Statistical significance testing of parallel pilot-scale coagulation optimization study to compare aluminum sulfate and polyaluminum chloride performance

Nicolás M. Peleato, John Armour and Robert C. Andrews

ABSTRACT

A 14 month pilot-scale coagulation optimization study was conducted at the Peterborough Water Treatment Plant (Ontario, Canada) to compare treatment performance resulting from the application of aluminum sulfate vs. polyaluminum chloride (PACl). This paper describes results obtained from applying a statistical analysis approach to evaluate impacts on pH, turbidity, total organic carbon (TOC), ultraviolet absorbance (UVA), particle counts, chlorine residuals, filter head loss, flow rate, trihalomethanes (THMs), and nine haloacetic acids (HAA$_9$). To allow a direct comparison, parallel pilot trains were operated such that they achieved equal settled water TOC by adjusting PACl dose, (52–74% of the alum dose by weight). Settled water turbidity was significantly higher (on average 0.23 NTU) in the alum treated water when compared to PACl. For equivalent filter run-times, head loss was greater by 0.002–0.011 m h^{-1} when applying alum. An increase in pH by approximately 0.7 units when using PACl was observed to cause a significant increase in THM formation (10–30%).

Key words | alum, coagulation, drinking water treatment, pilot, polyaluminum chloride

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LIST OF ABBREVIATIONS

Alum   Aluminum sulfate

EPA   Environmental Protection Agency

HAA$_9$ Haloacetic acids (monochloroacetic acid (MCAA), monobromoacetic acid (MBAA), dichloroacetic acid (DCAA), trichloroacetic acid (TCAA), bromochloroacetic acid (BCAA), dibromoacetic acid (DBAA), bromodichloroacetic acid (BDCAA), dibromochloroacetic acid (DBCAA), and tribromoacetic acid (TBAA))

MTBE   Methyl tert-butyl ether

NOM   Natural organic matter

NTU   Nephelometric turbidity unit

PACl   Polyaluminum chloride

THM   Trihalomethanes [trichloromethane (TCM), bromo-dichloromethane (BDCM), chlorodibromomethane (CDBM), and tribromomethane (TBM)]

TOC   Total organic carbon

UVA   Ultraviolet absorbance (at 254 nm)

UVT   Ultraviolet transmittance (at 254 nm)

INTRODUCTION

Implementing changes to water treatment processes has an inherent high degree of uncertainty. It is often not straightforward when scaling up the impacts of process changes at pilot testing, under controlled conditions, to full scale. In addition, challenges exist in observing seasonal impacts caused by changing source water quality. Pilot-scale studies have been shown as an effective means to address issues associated with scale and reduce errors in process optimization (Andrews *et al.* 2005; Knowles *et al.* 2012).

To take full advantage of pilot-scale studies, an appropriate experimental design must be established to confirm apparent process improvements and facilitate scale-up. At the core of robust pilot-based studies is the need to run two identical parallel trains where one serves as a control and is constantly compared to full-scale performance, while a second allows the impact of process changes to be observed. Fundamental to parallel pilot studies is the validation of similarity between both

pilot trains and the full-scale facility. Validation involves establishing, with statistical significance, that with equal treatment applied, both pilot trains and the full-scale train produce identical water quality at any given point in the process. This allows for the conclusion that observed water quality differences are attributable only to the controlled process changes (Anderson *et al.* 1993).

Pilot-scale studies were conducted with the objective to identify impacts on water quality from the use of alum versus polyaluminum chloride (PACl) as coagulants. The specific PACl selected for comparison to alum was chosen based on results of initial bench-scale jar tests of several coagulants. Since the primary objective of coagulation is to reduce natural organic matter (NOM), pilot trains were operated such that the filtered water total organic carbon (TOC) was equal and any observed water quality differences could be readily elucidated. While alum and PACl coagulation chemistry has been well studied, limited data exist regarding long term parallel comparisons at pilot or full scale. This paper first sets out to describe the analysis process applied in order to draw supportable conclusions from the extended pilot-scale study. The process includes setting up reasonable statistical tests and establishing water quality equivalence between pilot-scale plants as well as to the full-scale plant. Significant water quality differences between alum and PACl coagulation are then identified.

MATERIALS AND METHODS

The source water for both full- and pilot-scale trains was the Otonabee River, Ontario, Canada. A summary of typical water quality is shown in Table 1.

Table 1 | Peterborough raw water quality yearly ranges

Parameter	Range (yearly)
Temperature ($^\circ$C)	0.0–27.7
TOC (mg/L)	5.81–7.33
UVA (cm^{-1})	0.140–0.260
pH	7.43–8.62
Turbidity (NTU)	0.27–1.47

Pilot plant

Two identical pilot plant trains were designed to replicate the full-scale Peterborough water treatment plant. Figure 1 shows a simplified process flow diagram, which identifies major unit processes common to both full- and pilot-scale facilities.

The study consisted of two phases: baseline and experimental. During an initial baseline comparison phase, alum (General Chemical, Parsipanny, NJ) was applied to both pilot trains at a dose equal to the full-scale plant. This allowed for statistically establishing that treated water quality was equal between the two pilot trains as well as the full-scale plant. During the subsequent experimental phase, one pilot train continued to receive an alum dose equal to full scale (40.0–54.3 mg/L) whereas the second was dosed with PACl (HI-705, General Chemical, Parsipanny, NJ), (25.0–32.0 mg/L PACl) to achieve a filtered water TOC equal to the alum pilot.

Three sampling points in each treatment train were used including raw, settled (after coagulation), and filtered water. Online measurements included pH, temperature, and turbidity using a Hach 1720E (Mississauga, Ontario) low range turbidimeter and pH sensors; TOC using a General Electric Sievers 5310C on-line analyzer (Mississauga, Ontario); ultraviolet absorbance (UVA) at 254 nm with a RealTech UVT on-line analyzer (Whitby, Ontario); and particle counts using Hach 2200 PCX units (Mississauga, Ontario).

Disinfection by-product formation and analysis

Grab samples of filtered water collected from the full-scale and pilot treatment plants were chlorinated with sodium hypochlorite. The applied chlorine dose (2.3–3.6 mg/L total chlorine) was chosen to replicate the dose used at the full-scale plant. Chlorinated samples were sealed without
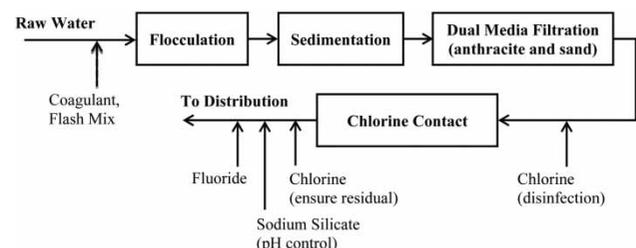

Figure 1 | Simplified process flow diagram.

head space and incubated in a water bath at the same temperature as the ambient treated water for 24 hours. Following 24 hours (± 0.5 hour) the free chlorine residual was measured and remaining chlorine quenched using ammonium chloride. Duplicate 25 mL head space free samples of quenched solution were retained for trihalomethane (THM) and nine haloacetic acids (HAA$_9$) analysis.

THM analyses were conducted as per EPA Method 551.1 using methyl tert-butyl ether (USEPA 1990). All four THM species were quantified: trichloromethane (TCM), bromodichloromethane (BDCM), chlorodibromomethane (CDBM), and tribromomethane (TBM). EPA Method 552.3 (United States Environmental Protection Agency [USEPA] 2003) was used for HAA$_9$ analyses which included: monochloroacetic acid (MCAA), monobromoacetic acid (MBAA), dichloroacetic acid (DCAA), trichloroacetic acid (TCAA), bromochloroacetic acid (BCAA), dibromoacetic acid (DBAA), bromodichloroacetic acid (BDCAA), dibromochloroacetic acid (DBCAA), and tribromoacetic acid (TBAA). For both THM and HAA$_9$, stock standard solutions from Supelco Inc. (Bellefonte, Pennsylvania, USA), were used for calibration and quality control. Analyses were conducted using a Hewlett Packard 5890 Series II Plus gas chromatograph (Mississauga, Ontario, CA) equipped with an electron capture detector and a J&W Science DB-5.625 durabond column (length: 30 m, inner diameter: 0.25 mm, film: 0.25 µm) (Agilent Technologies Canada Inc., Mississauga, Ontario, CA). Injections were run in splitless mode, with helium as carrier gas and an argon/methane (95%/5%) mix as makeup gas.

Statistical assessment

The majority of online parameters were recorded at 2 min intervals, resulting in 720 data points per day. The exception to this was the online TOC measurements which cycled through monitoring each stream for two hours at a time (total of 150–180 data points per day). For the purposes of statistical assessments, daily averages were used to facilitate data analysis and to reduce the impact of outliers.

Statistical assessments of both baseline and experimental data were first conducted using paired *t*-tests, to account for background effects, such as changing raw water quality and temperature, by considering differences between data pairs rather than absolute values. Formalized statistical tests are

useful tools, however establishing informed limits to absolute differences accounts for scaling issues, overall significance of impacts on water quality, and instrument accuracy. Furthermore, *t*-tests are carried out under a set of assumptions including normality, independence of observations, and equal variance of residuals. While there is some question whether formal testing for conformance to these requirements is necessary, there is an unknown level of error due to the degree to which the data adhere to the assumptions (Rasch *et al.* 2011). To determine limits or significance criteria, it was assumed that variations observed on a daily timescale were representative of instrumental and measurement error. Significance criteria were calculated as two times the average daily standard deviation for each measurement (Table 2). If the difference between two trains fell within the criterion, the trains were considered equal.

RESULTS AND DISCUSSION

Verification of operational scheme

Using paired *t*-tests and the significance criteria, filtered water UVA and TOC for both pilot trains were observed to be significantly equal during initial baseline testing (95% confidence) (Figure 2 and Table 3). The difference in UVA was insignificant when comparing pilot trains using PACl vs. alum during the subsequent experimental phase. During both testing periods a small difference in UVA between the

Table 2 | Significance criteria for assessment of differences between treatment trains

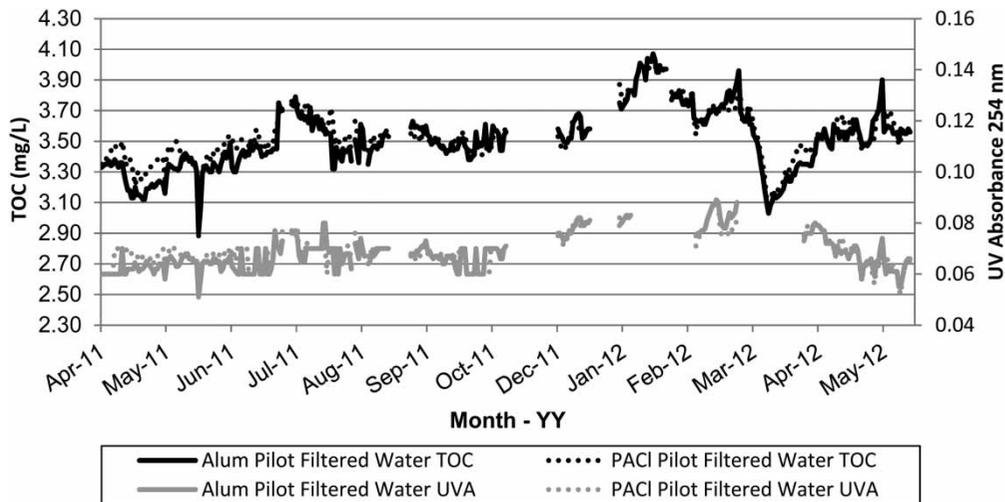| Parameter	Significance criterion
TOC (mg/L)	Within $\pm$ 0.12
UVA (cm^{-1})	Within $\pm$ 0.003
pH	Within $\pm$ 0.06
Turbidity (NTU)	Within $\pm$ 0.16
Particle counts (counts/mL)	
2–3 µm	Within $\pm$ 3.45
3–5 µm	Within $\pm$ 4.43
5–7 µm	Within $\pm$ 2.18
7–10 µm	Within $\pm$ 1.86
10–15 µm	Within $\pm$ 0.72
>15 µm	Within $\pm$ 0.36

Figure 2 | TOC and UVA of pilot plant settled water.

alum pilot and full scale was identified (≤ 0.001 cm^{-1}), but was not considered significant based on criterion specified in Table 2. Overall, it was determined that filtered water TOC and UVA were equal between the two pilot trains as well as between the full-scale and alum pilot trains.

Comparison of alum pilot and full-scale plant

Assessment of significant differences between the alum pilot and full-scale plant are presented in Tables 3 and 4. *t*-tests indicated that the majority of measured parameters were not equal (5/34 tests passed). However, by applying the significance criteria as shown in Table 2, better agreement between trains was observed for online measurements (11/24 tests passed). Turbidity in both settled and filtered water was found to be equal as well as settled water pH, TOC, and UVA. Significant differences were observed between filtered water pH and the majority of particle count size ranges. It was hypothesized that particle counts were not in agreement due to uncontrollable differences in filter scale-up and media age. Furthermore, it was not possible to backwash the pilot filters with exactly the same frequency as full scale. As such, results indicated that trends in particle counts observed at pilot scale may not always translate to full scale.

In general, free chlorine residuals and concentrations of total THMs/HAA$_9$ were found to be significantly equal between the alum pilot and full-scale plant. The exceptions were chlorine residual during the experimental phase

(0.06 mg/L difference) and total THMs during the experimental phase (2.7 μg/L difference). Aluminum residuals ranged between 0.000 and 0.094 mg/L at full scale and 0.000 to 0.052 mg/L in the alum pilot. Average differences were determined to be significant during both phases (0.007–0.008 mg/L greater at full scale). No significance criteria were determined for THMs/HAA$_9$, chlorine residuals, and aluminum residuals, since only one measurement was made per day. Overall, the observed differences were deemed to be small and it was concluded that there was a high degree of agreement between the alum pilot and full-scale plant.

Comparison of pilot trains (baseline phase)

Comparison of the two pilot trains during baseline testing indicated strong similarity both with *t*-tests (12/18 tests passed) and significance criteria (11/12 tests passed). Particle count size ranges comprised the majority of failed *t*-tests, likely due to the high level of measurement and instrument noise associated with the parameter. Settled water pH was also observed to be significantly different with an average difference of 0.01 units. This difference was deemed to be small and within the significance criterion. All grab sample parameters (chlorine residual, THM, HAA$_9$) were significantly equal when applying *t*-tests. The high degree of agreement between pilot trains was considered to be acceptable such that confidence could be placed in a comparison of the impact of coagulant type in the subsequent experimental phase.

Table 3 │ Statistical comparison of pilot and full-scale treatment trains: online parameters (baseline and experimental results)

Parameter		Alum and PACl pilot[a]			Alum pilot and full-scale plant[b]		
		Significantly equal?[c] (t-test)	Average difference	Within significance criterion?	Significantly equal?[c] (t-test)	Average difference	Within significance criterion?
Settled water turbidity (NTU)	Baseline	Yes	−0.03	Yes	No	0.12	Yes
	Experimental	No	0.23	No	No	0.12	Yes
Filtered water turbidity (NTU)	Baseline	Yes	0.00	Yes	No	−0.03	Yes
	Experimental	No	0.01	Yes	No	−0.01	Yes
Settled water pH	Baseline	No	0.01	Yes	Yes	0.03	Yes
	Experimental	No	−0.72	No	No	0.02	Yes
Filtered water pH	Baseline	Yes	0.00	Yes	No	−0.29	No
	Experimental	No	−0.73	No	No	0.07	No
TOC (mg/L)[d]	Baseline	Yes	0.00	Yes	No	−0.14	No
	Experimental	No	−0.03	Yes	No	−0.05	Yes
UVA[d]	Baseline	Yes	0.000	Yes	No	0.000	Yes
	Experimental	Yes	0.000	Yes	No	0.001	Yes
Particle counts (2–3 μm) (counts/mL)[d]	Baseline	Yes	−0.34	Yes	No	−2.83	Yes
	Experimental	No	1.91	Yes	No	−3.83	No
Particle counts (3–5 μm) (counts/mL)[d]	Baseline	No	3.34	Yes	No	−13.79	No
	Experimental	No	7.31	No	No	−5.09	No
Particle counts (5–7 μm) (counts/mL)[d]	Baseline	No	5.08	No	No	−8.18	No
	Experimental	No	3.43	No	No	−2.12	Yes
Particle counts (7–10 μm) (counts/mL)[d]	Baseline	No	0.54	Yes	No	−6.56	No
	Experimental	No	1.70	Yes	No	−2.32	No
Particle counts (10–15 μm) (counts/mL)[d]	Baseline	No	0.16	Yes	No	−1.81	No
	Experimental	No	0.41	Yes	No	−1.32	No
Particle counts (>15 μm) (counts/mL)[d]	Baseline	No	0.04	Yes	No	−0.66	No
	Experimental	No	0.07	Yes	No	−0.42	No
Total flow (L/min)	Baseline	Yes	0.00	NA	NA	NA	NA
	Experimental	Yes	0.00	NA	NA	NA	NA
Filter flow (L/min)	Baseline	Yes	0.00	NA	No	−0.15	NA
	Experimental	Yes	0.00	NA	No	−0.05	NA

[a]Difference = control pilot (alum) – experimental pilot (PACl).
[b]Difference = control pilot (alum) – full-scale plant.
[c]Assessments made through t-tests (95% confidence).
[d]Filtered water measurements.
NA: not applicable.

Comparison of pilot trains: alum vs. PACl (experimental phase)

During the experimental phase, water treated with PACl exhibited a pH increase of 0.72 ± 0.12 in settled water (Table 3). The addition of alum depressed settled water pH while the pre-hydrolyzed PACl did not result in the same effect, as has been noted in the literature (Hu et al. 2006). Alum treated settled water turbidity was found to be

significantly greater by 0.23 ± 0.23 NTU. Decreased turbidity in settled water due to the polymeric structure of PACl has been reported by other studies (Sinha et al. 2004). Differences in settled water turbidity between pilots were found to vary with raw water pH, although higher settled water turbidity in alum treated water was consistently observed over the pH range examined. Compared to alum, PACl turbidity removal was greatest (0.35 ± 0.27 NTU difference) between raw water pH of 7.8 and 8.0 and lowest above

Table 4 | Statistical comparison of pilot and full-scale treatment trains: grab samples (baseline and experimental periods)

Parameter		Control and experimental pilot[a]		Control pilot to full-scale plant[b]	
		Significantly equal?[c] **(*t*-test)**	**Average difference**	**Significantly equal?[c]** **(*t*-test)**	**Average difference**
Free chlorine residual (after 24 hours) (mg/L)[d]	Baseline	Yes	0.01	Yes	−0.05
	Experimental	No	0.11	No	−0.06
Aluminum residual (mg/L)[d]	Baseline	Yes	−0.004	No	−0.008
	Experimental	No	0.007	No	−0.007
THMs (μg/L)[d]	Baseline	Yes	2.3	Yes	−0.3
	Experimental	No	−7.6	No	2.7
HAAs (μg/L)[d]	Baseline	Yes	−3.0	Yes	−3.9
	Experimental	Yes	0.8	Yes	−3.2

[a]Difference = control pilot (alum) – experimental pilot (PACl).
[b]Difference = control pilot (alum) – full-scale plant.
[c]Assessments made with *t*-tests (95% confidence).
[d]Filtered water measurements.

pH 8 (0.10 ± 0.10 NTU difference). Following filtration, no statistically significant difference in turbidity was observed between pilot trains (0.1 ± 0.1 NTU). Average aluminum residuals were 0.020 and 0.012 mg/L for the alum and PACl pilots, respectively. The difference in aluminum residuals was determined to be significant based on *t*-tests.

To account for the impact of raw water temperature on coagulation efficiency and other treatment processes, the data-set was sub-divided into two ranges representing low temperature (0–14 °C) and >14 °C. The threshold value of 14 °C was chosen based on the approximate midpoint of the annual raw water temperature range. To assess temperature effects, *t*-tests were applied such that averages for each parameter could be compared for 0–14 °C and >14 °C ranges. Significant differences were identified only for filtered water pH, settled water turbidity, and selected particle count size ranges. Changes due to raw water temperature are shown in Table 5. Settled and filtered water pH increased during periods of higher temperatures which corresponded with changes in raw water pH (0–14 °C: 7.89, >14 °C: 7.95). Turbidity and particle counts both decreased in the higher temperature range. To further elucidate temperature impacts on coagulant efficiency, raw water temperature was plotted versus the difference between the alum and PACl pilot settled water turbidity (Figure 3). Results illustrate the increased efficiency of PACl at low water temperatures when compared to alum.

Total THMs were observed to vary between approximately 19 and 135 μg/L; total HAA₉ varied between 26

Table 5 | Comparison of pilot trains during low and high raw water temperatures. All parameters listed were found to be significantly influenced by temperature (based on *t*-tests at 95% confidence)

Parameter	Temperature	Control and experimental pilot[a] average difference
Settled water turbidity (NTU)	Low (0–14 °C)	0.34
	High (>14 °C)	0.10
Settled water pH	Low (0–14 °C)	−0.70
	High (>14 °C)	−0.75
Filtered water pH	Low (0–14 °C)	−0.68
	High (>14 °C)	−0.78
Particle counts (2–3 μm) (counts/mL)[b]	Low (0–14 °C)	3.41
	High (>14 °C)	−0.01
Particle counts (3–5 μm) (counts/mL)[b]	Low (0–14 °C)	9.08
	High (>14 °C)	5.06
Particle counts (>15 μm) (counts/mL)[b]	Low (0–14 °C)	0.10
	High (>14 °C)	0.03

[a]Difference = control pilot (alum) – experimental pilot (PACl).
[b]Filtered water measurements.

and 84 μg/L in all trains during the study period. Fluctuations were observed to be highly dependent on water temperature with minimums occurring during the cold winter months and maximums during the summer. Total THMs averaged 47 ± 28 and 56 ± 33 μg/L and total HAA₉ averaged 48 ± 14 and 52 ± 12 μg/L in the alum and PACl pilots, respectively. A significant increase in total THM concentrations in PACl treated water was observed (10–30%) based on weekly comparisons, while there was no
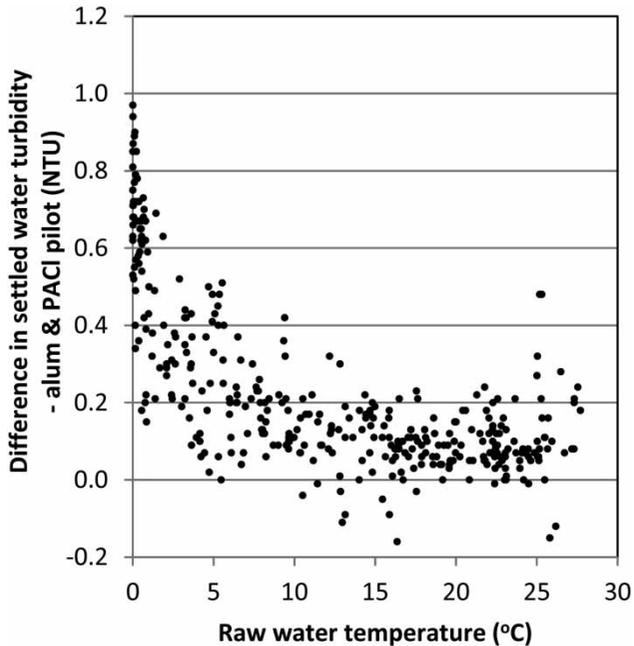
Figure 3 | Raw water temperature vs. settled water turbidity difference between pilot trains during the experimental phase.

significant difference in HAA_9 concentrations. Other studies suggest that the elevated pH of the PACl treated water could have caused the observed increase in THM formation (Singer 1994; Sadiq & Rodriguez 2004). To test this hypothesis, a series of parallel jar tests was conducted using alum and PACl, followed by chlorination at a controlled pH. Coagulant doses were applied to match pilot-scale operation

where settled water TOC was equal. Jar test results (not shown) demonstrated that when alum or PACl treated water was subsequently chlorinated at an equivalent pH (7.0 and 8.0, respectively) total THMs that formed following 24 hours were equal at a 95% confidence level.

Both the alum and PACl pilot filters were backwashed simultaneously to ensure equal filter run lengths. Typical monthly average total loss of head from a full filter run is presented in Figure 4. The alum pilot filters consistently had greater head loss when compared to the PACl pilot (0.002–0.011 m h^{-1}). Average differences for individual months were statistically confirmed using t-tests at a 95% confidence level. Individual filter run data were obtained at 2 min intervals. Selected examples of head loss development, which are representative of both baseline and experimental phases, are shown in Figure 5. Use of PACl decreased head loss rate from 0.011 to 0.007 m h^{-1} during the experimental phase.

Despite the increase in alum treated settled water turbidity, filtered water turbidity was observed to be significantly equal between pilots, which indicates that there was a greater particulate load deposited on the alum pilot filters. Therefore, it is suggested that the observed increase in head loss development for the alum pilot resulted from an increased turbidity in settled water. This implies that in addition to achieving equivalent TOC removal, PACl reduced particulate concentrations to a greater degree and
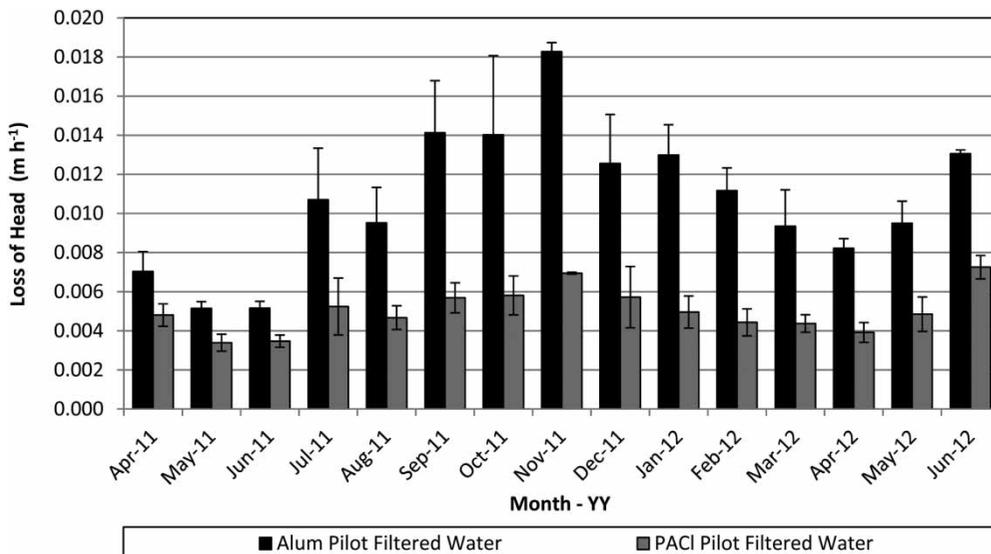

Figure 4 | Average monthly total loss of head for pilot plant filter. *Note:* error bars represent one standard deviation ($n = 2$–12).
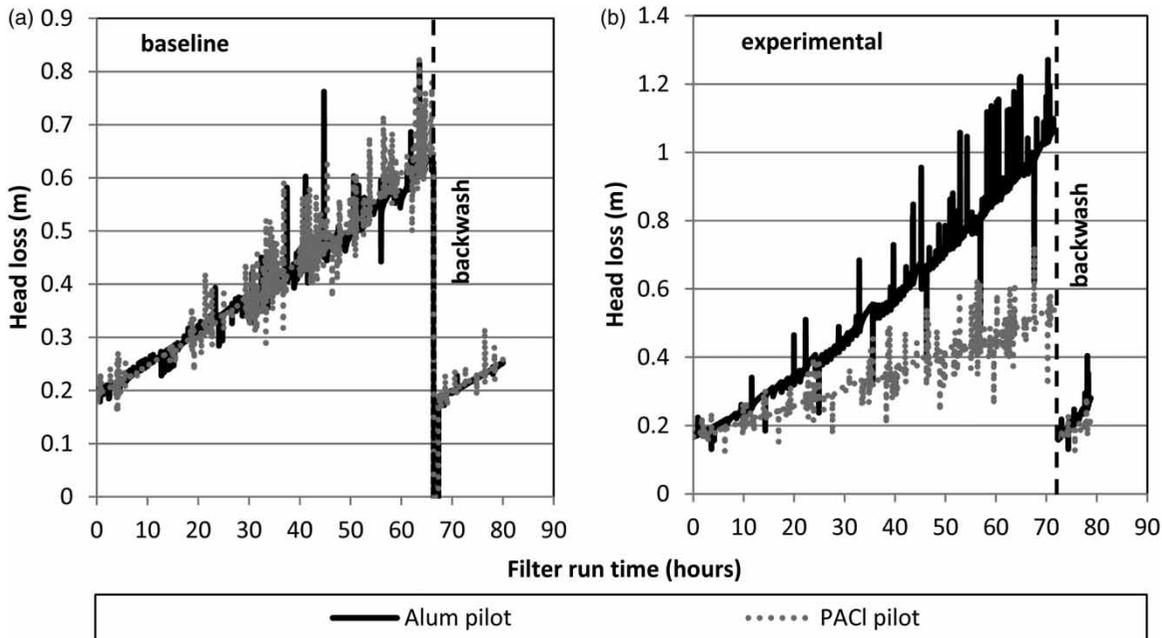
Figure 5 | Example head loss development during alum and PACl pilot filter runs during (a) baseline and (b) experimental testing.

ultimately decreased filter head loss development. The potential for extended filter run lengths when using PACl has been previously reported by Zouboulis *et al.* (2008).

Total head loss development rate for the alum filter (0.005–0.018 m h^{-1}) was found to fluctuate throughout the year to a greater degree than the PACl pilot (0.003–0.007 m h^{-1}) (Figure 4). To explain fluctuations in monthly averages, pairwise correlations between monthly average head loss development rate and water temperature, settled water turbidity, settled water pH, particle counts (each size range), coagulant dose, and TOC were conducted. These parameters were selected as they were most likely to influence seasonal head loss development. Relationships were found to be very weak (R^2: <0.01 to 0.16), indicating that individual parameters were not well correlated with yearly variations in head loss development. Although beyond the objective of this work, interactive effects between parameters could be considered in creating a better model to predict head loss development. Furthermore, the measurement of settled water TOC (not included as part of this study), could potentially provide a more accurate account for filter loading and resulting head loss development.

Particle counts were highly variable throughout the study period as evident from large standard deviations

(73–200% of the mean). Paired *t*-tests indicated that particle counts in the majority of size ranges were greater in the alum pilot when compared to the PACl train. The largest difference was noted in the 3–5 μm size range: 7.31 ± 9.90 counts/mL increase in alum treated water when compared to PACl. It must be considered, however, that validation of particle counts during the baseline period was not achieved. As such, limited significance can be given to the observed results during the experimental phase. No significant differences in filtered water turbidity were observed in individual filter runs, as supported by overall trends (Table 3). No turbidity breakthrough events were observed, indicating that the filters were not run to their maximum capacity.

As a result of maintaining equal settled water TOC concentrations among all trains, the overall required coagulant dose and corresponding sludge production could be estimated. This was based on the assumption that the mass of sludge produced from coagulation was composed of floc, which would be directly proportional to the amount of coagulant added as well as any organic matter removed from the raw water. While the mass of removed TOC was maintained constant, the PACl dose consisted of 52–74% by mass, compared to alum. As such, it was anticipated that the use of PACl would reduce overall sludge production.

CONCLUSIONS

This paper set out to describe the approach and results of a 14 month pilot-scale coagulation optimization study which compared treatment performance of alum and PACl. Two statistically based approaches including paired *t*-tests and significance criterion were employed to establish equivalence between parallel pilot trains as well as a full-scale plant. The significance criterion approach identified a greater number of parameters to be equivalent. It was hypothesized that the data did not conform to the underlying assumptions for paired *t*-tests and furthermore the large number of data points overestimated the measurement accuracy of the instruments. For example, differences in UVA of $<0.001\ \text{cm}^{-1}$ were observed to be significant through use of paired *t*-tests. Water quality results indicated there was strong agreement between pilot trains during baseline conditions (run with equal conditions) and between the control pilot and the full-scale plant.

Settled water turbidity in the alum pilot was significantly greater by 0.23 ± 0.23 NTU indicating that for equal TOC reduction, PACl was more efficient with respect to particulate removal. Furthermore, it is proposed that higher post-sedimentation turbidity caused the observed increase in filter head loss (0.002–$0.011\ \text{m h}^{-1}$) in the alum pilot train (for equivalent filter run-times). An increase in pH of approximately 0.7 units in PACl treated water was observed when compared to alum. This increase was directly associated with a significant increase in THM formation (10–30%). To achieve equal filtered water TOC, the mass of PACl coagulant required was lower, which was expected to directly translate into reduced sludge production while maintaining a desired TOC removal efficiency.

ACKNOWLEDGEMENTS

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