

Tools for monitoring distribution system water quality: a study using four parallel pilot systems

Mary Drikas, Rolando Fabris, Kalan Braun, Amanda Mussared and Lionel Ho

ABSTRACT

Monitoring and understanding water quality changes within the distribution system is essential to enable effective management to provide good quality water at the customer tap. A recent 2-year study utilised four parallel pilot distribution systems (PDS) and a range of simple tools to assess the impact improving treatment had on the water quality within the distribution system. Particle counting was more effective than turbidity to assess the impact of increasing treatment on sediment load entering the PDS while UV254 was as informative as dissolved organic carbon to assess organic load but has the additional potential benefit of on-line measurement. However, variability in water quality entering the PDS was often greater than measurable changes occurring within the PDS. It was critical to compare water quality entering the distribution system with the water quality at a defined point within the distribution system (at known hydraulic detention time) to enable effective assessment of water quality changes. Therefore, effective use of these simple tools requires monitoring of both inlet and distribution system locations, together with long term trending to monitor and compare changes within the system.

Key words | distribution systems, monitoring tools, parallel pilot systems, water quality

Mary Drikas (corresponding author)
Rolando Fabris
Kalan Braun
Amanda Mussared
Lionel Ho
Australian Water Quality Centre,
SA Water Corporation,
250 Victoria Square,
Adelaide,
SA 5000 Australia
E-mail: mary.drikas@sawater.com.au

INTRODUCTION

Water utilities have expended considerable investment over many years to improve water quality by increasing the extent of treatment applied to raw water sources. This has resulted in high quality water entering distribution systems, however dirty water events impacting customers continue to occur (Vreeburg & Boxall 2007). This is not only due to an aging infrastructure and historically poorly managed pipework, but also because of a general lack of understanding of the interactions between distribution system condition and management and water quality. Recent investigations into distribution system particle characterisation (Vreeburg *et al.* 2008; Peng *et al.* 2010) and microbial ecology (van der Kooij 2000; Berry *et al.* 2006; Douterelo *et al.* 2013; Liu *et al.* 2014) are exposing the importance of these systems in sediment accumulation (and release) and as bioreactors.

High quality water entering the distribution system is still an essential component of ensuring safe drinking water at the

customer tap and many studies have focused on the impact of improved water treatment on distribution system water quality (Volk & Le Chevallier 1999; Frias *et al.* 2001; Liu *et al.* 2013). However, monitoring and understanding water quality changes within the distribution system is also required to effectively manage distribution systems, and issues associated with sediment deposition and biofilm formation. Current distribution system management approaches focus on detection of asset failure, such as leaks and bursts (Allen *et al.* 2011) or assessing the security of supply by detection of contaminants (Hall *et al.* 2007; Storey *et al.* 2011). Water quality monitoring consists predominantly of parameters such as colour and turbidity with bacteriological quality based upon maintaining disinfectant residuals and minimising total coliforms.

Considerable research on particle deposition and characterisation has provided a greater understanding of their interactions within distribution systems, and a range of tools

to determine the dynamics of sediment accumulation have been developed (Matsui *et al.* 2007; Vreeburg *et al.* 2008). Modelling has also been used to simulate discoloration events from accumulated sediments and flow changes within distribution systems (Boxall & Saul 2005). Rapid bacteriological assessment tools such as flow cytometry (FCM) (Hoefel *et al.* 2003; Hammes *et al.* 2008) and adenosine triphosphate (ATP) measurement (van der Kooij *et al.* 1995; Delahaye *et al.* 2003; Hammes *et al.* 2010) are also gaining attention as possible techniques for understanding treatment and distribution system behaviour. However, these rapid techniques have not yet been adopted for routine use within the water industry and remain predominantly research techniques.

A recent 2-year study utilised four parallel pilot distribution systems (PDS) and a range of simple tools to assess the impact improving treatment had on the water quality within the distribution system. This was achieved by applying four different treatment processes to the same source water. Water quality was monitored on the inlet and outlet of each PDS using a range of water quality analyses to determine likely aesthetic customer impacts such as sediment deposition and biofilm formation. The focus was on simple tools that could be applied to effectively monitor both treatment and distribution systems within a normal operational environment. A review of these tools and their applicability to predict water quality changes in distribution systems, as observed within this study, forms the basis of this paper.

MATERIALS AND METHODS

The source water for all four treatment streams applied in the study was River Murray water taken from the Mannum to Adelaide pipeline at Mount Pleasant water treatment plant (WTP), located in the Adelaide Hills approximately 60 km from Adelaide.

Treatment streams

Conventional (Conv) treatment comprised alum coagulation followed by flocculation, sedimentation and dual media (sand/anthracite) filtration. This process was selected as it represents the most widely applied drinking water treatment process in Australia. Aluminium sulphate was used as the

primary coagulant at dose rates dependent on water quality with pH controlled between 6.2 and 6.5 using either sodium hydroxide or sodium bicarbonate, based on the source water alkalinity. Coagulant aids used included cationic polyacrylamide LT22 or LT425 or anionic polyacrylamide LT20; all supplied by BASF Chemicals, Australia.

MIEX plus coagulation (MIEX/Coag) utilised one stream of the MIEX-DOC[®] process implemented at the Mt Pleasant WTP. This comprises pre-treatment using a magnetic ion-exchange resin (MIEX) for dissolved organic carbon (DOC) removal coupled with coagulation/sedimentation/filtration treatment as a clarification step for turbidity reduction. The process has been described in detail by Drikas *et al.* (2011).

MIEX plus coagulation plus granular activated carbon (MIEX/Coag/GAC) was product water from MIEX/Coag followed by GAC filtration. Two gravity fed filter columns filled with F400, a coal based steam-activated GAC (Calgon Corporation, USA), were used to achieve an empty bed contact time of approximately 14 minutes with the product streams combined.

Nanofiltration with microfiltration pre-treatment (MF/NF) incorporated dual stage membrane filtration with a Siemens-Memcor submerged microfiltration (MF) pre-treatment for particulate removal followed by a DOW-Filmtec NF270 nanofiltration (NF) membrane for organics removal. This stream represented the most advanced treatment technology and consistently achieved the best treated water quality.

More detail about the treatment streams and their performance is available (Ho *et al.* 2012; Braun *et al.* 2014). All treated water streams were disinfected to meet a minimum 'Chlorine contact x time' factor – Ct of 30 mg.min/L, according to demand but deliberately controlled to retain no residual at the inlet to the PDS following 4 hours contact in the treated water storage tank. This strategy was chosen to replicate the worst case scenario at the ends of distribution systems, where disinfectant residual is often lost, and to encourage establishment of biofilms within the study period.

Pilot distribution systems

Four independent 1.05 km looped PDS using a combination of 150 mm OD polyvinyl chloride and 50 mm ID polyethylene pipe were constructed. Pipes were arranged in 75 m lengths with compact 180° bends allowing inlet and outlet to be collected at the same terminus. All pipe work was

buried a minimum 600 mm depth to maintain temperature stability. Each PDS operated in single-pass mode with a hydraulic detention time of 78.5 hours, which included three overnight stagnation periods of eight hours to mimic diurnal network flow rates. Samples were collected weekly and outlet samples were collected 3 days after the inlet sampling to account for the detention time within the PDS and capture the same water, within practical considerations.

Analyses

Water quality was considered under three general categories: physical, chemical and microbiological. Analyses undertaken consisted of those currently routinely used by water utilities to ensure satisfactory treatment operation and/or compliance with health regulations, such as colour, turbidity, aluminium iron and manganese, as well as a range of other possible parameters to elucidate water quality changes within the distribution system. Analyses assessed under the different categories are listed in Table 1.

Colour (456 nm) and UV absorbance at 254 nm (UV254) were measured following filtration through a 0.45 µm membrane using a 5 cm and 1 cm quartz cell, respectively, on an Evolution 60 Spectrophotometer (Thermo Scientific, USA) reported as Hazen units (HU) and Abs.cm⁻¹, respectively. Turbidity measurements were conducted on a 2100AN Laboratory Turbidimeter (Hach, USA) with results given in nephelometric turbidity units (NTU). DOC was measured following filtration through a 0.45 µm membrane using a Sievers 900 Total Organic Carbon Analyser (GE Analytical

Instruments, USA). Soluble aluminium, iron and manganese were all analysed by inductively coupled plasma mass spectrometry (Method 3125B, APHA *et al.* 2005).

Biodegradable dissolved organic carbon (BDOC) was measured according to the method of Joret *et al.* (1989). Briefly, the inoculum is biologically active sand (sand colonised by bacteria) originating from a local drinking WTP filter. A 900 mL water sample is inoculated with 300 g of sand and aerated for the duration of the experiment. DOC is measured at the beginning and then approximately every second day until a minimum value is reached (approximately 10–12 days). BDOC concentration is derived from the difference between the initial and minimum DOC values.

On-line particle counting was carried out with a laser particle counter measuring 15 channels between 0.5 and 20 µm (Liquilaz S-05, Particle Measurement Systems, USA). The instrument was connected directly to sample points at the beginning and the end of each PDS with flow controlled at the necessary calibrated flow rate using a peristaltic pump. On-line particle counting data were processed into differential counts per mL and grouped into broader size fractions to identify concentrations in key ranges of interest.

Biofilm formation potential (BFP) monitors (KWR, The Netherlands) based upon an upflow column filled with 12.4 cm² surface area glass coupons were employed (van der Kooij *et al.* 1995). Biofilm coupons were sampled aseptically using a pre-flamed stainless steel wire hook into sterile 30 mL Eppendorf tubes containing 10 mL of autoclaved tap water. Sample tubes containing the glass coupons were ultra-sonicated in a water bath for 10 minutes, then decanted into another sterile tube. Another 10 mL of sterile tap water was aseptically added to the original sample tube and sonicated for a further 10 minutes to remove additional biofilm. This procedure was repeated once more and all solutions combined to obtain a composite biofilm solution. This was centrifuged at 4,500 rpm for 30 minutes then the supernatant was removed to leave approximately 1 mL and the pellet. The pellet was then vortexed to resuspend and transferred to a smaller Eppendorf tube. ATP concentrations were determined according to the method of Hammes *et al.* (2010). A commercial kit (BacTiter Glo, Perkin Elmer) was applied with ATP calibration standards of 1 × 10⁻⁶, 1 × 10⁻⁷, 1 × 10⁻⁸, 1 × 10⁻⁹ and 1 × 10⁻¹⁰ M.

Heterotrophic plate count (HPC) numbers were performed in accordance with the Australian Standard AS/NZS

Table 1 | Analyses undertaken within the different categories

Category	Physical	Chemical	Microbiological
Analyses	• Turbidity	• True colour	• Heterotrophic plate counts (HPC)
	• Particle counting and size distribution	• UV254 • DOC • Metals (aluminium, iron, manganese)	• Flow cytometry (FCM) • Biodegradable organic matter (BDOC) • Biofilm formation potential (BFP)

4276.3.1 using R2A solid media (Oxoid, Australia). Dilutions, when necessary, were performed in maximum recovery buffer (0.1% (w/v) neutralised bacteriological peptone, 0.85% (w/v) NaCl, pH 7.0). Incubation was performed using standard conditions of 20 °C for 72 h. Results for HPC were presented as colony forming units per mL (CFU/mL).

FCM analysis was conducted using a FACSCalibur flow cytometer (Becton Dickinson, USA) equipped with an air-cooled 15 mW argon ion laser, emitting at a fixed wavelength of 488 nm. Total and active numbers of bacteria were enumerated following staining of the bacteria with SYTO-9 and the BacLight™ bacterial viability kit (Molecular Probes, USA) as described previously (Hoefel *et al.* 2003).

Each PDS was monitored weekly for a range of parameters with samples taken from the inlet and outlet of each PDS. Outlet samples were collected 3 days after the inlet sampling to account for the detention time within the PDS and capture the same water, within practical considerations, to enable direct comparison of any water quality changes within the PDS. Turbidity, colour, UV254, DOC, HPC and FCM were analyzed weekly whilst metals and BDOC were undertaken monthly. Particle size distribution was undertaken on a number of occasions during the study and BFP was undertaken for a 2-month period in the latter part of the study.

RESULTS AND DISCUSSION

Physical

Assessment of physical changes occurring within each PDS was undertaken by measuring turbidity and particle counts.

Turbidity of water entering all the PDS was below 0.3 NTU, with an average of 0.13 NTU, except for the Conv PDS where inability to effectively control treatment manually meant that higher turbidity levels did occasionally enter and exit the PDS (average 0.52 NTU) (Braun *et al.* 2014). The change observed by subtracting the weekly turbidity outlet result from the related weekly inlet result for each PDS stream over the study period is shown in Figure 1. Overall this indicates that turbidity decreased on passage through the PDS fed from the Conv stream, but there was no consistent trend apparent for the other three streams. When turbidity levels entering the PDS are near the limit of detection of the analytical method, it would not be possible to confidently determine differences between the inlet and outlet of a distribution system. Turbidity analysis is a good indicator for detecting a dirty water event, but when low turbidity water is entering distribution systems it is not useful as an indicator of developing problems or likely locations of sediment deposition (Verberk *et al.* 2007).

Monitoring of particle volume concentration and size distribution entering and exiting each of PDS was undertaken on a number of occasions with representative results shown in Figure 2. All four streams experienced an overall loss of material during passage through their respective PDS, with the greatest decrease in particle volume generally occurring in the larger particle size fractions. However, the MF/NF stream underwent a gain in particle volume in some size fractions due to extensive corrosion of pilot plant infrastructure (Byrne *et al.* 2014). Whilst particle size distributions of the four streams differed at the inlet, all four streams had similar particle size distributions at the outlet of the PDS. Particle loss via deposition appeared to be the primary process driving

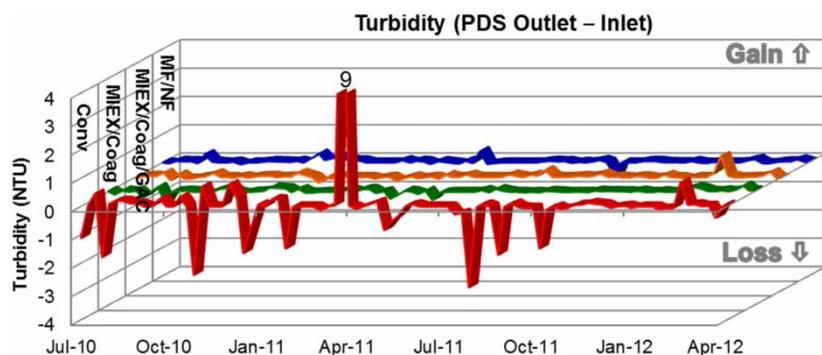


Figure 1 | Turbidity change on passage through PDS, outlet–inlet.

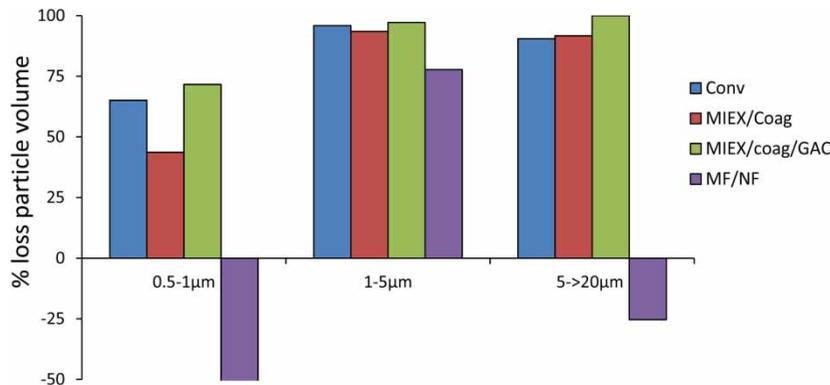


Figure 2 | Percent loss of particle volume (m^3/L) within particle size fractions, calculated by comparing particle volumes entering the system to those exiting the system.

particle concentration differences between the beginning and end of the PDS.

Particle monitoring either via direct counts and/or calculation of particle volume concentration was shown to be a much more sensitive and effective measure than turbidity for estimating the actual amounts of particulate material entering distribution systems and to illustrate effectiveness of the different treatment processes (Byrne *et al.* 2014). It was also useful to show the difference in amount of particulate material entering and exiting the PDS. Determining the change in particle size and concentration on passage of a specific block of water from beginning to end of an operational distribution system could assist with understanding the mechanisms causing these changes and allow correlation with impacts due to water velocities, flow direction and pipeline materials. Ikonen *et al.* (2013) have suggested that particle counting could also be feasible as an indicator of bacterial contamination. However routine particle monitoring of distribution systems on a continuous basis is considered problematic at the current time due to the need to correlate the changes in particle size and concentration observed with changes in the inlet water quality and operation of the distribution system.

Neither of the two physical techniques studied were useful as operational tools to detect developing problems and likely locations of sediment deposition. It is considered that practical tools that are applied within the distribution system to assess deposition, such as the resuspension potential method (Vreeburg *et al.* 2008), may prove more valuable in locating sediment deposition and assist with optimising cleaning frequency of mains.

Chemical

A range of analyses was used to assess the amount of organics entering and exiting the PDS. Observed changes could indicate utilisation for bacterial and/or biofilm growth within the PDS. The changes observed by subtracting the weekly outlet result from the related weekly inlet result for each PDS stream for colour, UV254 and DOC over the study are shown in Figure 3.

Comparison of all organic data shows that when considering the Conv PDS all three measurements generally provide similar results. However, when comparing the other streams, results differ between the colour data (Figure 3(a)) and the UV254/DOC data (Figures 3(b) and 3(c)). This is not unexpected as the colour of water entering all PDS except the Conv were all below 2 HU. As the limit of reporting for colour is 1 HU, any observed changes are very small, and the method is not accurate or sensitive enough to detect them and can provide misleading results. Trends observed with both UV254 and DOC were very similar for all streams with loss of organic matter measured on passage through the PDS, likely through incorporation into particles during deposition or biofilm formation. This contrasts with the study of Liu *et al.* (2013) who found no measurable difference in DOC concentration within their PDSs. However, their PDS consisted of small diameter PE (6 mm) tubing with a retention time of only 24 hours compared with this study which utilised longer retention times and larger diameter pipework of 150 and 50 mm diameter equivalent to that found in actual distribution systems. The increased surface area and retention time would increase the potential for

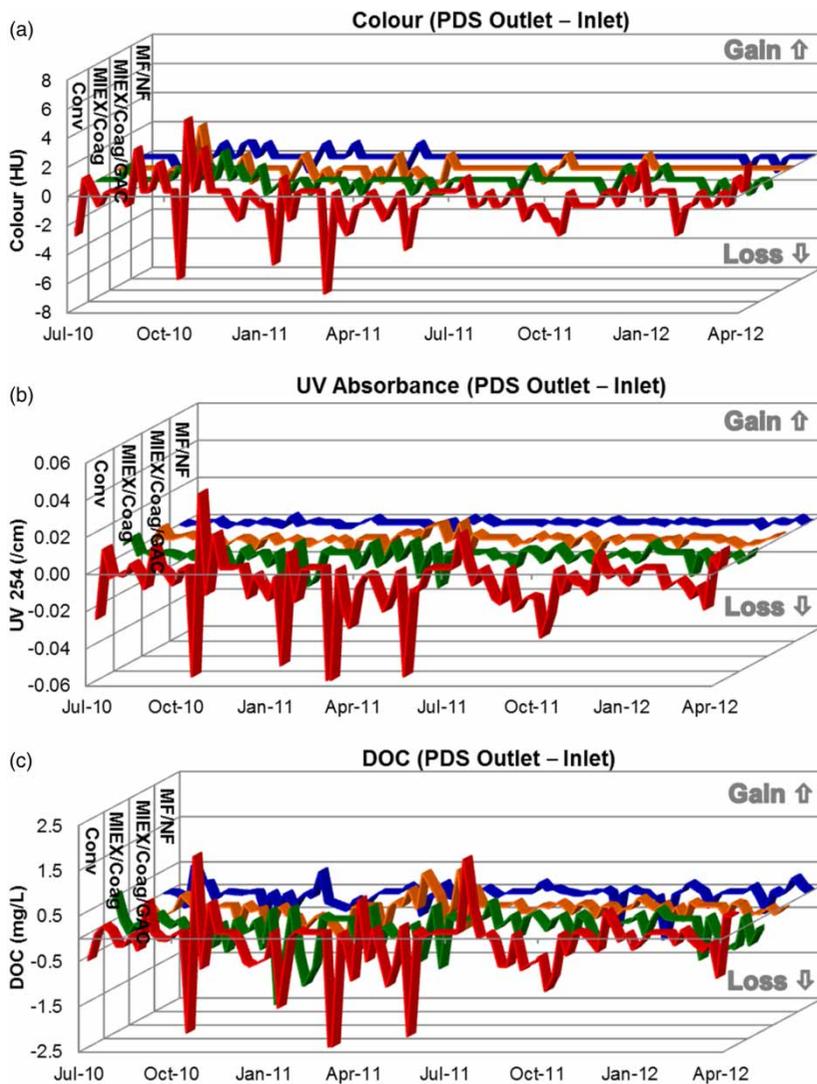


Figure 3 | Changes on passage through PDS, outlet-inlet for (a) colour, (b) UV254 and (c) DOC.

biofilm growth and hence the use of organic nutrients in the system used in this study.

Of the three techniques applied, while DOC clearly gave the best measure of change in organic concentration through the PDS, UV254 would be much more suitable as a routine monitoring tool as it is a simpler analytical technique with comparable ease of measurement but greater sensitivity than colour. UV254 also has greater potential for on-line measurement.

However the usefulness of these organic analyses to locate potential problem areas in the distribution system relates to the ability to compare water quality entering and

exiting the PDS rather than the actual value recorded. This is due to the variability of water entering the PDS. This is illustrated in [Figure 4\(b\)](#) which summarises UV254 data taken from the outlet of all PDS over the study. Monitoring only the outlet data would suggest that there was a decrease in UV254, in some cases very significant, at the ends of each of the PDS. Whilst there was indeed an overall decrease in UV254 in all the PDS (as shown in [Figure 3\(b\)](#)), direct comparison with monitoring of the inlet UV254 ([Figure 4\(a\)](#)) shows that the decreasing trend in UV254 at the outlet closely reflected a similar trend in water quality entering the PDS and that loss within the PDS was much

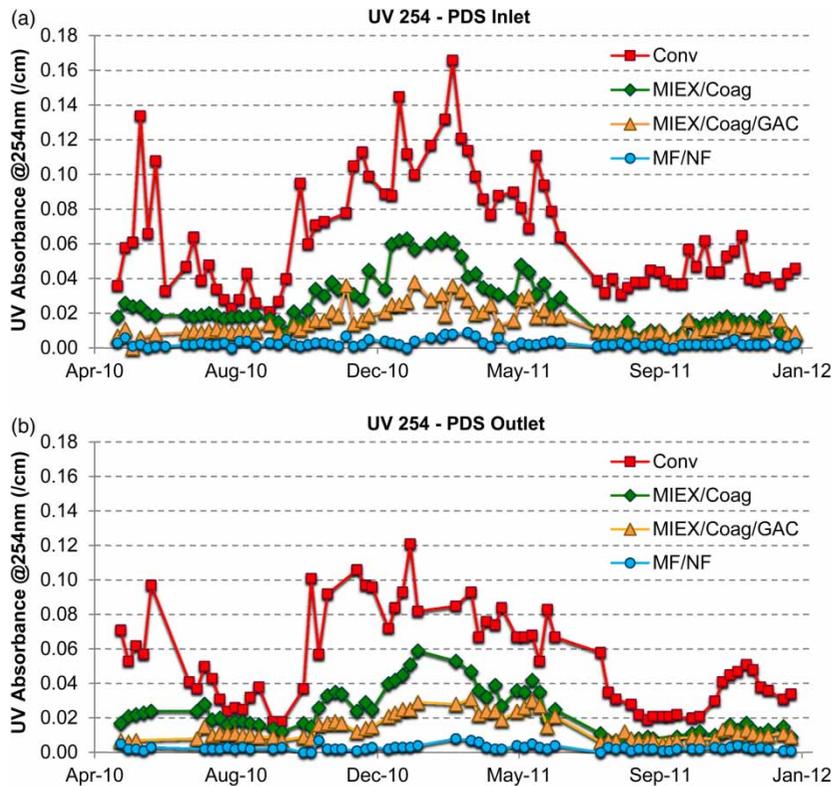


Figure 4 | UV254 for all four PDS streams for (a) inlet and (b) outlet.

less and more difficult to determine. Similar results were seen with DOC.

Monthly analysis of soluble aluminium, iron and manganese entering and exiting the PDS was also undertaken giving a total of 20 samples. Soluble aluminium was measured because aluminium sulphate was used in all treatment streams except the MF/NF. It should be noted that the manual control of the Conv process resulted in three exceedances of the 0.2 mg/L desirable soluble aluminium concentration recommended in the Australian Drinking Water Guideline (NHMRC & NRMCC 2011) at the inlet to the PDS (Figure 5(a)). Comparison of data for the Conv stream indicated that 70% of samples (14 of 20 samples) had lower aluminium concentrations when exiting the PDS whilst another 20% had higher aluminium concentrations. The MIEX/Conv stream experienced a loss of aluminium in 30% of samples on passage through the PDS, experienced during a period when inlet soluble aluminium concentration was between 0.015 and 0.020 mg/L, compared with inlet aluminium <0.01 mg/L for all other samples measured. No difference in aluminium concentration was observed for

the remainder of the samples from this stream or on passage through the MIEX/Coag/GAC PDS. Soluble aluminium above 0.1 mg/L can result in post-flocculation within the PDS (NHMRC & NRMCC 2011) and thus a decrease in soluble aluminium concentration as observed in the Conv PDS would be expected. The observed increase in aluminium concentration in the Conv PDS may have resulted from disturbance of previously deposited flocculated material following overnight stagnation periods.

Figures 5(b) and 5(c) show the soluble iron and manganese entering all the PDS. All results were more than an order of magnitude below the 0.3 mg/L aesthetic limit for iron and at least half the 0.1 mg/L aesthetic limit for manganese recommended in the Australian Drinking Water Guideline (NHMRC & NRMCC 2011). Comparison of data for all four streams indicated that there was little measurable change in soluble iron exiting the MIEX/Coag and MF/NF PDS, however both the Conv stream and the MIEX/Coag/GAC had higher inlet soluble iron levels and a loss in soluble iron was detected in 40 and 60% of samples on passage through their respective PDS. Although soluble manganese

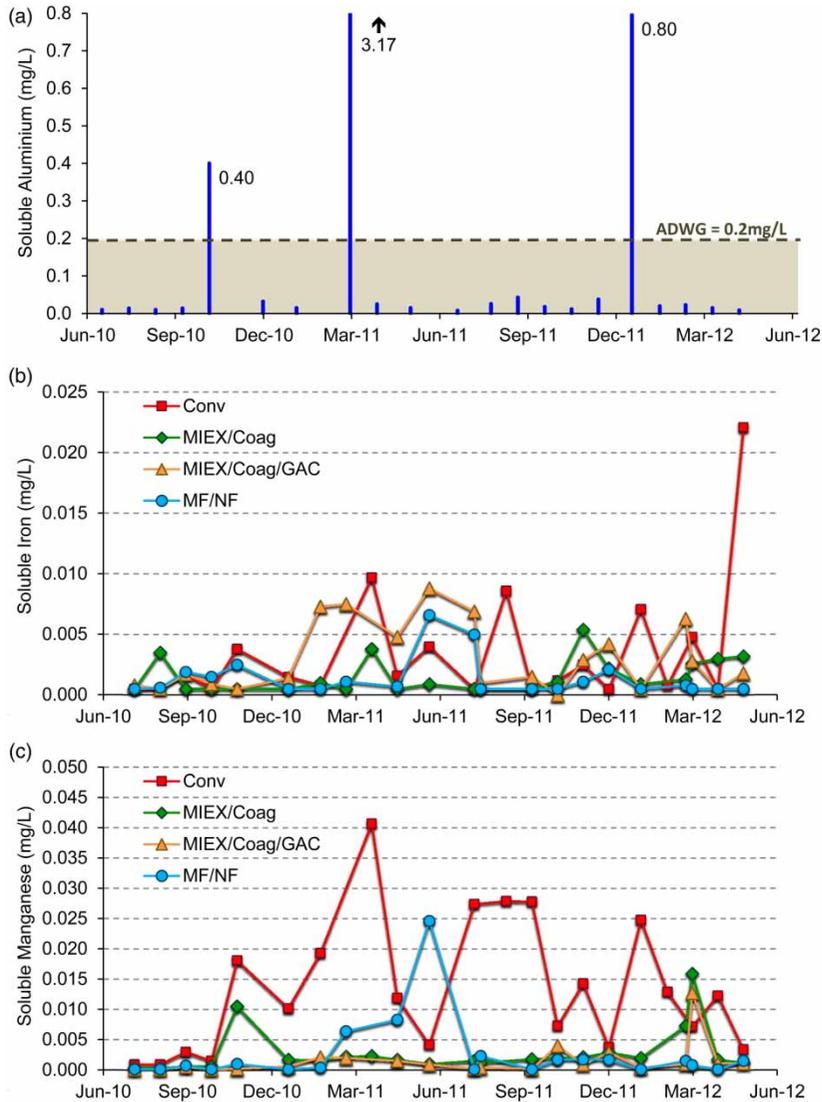


Figure 5 | Soluble (a) aluminium at the inlet of the Conv PDS, (b) iron and (c) manganese at the inlet to all four PDS.

concentrations entering all the PDS were generally very low (Figure 5(c)), soluble manganese concentrations decreased measurably on passage through all four PDS. This varied from a decrease in soluble manganese in 75–80% of samples on passage through the Conv and MIEX/Coag PDS to 40% and 30% in MIEX/Coag/GAC and MF/NF PDS, respectively. This supports previous opinion that low manganese concentrations can result in deposition and potential water quality issues in distribution systems (Sly *et al.* 1990).

Monitoring of metal concentrations entering distribution systems is essential to verify that good quality water is entering the system. In well operated treatment processes

these concentrations should be low and near the detection limit of the analytical methods, hence measurement of changes within the distribution system are difficult to determine accurately to enable losses to be correlated with specific problem areas. However, regular measurement of metal concentrations entering a distribution system would indicate the potential for deposition.

Microbiological

Bacterial quality entering and exiting the PDS was assessed by measuring FCM and HPC. The potential to support

bacterial growth within the PDS was also measured indirectly using BDOC and BFP.

FCM has previously been shown to be a good tool for monitoring bacterial treatment performance (Hammes *et al.* 2008; Ho *et al.* 2012) and was an excellent indicator of different water quality entering PDS in this study (Figure 6). Change in treatment operation resulted in changes in bacterial population during the course of the study and is discussed separately (Braun *et al.* 2013, 2014).

When PDS operation was initiated, this distinct difference in active FCM between the four streams was also apparent at the outlet of the PDS. However, subtracting the weekly active FCM outlet result from the related weekly inlet result for each PDS stream showed that bacterial numbers either decreased (Conv), increased (MIEX/Coag and NF/NF streams) or both (MIEX/Coag/GAC) on passage through the PDS over the period of the study (Figure 7). This suggests that bacterial numbers stabilised within the PDS, irrespective of the inlet water quality, establishing an equilibrium based on nutrient limitation and biofilm establishment. It also reinforces the observations with the other water quality parameters that monitoring only the ends of the system would not provide a sufficiently clear understanding of the water quality changes within the distribution system, but requires comparison with inlet water quality to understand the dynamics of bacterial interactions within such systems.

HPCs entering the PDS were very low (Figure 8(a)) but increased substantially at the ends of the PDS (Figure 8(b)) so this may be a better indicator of developing problems if

sampling is undertaken only at the end of distribution systems. The extent of increase in HPCs in the presence of a disinfectant residual is unclear but unlikely to be as distinct as in this study where no disinfectant residual was present for a period of 3 days. Ikonen *et al.* (2013) found that decreasing free chlorine concentration exhibited a strong correlation with increasing HPC when analysing distribution system water samples.

Measurement of the organic carbon utilised by bacteria can be used as an indirect measure of the potential to support bacterial growth. BDOC represents the extent that bacteria supported on media can utilise DOC and therefore can provide a measure of the potential for biofilm growth within a distribution system. Table 2 summarises the BDOC from monthly samples undertaken at the inlet to the PDS for each stream. The Conv stream contained the highest amount of BDOC with the other three streams indicating greater reduction with an increasing level of treatment. However, as individual results for these latter streams were often below quantifiable limits (<0.1 mg/L DOC), the differences cannot be considered significant. The BDOC analysis was not sensitive enough to detect changes occurring within the PDS and is therefore not considered suitable as a tool to determine water quality deterioration within distribution systems.

BFP monitors were also established on the inlet to each of the PDS towards the end of the study. The growth rate based on ATP measurement over the 150 days for each stream is shown in Table 3. After a 45-day lag period, biofilm activity in the Conv stream increased substantially, whilst the other three streams showed reduced rates of biofilm

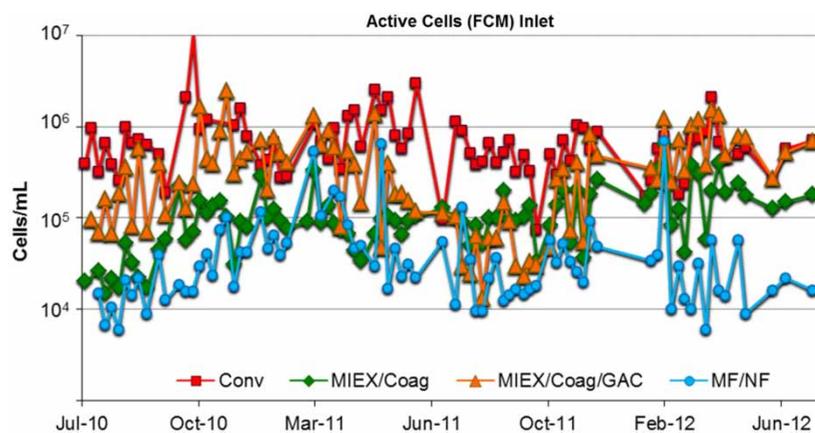


Figure 6 | Bacterial enumeration by flow cytometry (FCM) entering the PDS.

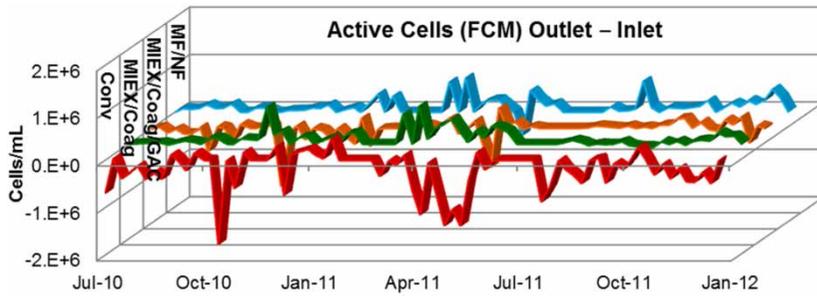


Figure 7 | Change in bacterial numbers by FCM on passage through PDS, outlet-inlet.

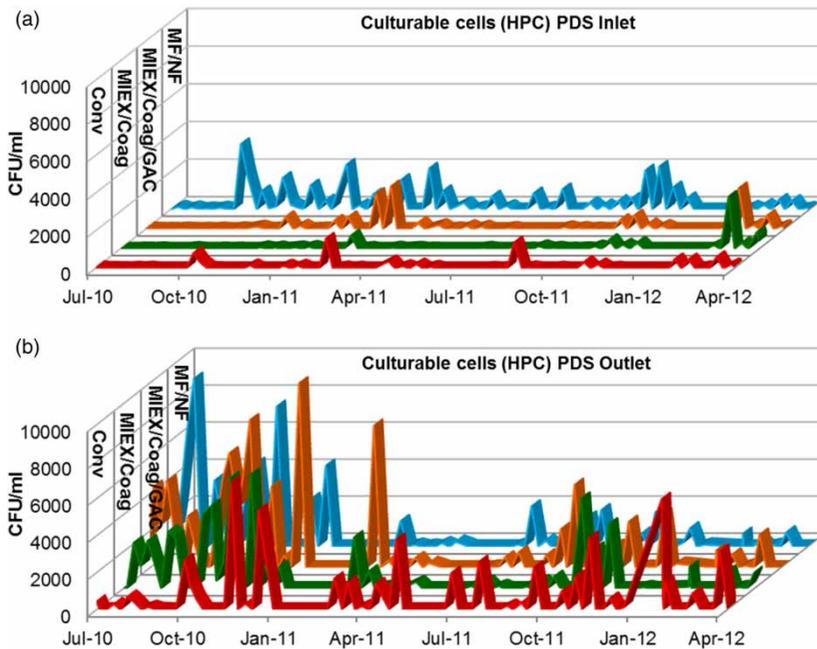


Figure 8 | HPCs at (a) the inlet and (b) the outlet of all PDS.

Table 2 | BDOC at the inlet to the PDS

	Conv	MIEX/Coag	MIEX/Coag/GAC	MF/NF
Mean BDOC (mg/L C)	0.400	0.100	0.027	0.009
Standard deviation	0.210	0.118	0.065	0.030

Table 3 | BFP at the inlet to the PDS from February to June 2012

	Conv	MIEX/Coag	MIEX/Coag/GAC	MF/NF
Growth rate (ATP/day)	3.309	1.489	0.432	0.442

growth. This suggests that BFPs may be a useful tool to predict effectiveness of different water treatment processes to reduce biofilm formation but due to the long time required for biofilm development are not suitable for assessing short term changes in treatment performance nor for applying within a distribution system to detect specific water quality deterioration. The use of other specific techniques that measure the potential for bacterial growth such as assimilable organic carbon (van der Kooij 2000) or bacterial regrowth potential (Page et al. 2002) may be beneficial in detecting potential changes within distribution systems but these techniques were not able to be applied in this study.

CONCLUSIONS AND RECOMMENDATIONS

This study has shown that while increasing treatment will improve water quality it will not completely eliminate water quality changes in the distribution system, but will reduce the rate and extent of particle deposition and biofilm growth in an unchlorinated distribution system. A number of the tools assessed were very useful for monitoring both treatment effectiveness and water quality entering the distribution systems. Particle counting was more effective than turbidity to assess the impact of increasing treatment on particulate load entering the PDS while UV254 was as informative as DOC to assess organic content but has the additional potential benefit of ease of on-line measurement. Monitoring of metal concentrations was also useful on the inlet to the PDS to indicate the potential for deposition. Bacterial load entering and exiting the PDS was effectively monitored by active FCM whilst HPC could only be used to indicate deterioration at the ends of the PDS. Both BDOC and BFP monitors were useful tools to determine the potential to support bacterial and biofilm growth of waters entering the PDS but were not suitable to determine water quality changes occurring within the PDS.

However, even within the simple distribution system used in this study, variability in water quality entering the PDS was often greater than measurable changes occurring within the PDS for parameters such as UV254, DOC, particle counting and FCM. It was critical to compare water quality entering the distribution system with the water quality at a defined point within the distribution system (at known hydraulic detention time) to enable effective assessment of water quality changes. Therefore, effective use of these tools requires monitoring of both inlet water quality and the distribution system locations, together with long term trending to monitor and compare changes within the system. To this end, simple tools that are able to be monitored continuously using on-line measurements, such as UV254, will be most useful.

Better tools that could be used to assist with management of distribution systems and to predict water quality changes within distribution systems have been identified. Regular, or preferably on-line, monitoring at the inlet to, and appropriate locations within, distributions systems is

required to enable understanding of the water quality changes occurring. Additionally practical tools that can be applied within the distribution system to assess locations of deposited material, prior to the onset of dirty water quality events, may prove valuable in assisting to determine the frequency of cleaning of mains. It is also important to note that whilst biofilm formation cannot be eliminated, its impact on water quality can be minimised.

ACKNOWLEDGEMENTS

This project was financially supported by the Co-operative Research Centre for Water Quality and Treatment (CRC-WQT) (project 2417) and Water Research Australia (project 1008), and included contributions by South Australian Water Corporation, United Water International, Grampians Wimmera Mallee Water, Water Corporation, Delft University of Technology, DCM Process Control and Orica Watercare. The project was located at the Mt Pleasant WTP, a facility of the South Australian Water Corporation, Adelaide, and undertaken by SA Water research staff. The authors wish to thank Mt Pleasant WTP staff Nick Nedelkov and Ken Bray for their support.

REFERENCES

- Allen, M., Preis, A., Iqbal, M., Srirangarajan, S., Lim, H. B., Girod, L. & Whittle, A. J. 2011 Real-time in-network distribution system monitoring to improve operational efficiency. *Journal AWWA* **103**, 63–75.
- APHA, AWWA & WEF 2005 *Standard Methods for the Examination of Water and Wastewater*, 21st edn. American Public Health Association, American Water Works Association and Water Environment Federation, Washington, DC.
- Berry, D., Xi, C. & Raskin, L. 2006 *Microbial ecology of drinking water distribution systems*. *Current Opinion in Biotechnology* **17**, 297–302.
- Boxall, J. B. & Saul, A. J. 2005 *Modelling discoloration in potable water distribution systems*. *Journal of Environmental Engineering* **131**, 716–725.
- Braun, K., Cruaux, L., Fabris, R., Morran, J., Ho, L. & Drikas, M. 2013 *Comparison of conventional and MIEX coagulation processes for bacterial removal, utilising real time optical monitoring techniques*. *Environmental Technology* **35**, 1038–1045.

- Braun, K., Morran, J., Fabris, R., Ho, L. & Drikas, M. 2014 Drought to flood: a comparative assessment of four parallel surface water treatments during the 2010–2012 inflows in the Murray–Darling Basin, South Australia. *Science of the Total Environment* **488–489**, 36–45.
- Byrne, A., Braun, K., Fabris, R., Morran, J. & Drikas, M. 2014 Behaviour of small particles in distribution systems—impact of improving treatment. *Journal AWWA* **106**, 67–68.
- Delahaye, E., Welté, B., Levi, Y., Leblon, G. & Montiel, A. 2003 An ATP-based method for monitoring the microbiological drinking water quality in a distribution network. *Water Research* **37**, 3689–3696.
- Douterelo, I., Sharpe, R. L. & Boxall, J. B. 2013 Influence of hydraulic regimes on bacterial community structure and composition in an experimental drinking water distribution system. *Water Research* **47**, 503–516.
- Drikas, M., Dixon, M. & Morran, J. 2011 Long term case study of MIEEX pre-treatment in drinking water; understanding NOM removal. *Water Research* **45**, 1539–1548.
- Frias, J., Ribas, F. & Lucena, F. 2001 Effects of different nutrients on bacterial growth in a pilot distribution system. *Antonie Van Leeuwenhoek* **80**, 129–138.
- Hall, J., Zaffiro, A. D., Marx, R. B., Kefauver, P. C., Krishnan, E. R., Hought, R. C. & Herrmann, J. G. 2007 On-line water quality parameters as indicators of distribution system contamination. *Journal AWWA* **99**, 66–77.
- Hammes, F., Berney, M., Wang, Y., Vital, M., Köster, O. & Egli, T. 2008 Flow-cytometric total bacterial cell counts as a descriptive microbiological parameter for drinking water treatment processes. *Water Research* **42**, 269–277.
- Hammes, F., Goldschmidt, F., Vital, M., Wang, Y. & Egli, T. 2010 Measurement and interpretation of microbial adenosine triphosphate (ATP) in aquatic environments. *Water Research* **44**, 3915–3923.
- Ho, L., Braun, K., Fabris, R., Hoefel, D., Morran, J., Monis, P. & Drikas, M. 2012 Comparison of drinking water treatment process streams for optimal bacteriological water quality. *Water Research* **46**, 3934–3942.
- Hoefel, D., Grooby, W. L., Monis, P. T., Andrews, S. & Saint, C. P. 2003 Enumeration of water-borne bacteria using viability assays and flow cytometry: a comparison to culture-based techniques. *Journal of Microbiological Methods* **55**, 585–597.
- Ikonen, J., Pitkänen, T. & Miettinen, I. T. 2013 Suitability of optical, physical and chemical measurements for detection of changes in bacterial drinking water quality. *International Journal of Environmental Research and Public Health* **10**, 5349–5363.
- Joret, J. C., Levi, Y. & Gibert, M. 1989 The measurement of bioeliminable dissolved organic carbon. (BDOC): a tool in water treatment. *Water Supply* **7**, 1–5.
- Liu, G., Lut, M. C., Verberk, J. Q. J. C. & van Dijk, J. C. 2013 A comparison of additional treatment processes to limit particle accumulation and microbial growth during drinking water distribution. *Water Research* **47**, 2719–2728.
- Liu, G., Bakker, G. L., Li, S., Vreeburg, J. H. G., Verberk, J. Q. J. C., Medema, G. J., Liu, W. T. & Van Dijk, J. C. 2014 Pyrosequencing reveals bacterial communities in unchlorinated drinking water distribution system: an integral study of bulk water, suspended solids, loose deposits, and pipe wall biofilm. *Environmental Science and Technology* **48**, 5467–5476.
- Matsui, Y., Yamagishi, T., Terada, Y., Matsushita, T. & Inoue, T. 2007 Suspended particles and their characteristics in water mains: developments of sampling methods. *J. Water Supply: Research and Technology – Aqua* **56**, 13–24.
- NHMRC & NRMCC 2011 *Australian Drinking Water Guidelines Paper 6 National Water Quality Management Strategy*. National Health and Medical Research Council, National Resource Management Ministerial Council, Commonwealth of Australia, Canberra.
- Page, D. W., van Leeuwen, J. A., Spark, K. M., Drikas, M., Withers, N. & Mulcahy, D. 2002 Effect of alum treatment on the trihalomethane formation and bacterial regrowth potential of natural and synthetic waters. *Water Research* **36**, 4884–4892.
- Peng, C. Y., Korshin, G. V., Valentine, R. L., Hill, A. S., Friedman, M. J. & Reiber, S. H. 2010 Characterization of elemental and structural composition of corrosion scales and deposits formed in drinking water distribution systems. *Water Research* **44**, 4570–4580.
- Sly, L. I., Hodgkinson, M. C. & Arunpairojana, V. 1990 Deposition of manganese in a drinking water distribution system. *Applied and Environmental Microbiology* **56**, 628–639.
- Storey, M. V., Van der Gaag, B. & Burns, B. P. 2011 Advances in on-line drinking water quality monitoring and early warning systems. *Water Research* **45**, 741–747.
- Van der Kooij, D. 2000 Biological stability: a multi-dimensional quality aspect of treated water. *Water, Air and Soil Pollution* **123**, 25–34.
- Van der Kooij, D., Veenendaal, H. R., Baars-Lorist, C., van der Klift, D. W. & Drost, Y. C. 1995 Biofilm formation on surfaces of glass and teflon exposed to treated water. *Water Research* **29**, 1655–1662.
- Verberk, J. Q. J. C., O'Halloran, K. J., Hamilton, L. A., Vreeburg, J. H. G. & van Dijk, J. C. 2007 Measuring particles in drinking water transportation systems with particle counters. *J. Water Supply: Research and Technology – Aqua* **56**, 345–355.
- Volk, C. J. & LeChevallier, M. W. 1999 Impacts of the reduction of nutrient levels on bacterial water quality in distribution systems. *Applied and Environmental Microbiology* **65**, 4957–4966.
- Vreeburg, J. H. G. & Boxall, D. J. B. 2007 Discolouration in potable water distribution systems: a review. *Water Research* **41**, 519–529.
- Vreeburg, J. H. G., Schippers, D., Verberk, J. Q. J. C. & van Dijk, J. C. 2008 Impact of particles on sediment accumulation in a drinking water distribution system. *Water Research* **42**, 4233–4242.