ASSESSING THE IMPACT OF TREATED WATER QUALITY ON DEPOSITION WITHIN PILOT DISTRIBUTION SYSTEMS

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ABSTRACT

A unique study utilising 4 parallel distribution systems with realistic methodology was supplied with treated water of differing quality through combination of various treatment technologies. After 26 months of operation, an autopsy of pipe sections at the beginning and end of the systems revealed a number of characteristics. Inorganic particulates were transported throughout the distribution system and accumulated at the outlet. Conversely dissolved metals were precipitated and deposited predominantly at the inlet of the distribution systems. Regardless of the amount of organic nutrients within the treated water stream, biofilm expressed low activity levels and uneven surface coverage.

INTRODUCTION

It has become evident over the last decade that the distribution system is one of the largest uncertainties in the provision of high quality drinking water at the customer tap. This is partly due to aging and historically unmanaged infrastructure and also because of the poorly understood interaction between the distribution system and the water. Control of the water quality entering the distribution system is the key approach to minimise particulate deposition and biodegradable natural organic matter as a nutrient source for biofilms.

More recently, there has been a greater focus on distribution systems as a dynamic rather than static infrastructure components (Kerneïs et al., 1995). Recent investigations into distribution system particle characterisation (Vreeberg et al., 2008) and microbial ecology (Douterelo et al., 2013) are revealing their nature as bioreactors, and propagators of sediment accumulation and release. Despite this, standard water quality analyses such as colour and turbidity are still the predominant mode of monitoring quality, with bacteriological quality based upon maintaining chlorine residual and minimising heterotrophic plate counts. Rapid bacteriological assessment tools such as flow cytometry (Hoefel et al., 2003; Berney et al., 2008; Hammes et al., 2008) and adenosine triphosphate (ATP) measurement (van der Kooij et al., 1995; Delahaye et al., 2003; Hammes et al., 2010) have been gaining greater use in treatment and distribution systems monitoring. These rapid assessments have not yet progressed beyond use as research techniques.

A number of distribution system investigations have been reported using pilot facilities to study behaviour in a controlled environment. The most common is the ‘TORUS’ pilot distribution facility, developed by Thames Water (Holt et al., 1994; Smith et al., 1999; Maier et al., 2000; Boxall and Saul, 2005). A number of other investigations have also examined the effect of water quality, nutrients and flow on the bacteriological stability of pilot distribution systems (Piriou et al., 1998; Volk and LeChevallier, 1999; Frias et al., 2001; Lehtola et al., 2006).

Following a 26 month project to determine the level of treatment required to minimise water quality deterioration within multiple pilot distribution systems, representative pipe sections at the beginning and end of each distribution system were removed and autopsied for a variety of physical, chemical and microbiological parameters.

METHODOLOGY

The source water from the River Murray was treated using four different parallel treatment combinations:

<table>
<thead>
<tr>
<th>Stream</th>
<th>Description</th>
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<tbody>
<tr>
<td>S1</td>
<td>Conventional alum coagulation (enhanced) with dual-media (sand &amp; anthracite) filtration</td>
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<tr>
<td>S2</td>
<td>Magnetic ion-exchange resin (MIEX) contact followed by coagulation/filtration clarification</td>
</tr>
<tr>
<td>S3</td>
<td>MIEX/coagulation followed by granular activated carbon (GAC) filtration</td>
</tr>
<tr>
<td>S4</td>
<td>Dual-stage membrane filtration (microfiltration followed by nanofiltration)</td>
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Through these treatments, four different treated water qualities were achieved from the well established and commonly applied coagulation...
process, through to more advanced processes consisting of micro and nanofiltration.

Figure 1: Schematic of one of four pilot distribution systems. SP1 = PDs inlet; SP5 = PDS outlet.

Four pilot distribution systems (PDS) composed of both 300m of 150mm OD poly-vinyl chloride and 700m of 50mm ID poly-ethylene (PE) pipe of total length of 1km each were laid underground at the Mount Pleasant Water Treatment Plant (WTP) in South Australia (Figure 1). At a laminar feed flow of 250L/hr, these PDS provided a hydraulic detention time of 76 hours, including 3 stagnation periods of 8 hours to replicate normal diurnal flow variation. Treated waters were subjected to primary, but not secondary disinfection, as the absence of chlorine residual in the PDS was used to create a ‘worst-case’ scenario for biofilm growth.

Figure 2: Trenching for PDS pipe segment removal (left) and an ultrasonicated pipe sample (right).

At the termination of the project, after 26 months of operation, segments of PE pipe supplying the inlet (sp1 – 20mm ID x 0.62m) and outlet (sp5 – 50mm ID x 0.35m) were aseptically removed (Figure 2). Sub-segments of each were processed by a combination of ultrasonication and physical scraping to suspend all material in a fixed volume of ultrapure water for a variety of analyses. These included water quality parameters (turbidity, colour, UV absorbance and dissolved organic carbon (DOC)); composition (suspended solids, metals) and metabolic activity by ATP determination. Samples for DOC, colour and UV absorbance at 254 nm (UV$_{254}$) analyses were filtered through 0.45 µm pre-rinsed membranes. UV$_{254}$ and colour were measured using an Evolution 60 Spectrophotometer (Thermo Scientific, USA). DOC was measured using a Sievers 900 Total Organic Carbon Analyser (GE Analytical Instruments, USA). Residual metals were analysed by ICP-MS according to method 3125B and suspended solids by method 2540 (APHA et al., 1998).

ATP concentrations were determined according to the method of Hammes et al. (2010). A commercial bacterial kit (BacTiter Glo, Perkin Elmer) was applied with ATP calibration standards of 1x10$^{-6}$, 1x10$^{-7}$, 1x10$^{-8}$, 1x10$^{-9}$ and 1x10$^{-10}$ M.

RESULTS/OUTCOMES

The data from analysis of deposited material at the inlets and outlets of the 4 distribution systems highlighted some key differences, not just between the effects of different input water qualities, but also between the composition of bulk water quality and pipe surface deposits. Understanding that almost immeasurable changes to water quality can still result in significant levels of deposited materials over extended operation is both the source of considerable confusion and simultaneously the key to interpretation of the data. Quantitative parameters were normalised for response per unit surface area of the pipe, allowing direct comparison despite the differences in pipe diameters between the inlet and outlet of the PDS.

Table 1 contains selected water quality parameters measured at the inlet to the distribution systems. While the average values show a clear improvement in the water quality of the more advanced multi-stage treatments (S2, S3 & S4) compared to conventional coagulation (S1), of equal importance is the fact that the range of values were more varied for S1. This is indicative of more transient events where water delivered to the PDS was the result of un-optimised coagulation, resulting in the high volatile suspended solids and aluminium removed from the surface of the inlet pipe (Figures 3 and 4).

Figure 3: Normalised suspended solids (mg/cm$^2$) in inlet (left) and outlet (right) pipe segments.
Suspended solids were low in the PDS inlet of the advanced treatment streams (S2, S3 & S4) but high in the conventional coagulation stream (S1) due to less effective removal through a single-stage treatment (Figure 3). All treatment streams had a higher mass of inorganic solids deposited at the end of the distribution systems suggesting that either particles were progressing through as colloids and agglomerating within the latter part of the PDS, alluded to by other researchers (Verberg et al., 2006; Vreeberg and Boxall, 2007), or precipitating and accumulating from dissolved components.

Conversely, metals present in the produced treated waters precipitated on the pipe surface at the beginning of the distribution system and were present at concentrations thousands of times the levels in the distributed waters (Table 1; Figure 4 left). Surface metal concentrations at the end of the PDS were much lower and indicate that in the absence of additional sources of dissolved metals within the distribution system that more distant parts of the network should not be impacted greatly by metal deposits (Figure 4 right).

Analysis of ATP can provide a semi-quantitative and highly sensitive measure of the level of biological activity through the monitoring of the major aerobic energy transport process in living cells. Levels in the inlet and outlet of the PDS were generally low and were not relatable to the level of treatment applied but were responsive to the ‘type’ of treatment applied (Figure 5). The highest average levels of activity were detected in the outlet of the S4 PDS supplied with low DOC, dual-stage membrane treated water. It is believed that this was largely the result of removal of most of the competitive biota through the nanofiltration process, creating more favourable conditions to allow opportunistic environmental bacteria to proliferate. The lowest was S3 which included a biological treatment step (GAC). Importantly, it was observed that there was a high degree of variation in response from different replicate pipe segments, regardless of the stream, suggesting that the coverage of biofilm was not uniform.

CONCLUSION

Autopsy of 4 pilot distribution systems supplied with different water quality for 26 months showed that while metals were deposited near the inlet of the distribution systems, non-metallic inorganic particles travelled throughout the distribution system and settled at the outlet. Biofilm activity was generally low with uneven surface coverage, but always present in both the inlet and outlet of the distribution system in the absence of disinfection residuals. Overall the results showed that increasing levels of treatment did not completely preclude the possibility of physical deposition and biological activity within the distribution system without disinfection over longer term operation, but that multi-stage treatments were superior to coagulation alone in managing these effects.

ACKNOWLEDGMENT

The authors would particularly like to acknowledge the support of the management and operators of the Mt. Pleasant WTP and collaborators, James Morran and Paul Colby. This project was supported by Water Research Australia, South Australian Water Corporation, United Water International, Grampians Wimmera Mallee Water, Western Australian Water Corporation, Delft University of Technology, DCM Process Control and Orica Watercare.

REFERENCES


Table 1: Range and average of inlet water quality to each PDS over 26 months operation

<table>
<thead>
<tr>
<th></th>
<th>S1 Conv</th>
<th>S2 MIEX/Coag</th>
<th>S3 MIEX/Coag/GAC</th>
<th>S4 MF/NF</th>
</tr>
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<tbody>
<tr>
<td><strong>Turbidity (NTU)</strong></td>
<td>4.40 – 0.09</td>
<td>1.18 – 0.04</td>
<td>0.60 – 0.04</td>
<td>0.60 – 0.00</td>
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<tr>
<td></td>
<td>(0.55)</td>
<td>(0.16)</td>
<td>(0.14)</td>
<td>(0.12)</td>
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<tr>
<td><strong>DOC (mg/L)</strong></td>
<td>8.8 – 1.7</td>
<td>5.7 – 0.8</td>
<td>4.1 – 0.7</td>
<td>2.0 – 0.2</td>
</tr>
<tr>
<td></td>
<td>(3.9)</td>
<td>(2.3)</td>
<td>(1.8)</td>
<td>(0.5)</td>
</tr>
<tr>
<td><strong>UV\textsubscript{254} (/cm)</strong></td>
<td>0.166 – 0.019</td>
<td>0.063 – 0.000</td>
<td>0.038 – 0.000</td>
<td>0.010 – 0.000</td>
</tr>
<tr>
<td></td>
<td>(0.063)</td>
<td>(0.023)</td>
<td>(0.013)</td>
<td>(0.003)</td>
</tr>
<tr>
<td><strong>Al (mg/L)</strong></td>
<td>3.17 – 0.01</td>
<td>0.020 – 0.004</td>
<td>0.010 – 0.001</td>
<td>0.012 – 0.001</td>
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<tr>
<td></td>
<td>(0.215)</td>
<td>(0.008)</td>
<td>(0.002)</td>
<td>(0.002)</td>
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<tr>
<td><strong>Fe (mg/L)</strong></td>
<td>0.022 – 0.001</td>
<td>0.017 – 0.001</td>
<td>0.010 – 0.001</td>
<td>0.007 – 0.001</td>
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<tr>
<td></td>
<td>(0.004)</td>
<td>(0.002)</td>
<td>(0.004)</td>
<td>(0.002)</td>
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