3000 s^{-1} and a detention time of less than 1 s. The tapered, three-stage flocculation basins provided *G*-values of approximately 70, 50 and 30 s^{-1}, respectively. The total detention time in the flocculation basins was approximately 22 min during high-rate filtration. The hydraulic loading rate for the Lamella® plate settlers in the sedimentation basins was 0.86 m/h (0.35 gpm/ft²) during high-rate filtration. The dual media
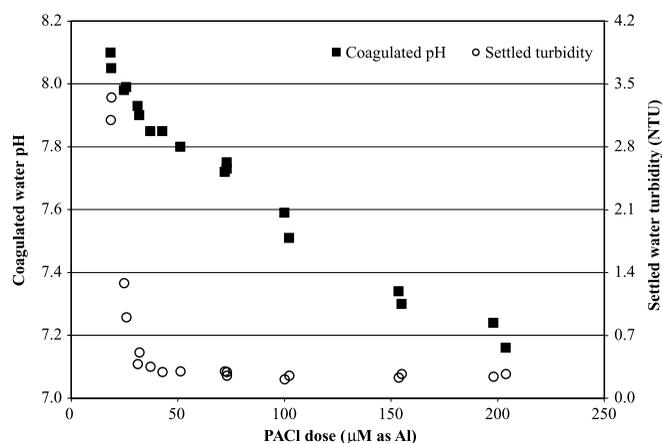
filters consisted of 1.37 m (54 in) of anthracite coal and 254 mm (10 in) of silica sand. Filter media specifications were identical to those provided earlier for the filter columns in the pilot system. Leopold underdrains supported the filter media. The filter-loading rate during the full-scale tests was 15.9 m/h (6.5 gpm/ft²). The filters were backwashed based on either filter head loss, filter effluent turbidity, or filter effluent particle counts.

During full-scale tests, CO_2 was used to adjust and maintain the pH of the raw water at a desired pH for a period of approximately 2 weeks. The objective of the full-scale tests was to monitor the overall effectiveness of treatment while using CO_2 to control fluctuations in the pH of the raw water.

RESULTS AND DISCUSSION

Bench-scale testing

The results of initial jar tests that were conducted using a large range of PACl doses to determine appropriate conditions for effective turbidity removal are shown in Figures 4 & 5. The minimum required dose of PACl for effective removal of turbidity was around 30 to 50 μM as aluminium (0.80 to 1.35 mg/l as Al), as shown in Figure 4. For these doses, the pH of the coagulated water was around pH 7.8 to pH 7.9. Higher doses of PACl also
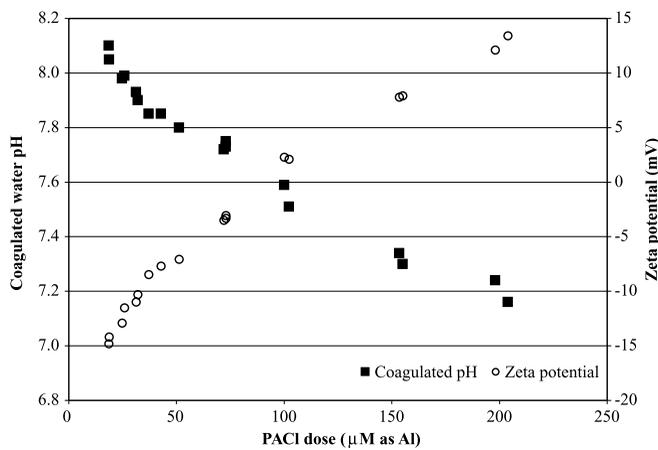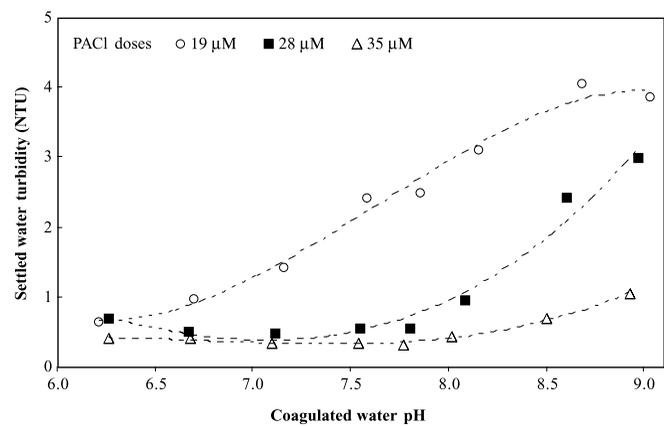
Figure 5 | Variations in coagulated water pH and zeta potential of floc particles with PACl dose.
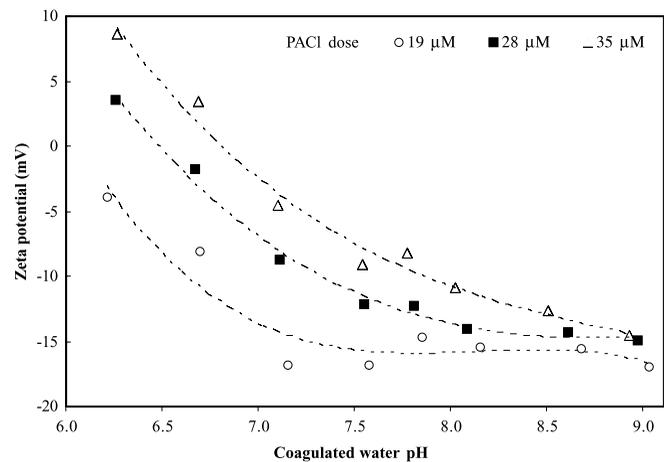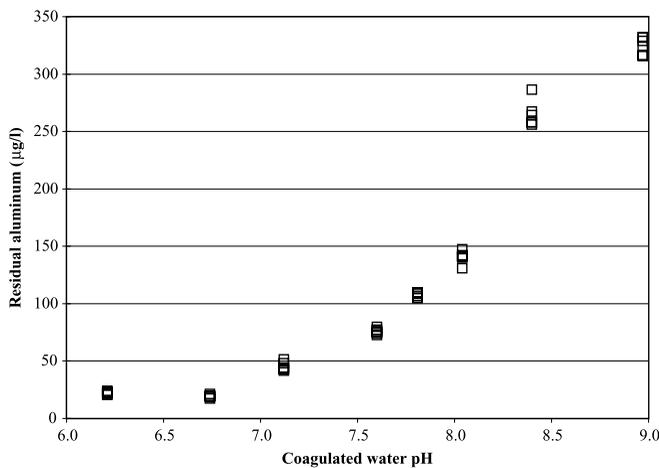

Figure 6 | Variations in settled water turbidity with coagulated water pH for different PACl doses.

Figure 7 | Variations in zeta potential of floc particles with coagulated water pH for different PACl doses.

effectively removed turbidity, but these coagulant doses were excessive. Turbidity was not effectively removed when the dose of PACl exceeded 815 μM as aluminium (22.0 mg/l as Al). Data for PACl doses greater than 204 μM as aluminium (5.50 mg/l as Al) were not shown in the figures since such high doses of PACl are excessive for this water.

The variation in the zeta potential of floc particles with the dose of PACl is shown in Figure 5. As the PACl dose increased, the zeta potential became less negative and increased in positive value when the PACl dose exceeded 90 μM as aluminium (2.43 mg/l as Al). In general, turbidity removal was effective when the zeta potential was approximately − 10 mV or less negative. The isoelectric point corresponded to a PACl dose of approximately 90 μM as aluminium. Above this dose, charge reversal occurred. However, turbidity removal was still effective. This was consistent with reports from treatment plant operators at Chalk Bluff that PACl provided effective turbidity removal even during 'overdosing'.

Figures 6 & 7 show the results of a series of jar tests conducted at three doses of PACl over a range of pH conditions. The pH of the raw water was adjusted using CO₂ prior to the addition of PACl. The effects of the PACl dose and the coagulated water pH on turbidity removal are shown in Figure 6. For a PACl dose of 19 μM as aluminium (0.51 mg/l as Al), turbidity removal was only

effective when the pH of the coagulated water was pH 6.2. The higher doses of PACl resulted in effective removal of turbidity over a broader range of pH conditions. A PACl dose of 28 μM as aluminium (0.76 mg/l as Al) was equally effective for pH conditions from pH 6.2 up to pH 8, and a PACl dose of 35 μM as aluminium (0.94 mg/l as Al) was effective from pH 6.2 up to approximately pH 8.5. These results clearly demonstrated that lower PACl doses require lower pH conditions for comparable removal of turbidity. Thus, if a specific objective of water treatment is to minimize the required PACl dose, the pH conditions must be carefully controlled. However, if higher PACl
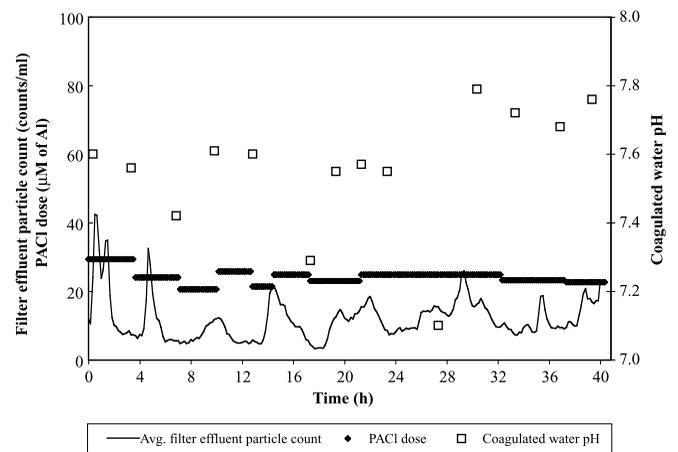
Figure 8 | Variations in concentration of residual aluminum with coagulated water pH.

Figure 9 | Effect of coagulation using PACl on filter effluent particle counts at lower raw water pH conditions.

Figure 10 | Filter performance using PACl at lower raw water pH conditions.
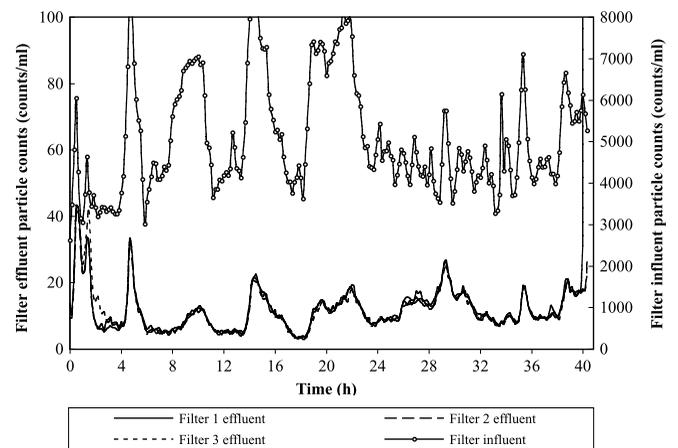
doses are used, control of the pH conditions is not as critical for effective removal of turbidity.

The effect of PACl dose and the coagulated water pH on the zeta potential of floc particles is shown in Figure 7. Consistent with the results shown in Figure 5, turbidity removal was most effective when the zeta potential of the floc particles was approximately −10 mV or less. As expected, the zeta potential became more positive as the pH decreased. For a given PACl dose, lower pH conditions enhanced particle destabilization, which generally improves flocculation, sedimentation, and filtration. In addition, the pH of the isoelectric point increased as the PACl dose increased. This indicates that an increase in the PACl dose can be used to enhance particle destabilization under higher pH conditions.

During a series of jar tests using PACl at a dose of 31 μM as aluminium (0.84 mg/l as Al), samples were collected at the end of the settling period and were filtered through cellulose filter papers with pore sizes of either 0.8 μm or 0.45 μm. These filtered samples were then analysed to determine the concentration of residual aluminium. There was no detectable difference in residual aluminium between the two pore sizes of the filter papers indicating that the residual aluminium was dissolved rather than particulate in nature. Figure 8 shows that the minimum concentration of residual aluminium was approximately 20 μg/l at a pH of approximately 6.7.

Pilot-scale testing

Figures 9 & 10 show the results from pilot-scale testing using PACl as the coagulant while maintaining the pH of the raw water within the range of pH 7.5 to pH 8.0 by adding CO_2. During this test, the coagulated water pH ranged from pH 7.4 to pH 7.8, depending on the doses of CO_2 and PACl. In Figure 9, the filter effluent particle counts from the three pilot filter columns have been averaged together. In Figure 10, the filter effluent particle counts for each of these filters are shown.

During most of this test, the average filter effluent particle counts were well below the target level of 20
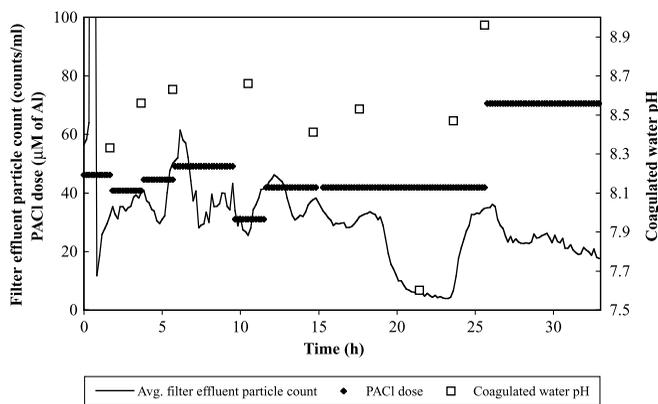
Figure 11 | Effect of coagulation using PACl on filter effluent particle counts at higher raw water pH conditions.
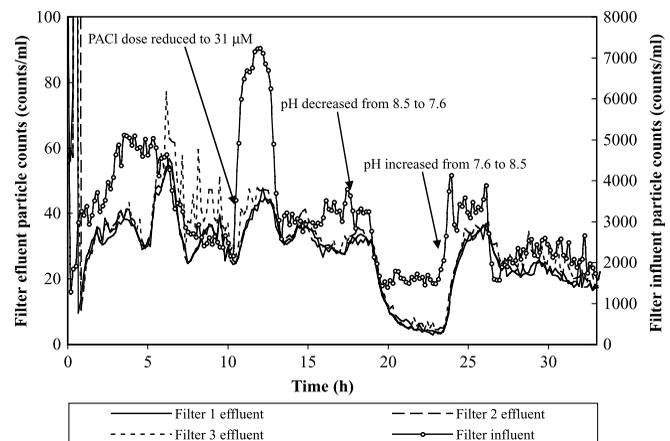
Figure 12 | Filter performance using PACl at higher raw water pH conditions.

counts/ml. However, the filter effluent particle counts generally exceeded 20 counts/ml whenever the filter influent particle counts exceeded about 5,500 counts/ml. The filter influent particle counts fluctuated widely depending on the dose of PACl and the pH of the coagulated water. In general, this occurred whenever the dose of PACl was less than 25 μM as aluminium (0.68 mg/l as Al) and/or the pH of the coagulated water was pH 7.5 or higher.

This suggests that the stability of the treatment processes could have been improved by increasing the dose of PACl and/or by operating at lower pH conditions. Otherwise, water treatment plant operators would need to monitor process performance much more carefully when operating at lower coagulant doses and/or when experiencing fluctuating raw water pH conditions. Operating at a higher coagulant dose and/or lower pH conditions would indeed improve the stability of the treatment processes; however, overall treatment costs would be higher.

Figures 11 & 12 show the results from pilot-scale testing using PACl while adjusting and maintaining the pH of the raw water pH within the range of pH 8.7 to pH 9.2. During this test, the pH of the coagulated water varied between pH 8.3 and pH 8.9, depending on the dose of PACl. However, at one point, the pH of the coagulated water dropped to pH 7.6 when the NaOH feed into the raw water supply was temporarily interrupted after about 18 h of run time.

The effect of the dose of PACl on the filter influent particle counts is clearly demonstrated in Figures 11 & 12. After approximately 10 h of run time, the dose of PACl was reduced from 49 μM as aluminium (1.32 mg/l as Al) to 31 μM as aluminium (0.84 mg/l as Al). As a result, the filter influent particle counts were observed to increase dramatically from approximately 2,000 counts/ml to more than 7,000 counts/ml within a very short period of time. The increase in filter influent particle counts suggested that particles did not flocculate or settle well at the reduced dose of PACl. When the dose of PACl was 49 μM as aluminium, the zeta potential of floc particles was -10 ± 0.4 mV. When the dose of PACl was decreased to 31 μM as aluminium, the zeta potential of the floc particles was -14 ± 0.5 mV. Thus, the decrease in PACl dose reduced particle destabilization.

During most of this test, the particle counts in the filter effluent were seldom below 20 counts/ml except during an episode after about 18 h of run time when the NaOH feed into the raw water supply was interrupted. During this episode, the dose of PACl was maintained at 42 μM as aluminium (1.13 mg/l as Al). As a result of no addition of NaOH, the pH of the coagulated water dropped from pH 8.5 to pH 7.6. After approximately 24 h of run time, the NaOH feed into the raw water supply was restored. Subsequently, the pH of the coagulated water increased from pH 7.6 to pH 8.5. This episode clearly demonstrated the influence of pH on the performance of filtration.

Particle counts in the filter influent dropped from approximately 3,200 counts/ml when the pH of the coagulated water was pH 8.5 to approximately 1,500 counts/ml at pH 7.6. Correspondingly, particle counts in the filter effluent dropped from about 35 counts/ml to below 5 counts/ml.

The reduction in pH affected the zeta potential of the floc particles. When the pH of the coagulated water was pH 8.5, the zeta potential of the floc particles was -11 ± 0.6 mV. When the pH of the coagulated water dropped to pH 7.6, the zeta potential of the floc particles was -6 ± 0.5 mV. This indicated that the reduction in pH enhanced the destabilization of the floc particles and subsequently improved the removal of particles during sedimentation and filtration.

Near the end of this test, the dose of PACl was increased from 42 μM as aluminium (1.13 mg/l as Al) to more than 70 μM as aluminium (1.89 mg/l as Al). This increase in coagulant dose reduced the particle counts in the filter effluent to around 20 counts/ml. The improved performance of filtration resulted from enhanced particle destabilization as evidenced by the change in the zeta potential of floc particles from -11 ± 0.6 mV at a PACl dose of 42 μM as aluminium to -5 ± 0.4 mV at a PACl dose of 70 μM as aluminium.

For the pilot test conducted under the lower pH conditions, particles were more effectively removed when the pH of the coagulated water was approximately pH 7.6 or lower and the dose of PACl was approximately 25 μM as aluminium (0.68 mg/l as Al). For the pilot test conducted under the higher pH conditions, particles were more effectively removed when the pH of the coagulated water was approximately pH 8.6 or lower and the dose of PACl was approximately 70 μM as aluminium (1.89 mg/l as Al).

Full-scale testing

During full-scale testing, the pH of the raw water was adjusted and maintained within a narrow range for an extended period of time. Since the CO_2 feed system at Chalk Bluff was only a temporary installation, automatic pH controllers were not installed. The CO_2 dose was adjusted manually by the water treatment plant operators
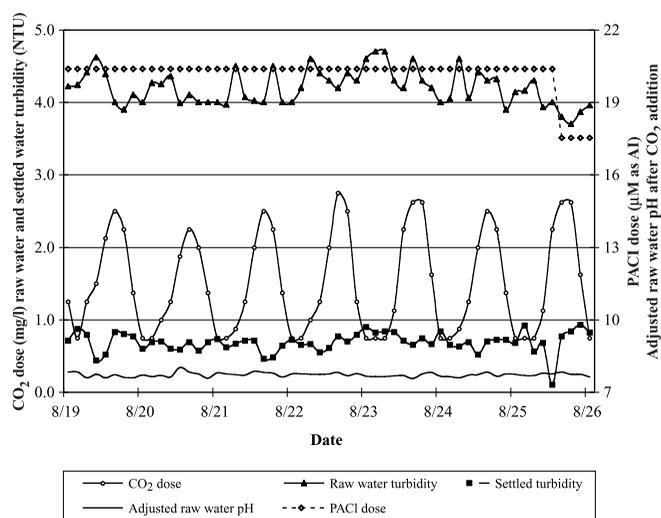
Figure 13 | Variations in settled water turbidity during full-scale testing using carbon dioxide to control fluctuations in raw water pH.

at Chalk Bluff whenever necessary. Typical doses of CO_2 ranged from 0.2 to 3.6 mg/l.

Figure 13 shows the results of a full-scale test when the pH of the raw water was adjusted and maintained using CO_2. Over the duration of this test, the average pH of the raw water after the addition of CO_2 was pH 7.7. During this test, the PACl dose was maintained constant at 20.4 μM as aluminium (0.55 mg/l as Al) for almost the entire period. The turbidity of the settled water was consistently around 0.8 NTU or less. As shown earlier in Figure 2, when the raw water pH was not adjusted using CO_2, frequent adjustments in the PACl dose were required. Under those conditions, the PACl dose varied from 25.5 to 40.8 μM as aluminium (0.69 to 1.10 mg/l as Al). In addition, the turbidity of the settled water fluctuated between 0.5 and 1.7 NTU. In comparison with the full-scale results shown in Figure 2, these full-scale results demonstrated that using CO_2 to control fluctuations in the raw water pH reduced the required dose of PACl and helped to stabilize treatment.

The highest concentration of residual aluminium during full-scale testing was 85 μg/l. The average concentration of residual aluminium in the filter effluent was 52 μg/l. TMWA has adopted a treatment objective of maintaining the concentration of residual aluminium in

the finished water at 100 µg/l or less. The data from full-scale testing indicated that this objective was achieved as long as the raw water pH is adjusted to pH 8.0 or less using CO_2. Also, if the raw water pH was adjusted and maintained at pH 7.8, fewer changes in coagulant doses were required throughout the day compared with higher pH conditions. Operating at pH 7.8 was also shown to minimize overall chemical costs.

The gas transfer efficiency was determined to be 50 to 100%, depending on the raw water pH and the desired pH of the water after the addition of CO_2. For the temporary CO_2 feed system that was utilized, the gas transfer efficiency was greater than 80% for a target pH of 7.8 and water with an average alkalinity of 43 mg/l as CaCO3 and average temperature of 20°C. The gas transfer efficiency decreased when the pH was less than the target of pH 7.8. During the full-scale tests when the raw water pH fluctuated between pH 7.7 and pH 8.7, approximately 300 kg of CO_2 was required daily to achieve a target pH of 7.8 when the plant flow rate was around 0.265×10^6 m³/d (70 mgd).

CONCLUSIONS

Bench-scale testing, pilot-scale testing, and full-scale testing confirmed that using carbon dioxide to adjust and maintain the raw water pH will: (1) improve coagulation, flocculation, sedimentation and filtration by enhancing particle destabilization; (2) eliminate the need to frequently adjust the PACl dose to compensate for fluctuations in raw water pH; (3) reduce the required coagulant dose; and (4) reduce the concentration of residual aluminium in the finished water.

In bench-scale testing, using carbon dioxide to control fluctuations in the raw water pH reduced the required PACl dose and improved coagulation, flocculation and sedimentation. Lower pH conditions promoted better-floc formation which reduced settled water turbidities and minimized residual soluble aluminium. Evidence of improved coagulation and flocculation was provided by monitoring zeta potential of floc particles. The minimum concentration of residual aluminium was achieved when the pH of the coagulated water was around pH 6.7.

Pilot-scale testing confirmed that the performance of dual media filtration was improved at lower pH conditions. Results indicated that minor variations in pH and/or coagulant dose can significantly affect the performance of dual media filtration, as evidenced by changes in the particle counts of the filter influent and filter effluent. Careful control of coagulant dose and pH conditions is essential in order to optimise coagulation and maintain consistent performance of dual media filtration. In general, an increase in coagulant dose reduced particle counts in the filter influent and filter effluent. For a fixed coagulant dose, a decrease in the pH of the coagulated water reduced particle counts in the filter influent and filter effluent.

Full-scale testing revealed that using CO_2 to reduce the raw water pH helped to stabilize treatment and reduced the need to adjust the PACl dose to compensate for higher pH conditions during fluctuations in raw water pH. At Chalk Bluff, using CO_2 to adjust and maintain the pH of the raw water at pH 7.8 was shown to minimize overall chemical costs. Based on the results from this testing, a permanent full-scale CO_2 system has been installed at the Chalk Bluff Water Treatment Plant.

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