The origin and risks associated with loose deposits in a drinking water distribution system

Amanda Mussared, Rolando Fabris, Jan Vreeburg, Jenny Jelbart and Mary Drikas

ABSTRACT

Sediment accumulates in distribution systems over time, and can potentially result in dirty water events. The primary origin of these particles in most networks has not been examined. Controlled sediment resuspension (flushing) events were performed at 10 sites in a drinking water distribution system and repeated six months later to observe redeposition. Different patterns of sediment deposition observed are suspected to be related to particle origin. A large proportion of pipe sediment resuspended during the first flushing event was composed of iron, most likely arising from corrosion of distribution system infrastructure. This sediment appears to play a role in sheltering microbial cells from secondary disinfection. In this study, a source of particles was identified that may provide an alternate explanation for the presence of iron deposits in systems not dominated by iron pipework.

Key words | distribution system, pipe sediment, resuspension potential measure (RPM)

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INTRODUCTION

Maintaining quality of drinking water supply remains a challenge for water utilities worldwide, as they strive to meet more stringent health and aesthetic-based targets, as well as higher consumer expectations. Optimisation of source water and treatment processes are commonly employed to address these challenges, with key aims being to eliminate pathogens and minimise particulate content and organics entering distribution networks. However, distribution systems fed with high quality water are still subject to customer complaints of 'dirty' water, where consumers receive water with high concentrations of particles.

Particles may form and accumulate in distribution systems over time as a result of a number of physical, chemical and biological processes (Vreeburg & Boxall 2007). The risk of particulate presence in distribution networks is twofold; firstly, these accumulated particles may be resuspended during unplanned velocity/flow increases to produce dirty water events and result in poor customer perception of drinking water quality. Additionally, sediments may pose an actual water quality/public health risk to consumers by supporting microbiological growth (Zacheus *et al.* 2001), providing a substrate or source of other water contaminants such as metals (Friedman *et al.* 2016), and through supply of reactive material to potentially accelerate disinfectant residual decay (Özdemir & Tüfekci 1997; Vikesland & Valentine 2002). During resuspension events, these water quality impacts may be exacerbated.

Incidence of resuspendable pipe deposits as a cause of dirty water events has been previously examined by researchers in the Netherlands and the United Kingdom, with tools such as the resuspension potential measure (RPM), and prediction of discolouration in distribution systems (PODDS) model developed to quantify discolouration potential across distribution systems, so that proactive maintenance programs can be developed (Boxall & Saul 2005; Vreeburg 2007). Links between discolouration

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potential and particle origin may be of interest if certain particulates are more often implicated in causing discolouration risk. Identification of the particle origins are also of importance in preventing formation of these deposits, and may have relevance in identifying maintenance and/or replacement of pipework infrastructure.

Several works have similarly sought to investigate water quality and health risk posed by loose deposits based on their physical/chemical/microbiological characteristics. These studies often involve characterisation of pipe sediments collected during flushing events; however, some studies have also focused on the composition of suspended sediments in the bulk water (Gauthier *et al.* 2001a). Analysis of loose deposits has included examination of particle number and volume, organic vs inorganic composition, presence of metallic compounds, and occasionally, mineral content (Seth *et al.* 2004; Verberk *et al.* 2006, 2009; Echeverría *et al.* 2009). Additional work has investigated the microbiological contribution and implications of loose deposits, including examination of attached species increased tolerance to disinfection, and the potential role of sediment as sources of biota to the bulk water (Ridgway & Olson 1982; LeChevallier *et al.* 1988; Gauthier *et al.* 2001b; Zacheus *et al.* 2001; Lehtola *et al.* 2004; Liu *et al.* 2013a, 2014). Only a few works have sought to characterise both the physical–chemical and biological characteristics of deposited particles together (Gauthier *et al.* 2001b; Lehtola *et al.* 2004; Liu *et al.* 2013b).

There is an ongoing need for a better understanding of the links between discolouration potential and particle composition/origin in distribution systems. If high discolouration potential areas are related to known particle sources, mitigation of particle accumulation may be possible. Mitigation activities may include removal of particulate sources, or altering of network operational conditions to restrict particle deposition and formation in these areas. Additionally, knowledge of the potential water quality risks posed by sediments may provide further justification for network cleaning and maintenance strategies for the protection of public health.

In the current work, discolouration potential and particle character, including physico–chemical composition and biological activity were examined in a large metropolitan drinking water distribution system (DWDS). Despite being supplied with low particulate water (turbidity $\leq$0.15 NTU), approximately half the customer complaints in this system are attributed to dirty water events. Current operational strategies to combat dirty water are generally reactive (retrospective flushing of main). Better understanding of the origin and characteristics of sediment across the system will allow prioritisation of proactive management initiatives based not only on discolouration risk (volume of resuspendable sediment), as well as any potential water quality risk posed by the sediment (e.g. microbiological).

MATERIAL AND METHODS

Adelaide DWDS

The Adelaide DWDS supplies approximately 486,000 customers over an area of 1,500 km^2. It is a large, looped network comprised of a wide variety of pipe materials including asbestos cement (AC) (43%), cast iron cement lined (CICL) (25%), ductile iron concrete lined (DICL) (4.5%), unlined cast iron (CI) (2.4%) and polyvinyl chloride (PVCM, PVCO and PCVC) (4.1%, 2.6% and 5.7%, respectively). Customer supply mains are typically between 80 mm and 150 mm with ambient velocity ranging from <0.1 m/s (normal) to 0.25 m/s (peak demand conditions).

The DWDS is supplied by four main water treatment plants (WTPs); Happy Valley, Hope Valley Anstey Hill and Myponga. These WTPs all treat a combination of water from both the Mount Lofty Ranges, and River Murray water supplied from large transfer pipelines. These treatment plants employ conventional coagulation with aluminium sulphate, sedimentation, filtration and disinfection with chlorine. Since 2011, filtered water from Happy Valley has been blended with product water from the Adelaide Desalination Plant (ADP) prior to reticulation. The Myponga WTP treats water from the lower Mount Lofty ranges using a dissolved air flotation filtration (DAFF) treatment process, followed by filtration and disinfection.

Study sites

Ten sites were selected for study across the Adelaide metropolitan DWDS (referred to as S1–S10). The location of sites was selected based on proximity to historical clusters of customer complaints. Other considerations included logistical characteristics that would allow an RPM measurement to be accurately performed (i.e. unidirectional flow possible with pipe isolation, hydrant/fire plug access, diameter <150 mm, minimum continuous 200 m straight pipe section). Initially, it was intended that pipe sections with consistent characteristics (i.e. material, diameter, etc.) be tested, predominantly so that velocity disturbance impact would be consistent across the entire section tested. However, investigation of mains in the system showed that many customer mains are a combination of materials and ages, as streets over time have been expanded with population increase. In all but one case, it was possible to utilise mains of consistently 100 mm diameter (Table 1).

Resuspension potential measure

Discolouration potential in different areas of the network was measured using the RPM tool defined in previous works (Vreeburg 2007). The RPM method involves isolation of a section of network pipe, and initiation of a controlled velocity increase to simulate a real network disturbance.

Table 1 | Pipe characteristics of mains where RPM testing was carried out

Site	Pipe material[a]	Pipe diameter (mm)	Year of installation
S1	AC	100	1960
	CICL	80	1940
S2	CICL	100	1966
S3	AC	100	1977
	DICL	100	1990
S4	AC	100	1972
	AC	100	1962
S5	CICL	100	1948
	CICL	100	1958
S6	AC	100	1970
	CI	100	1938
S7	AC	100	1986
	AC	100	1984
	AC	100	1978
S8	AC	100	1975
	AC	100	1973
S9	CICL	100	1962
	CI	100	1952
S10	AC	100	1975

[a]AC, asbestos cement; CICL, cast iron concrete lined; DICL, ductile iron concrete lined; CI, cast iron.

The velocity increase is not intended to achieve complete pipe cleaning or scouring in the pipe, but to allow resuspension of loose deposits only, which are the particles generally responsible for discolouration events. Before, during and after the velocity disturbance, online turbidity is monitored. Key steps of the method are described below.

A straight pipe section was isolated to provide unidirectional flow, preferably in the normal flow direction of the pipe. Valves to adjacent side streets were closed to ensure that water drawn during the test came only from the pipe section being monitored and from a single source upstream of the pipe section. A standpipe was attached to the fireplug and connected to a measurement pipe module providing laminar flow for online turbidity and water quality grab samples (Figure 1). Baseline turbidity was determined prior to the velocity increase under normal low flow conditions. The flow out of the pipe was increased to provide a velocity increase in the pipe of 0.35 m/s above the ambient velocity for a period defined by the volume of the pipe section being monitored. Online turbidity was monitored during the disturbance. Finally, the flow velocity was restored to ambient conditions, and the rate at which turbidity settles was monitored for a set period, usually 15 min.

The online turbidity data collected during the RPM measurement define the discolouration potential by means of an RPM scoring table (Vreeburg 2007). The scoring table assigns values based on the maximum and average turbidity values during the resuspension event and the time taken for turbidity to return to ambient conditions (Table 2). The values for each parameter are added to produce a total RPM score. Sites with high RPM scores represent a higher discolouration potential.

RPM tests were performed on sites for the first time in September 2014 and repeated six months later in March 2015. As the first RPM test mobilised, loose deposits accumulated in the pipe over an unknown time period; it was believed that RPM scores in March 2015 would represent the discolouration potential created by the redeposition of new sediments.

Water quality analysis

During the sediment resuspension phase of the RPM tests, water samples were taken via a sampling port attached to

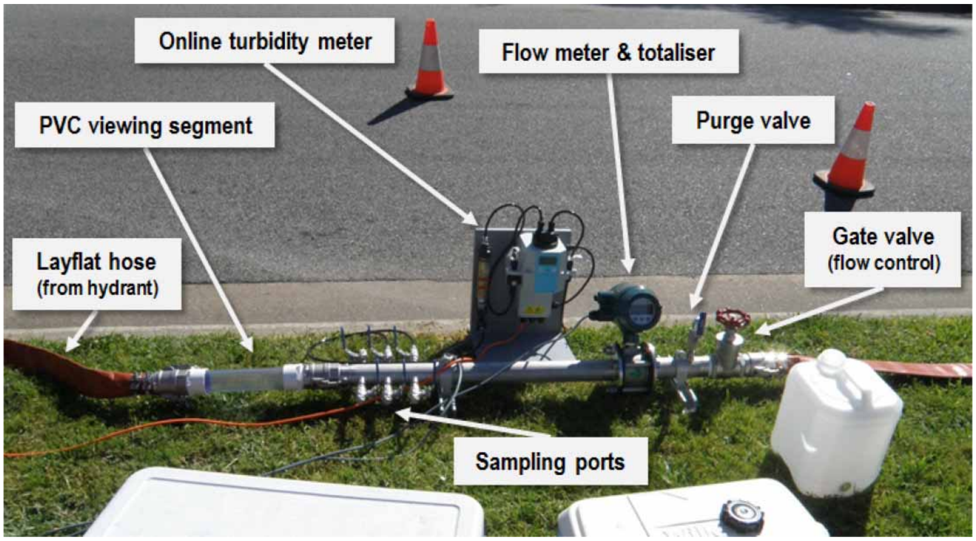

Figure 1 | RPM module and site set up.

a standpipe for total metals, particle volume concentration and heterotrophic plate counts (HPC). Water quality grab samples were taken at set intervals during RPM tests to characterise the physical, chemical and microbiological components of bulk water and resuspended sediment.

Turbidity grab samples were taken every 2 min during the RPM for laboratory analysis, to verify online turbidity measurements. Turbidity was measured on a 2100AN Laboratory Turbidimeter (Hach, USA) with results given in nephelometric turbidity units (NTU). Turbidity was monitored during the RPM using an online turbidity meter (Endress + Hauser, Switzerland). Flow was measured by an in line magnetic flow meter (Yokogawa, Japan). Online data (flow and turbidity) were collected by a data logger (Simex, Poland).

Particle counting and size distribution analysis was performed on samples taken before the disturbance, 3 and 6 min during the disturbance, and following the 15 minute resettling period. Analysis was conducted using a Liquilaz S05 (Particle Measuring Systems, USA) particle counter capable of measuring particles in twenty size channels ranging from 0.5–20 μm. Particle volume concentration analysis was performed by the method outlined in Vreeburg *et al.* (2008), where the particles were assumed to be spherical in shape with diameter equal to the linear average of the boundaries of the size channel.

Total suspended solids analysis (TSS), volatile suspended solids (VSS) and inorganic suspended solids (ISS) were determined according to method 2540 (APHA *et al.* 1998). Total metals analysis for five elements (aluminium, iron, copper, calcium and zinc) was performed on samples taken before, during and after the velocity resuspension. Analysis was by inductively coupled plasma mass spectrometry (ICP-MS) according to method 3125B (APHA *et al.* 1998), against reference standards.

Heterotrophic plate count (HPC) measurements were taken on water collected in 300 mL sterilised polyethylene

Table 2 | RPM ranking criteria, adapted from Vreeburg (2007) for 10 min resuspension period

Score	0	1	2	3
Maximum first 5 min	<3 NTU	3–10 NTU	10–40 NTU	>40 NTU
Average first 5 min	<3 NTU	3–10 NTU	10–40 NTU	>40 NTU
Maximum last 5 min	<3 NTU	3–10 NTU	10–40 NTU	>40 NTU
Average last 5 min	<3 NTU	3–10 NTU	10–40 NTU	>40 NTU
Time to clear	<5 min	5–15 min	15–60 min	>60 min

terephthalate (PET) bottles dosed with 1 mL of 1% w/v sodium thiosulphate solution to reduce any residual chlorine. HPCs were performed in accordance with the Australian Standard AS/NZS 4276.3.1 (Australian Standard, 1995) 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 under standard conditions of 20 °C for 72 h. Results for HPC were presented as colony forming units per mL (CFU/mL).

Adenosine triphosphate (ATP) analysis was performed on samples during the second RPM according to the method of Hammes *et al.* (2010). A commercial bacterial kit (BactTiter-Glo™, Promega) was applied with ATP calibration standards of 1×10^{-8}, 1×10^{-9}, 1×10^{-10}, 5×10^{-11} and 1×10^{-11} M.

RESULTS AND DISCUSSION

Discolouration potential

There was considerable variation in RPM scores across distribution system sites (Table 3). RPM scores ranged from 4–12 during the first RPM measurements in September 2014. Three of the 10 sites measured had the maximum RPM score of 12, representing a high discolouration potential, also reflected by high TSS in samples collected during resuspension. There was an improvement in RPM score at most (7/10) sites during the second RPM round, indicating that despite flushing/scouring velocities not being reached, the first RPM event had resulted in the mobilisation of a significant portion of loose deposits from sampled pipes. This was further supported by a reduction in TSS at 9 of the 10 sites during the March 2015 RPMs. At some sites, such as S1, S5 and S6, the RPM score remained high after the six month reaccumulation period, suggesting a greater input of particulate material at these locations. Sites with very low RPM scores after the second round (S3, S4, S7 and S9) appeared to be located in areas of the network with reduced sources of particle input and/or minimal opportunity for particle transport due to consistently low velocity.

The RPM scores highlight that discolouration potential varies widely across the distribution system. During the initial site selection, effort was made to select sites of varied spatial distribution; however, geographical location (and pipe length distance) did not appear to correlate well with sediment deposition. Hydraulic retention times (HRT) of the locations were similarly examined (data not shown), but in addition to being extremely variable at each site (HRTs ranging from 21 to 106 h at one location, depending on network operation), network complexity (location and residence time of storages, differences in water pathways, etc.) upstream of each location limit HRT as a factor to explain differences in deposition rate. The improvement in RPM scores after one low-level flushing event (the first RPM) indicates that proactive pipe flushing/cleaning is likely to reduce the risk of discolouration, and subsequent customer complaints. The variation in distribution and reaccumulation of loose deposits in different areas of the network has implications for ongoing network maintenance activities. As noted in Vreeburg *et al.* (2008), sites with a lower reaccumulation of material will require less regular maintenance/flushing programs, allowing prioritisation of sites with a comparatively high particle input. Understanding of the location of these high-deposit areas may, in time, allow the identification of particulate sources so that these can be mitigated.

Due to both the limited sample size in this study and variation in pipe materials along mains, it was not possible to assess whether pipe material related directly to discolouration potential. Sites S6 and S9 both contained over 100 m of unlined cast iron; however, the amount of resuspended sediment and iron extracted from these pipes was vastly different, although it should be noted that the CI main at S6 was older than that at S9 (1938 vs 1952) (Table 1). Similarly, site S8, which was composed solely of AC pipe, had similar RPM to S9.

Mains containing either CI or CICL did not consistently produce the highest RPM scores, contrary to the proposition that discolouration potential is caused solely by cast iron mains. Seth *et al.* (2004) also noted the poor correlativity between pipe characteristics and sediment accumulation, with two mains in a distribution of similar age, pipe material, diameter and condition displaying very different turbidity and metal concentrations on flushing. In this study, flushing of mains composed of multiple pipe materials in a looped network also returned a high diversity of turbidity responses.

Table 3 | Physicochemical properties of flush water (early flush) from distribution RPMs

Site	Flush cycle	Turbidity (NTU)	RPM Score	TSS (mg/L)	% ISS	% VSS	Total Al (mg/L)	Total Fe (mg/L)	Total Mn (mg/L)	Total Cu (mg/L)	Iron % of metals*
S1	Initial	125	**12**	220	76	24	17.6	23.2	7.0	1.4	47.1
	+6 months	▼ 35.0	▼ **9**	▼ 72	72	28	▼ 3.8	▲ 33.2	▼ 0.8	▼ 0.2	▲ 87.4
S2	Initial	15.6	**4**	24	75	25	1.6	2.6	0.4	0.2	54.1
	+6 months	▲ 16.8	◆ **4**	▼ 24	79	21	▲ 1.7	▲ 4.0	▲ 0.6	◆ 0.2	▲ 61.8
S3	Initial	14.8	**7**	12	75	25	0.2	1.4	0.2	0.1	71.6
	+6 months	▼ 2.1	▼ **2**	▼ 1	>99	<1	▼ 0.1	▼ 0.8	▼ 0.1	▼ <0.1	▲ 78.2
S4	Initial	25.7	**8**	26	69	31	1.0	7.0	1.0	0.3	74.1
	+6 months	▼ 5.3	▼ **2**	▼ 8	50	50	▼ 0.3	▼ 1.7	▼ 0.3	▼ 0.1	▼ 72.1
S5	Initial	46.2	**8**	63	78	22	2.1	5.4	0.5	0.4	64.5
	+6 months	▲ 49.1	◆ **8**	▼ 43	79	21	▲ 3.9	▲ 12.4	▲ 1.4	▲ 0.5	▲ 68.0
S6	Initial	191	**12**	70	73	27	7.5	21.0	2.7	1.4	64.3
	+6 months	▼ 128	◆ **12**	▼ 25	68	32	▼ 0.8	▼ 4.7	▼ 0.3	▼ 0.2	▲ 77.7
S7	Initial	5.0	**4**	8	38	62	0.6	0.9	0.1	0.1	51.3
	+6 months	▼ 0.5	▼ **0**	▼ 3	67	33	▼ 0.1	▼ 0.1	▼ <0.1	▼ <0.1	▲ 60.6
S8	Initial	23.1	**7**	53	58	42	3.8	13.8	1.1	0.8	70.6
	+6 months	▼ 20.3	▼ **6**	▼ 7	71	29	▼ 0.4	▼ 0.6	▼ 0.1	▼ 0.1	▼ 52.6
S9	Initial	27.8	**8**	32	59	41	3.4	4.5	1.0	0.3	48.9
	+6 months	▼ 2.1	▼ **1**	▼ 4	50	50	▼ 0.2	▼ 0.4	▼ 0.1	▼ <0.1	▲ 53.3
S10	Initial	35.7	**12**	102	74	26	11.5	5.0	4.9	1.6	21.5
	+6 months	▼ 5.4	▼ **5**	▼ 13	54	46	▼ 0.4	▼ 0.3	▼ 0.1	▼ 0.1	▲ 33.0

Metals* is sum (Al, Fe, Mn and Cu).

Sediment composition

The composition of pipe sediment was primarily inorganic across all sites measured with approximately 20–40% VSS and 60–80% ISS (Table 3). The proportion of organic to inorganic material remained the same for the second flushing event ($\alpha = 0.01$), indicating that similar material was redepositing during this period. Other works investigating the organic/inorganic composition of distribution system particles have generally yielded higher proportions of organics than observed in this study. The proportion of organics in suspended deposits in distribution systems measured in Montreal, Quebec, Canada ranged from 43–65% (Gauthier *et al.* 2001a) to as high as 76% in a system in Nancy, France (Gauthier *et al.* 2001b). However, these measurements were for suspended particles, rather than resuspended deposits. Deposited particles in the Amsterdam DWDS were resuspended by flushing as described in Vreeburg *et al.* (2008), and the organic proportion ranged between 42.5 and 60.6% in distribution systems supplied with normal treated water and particle-free water, respectively.

In this study, the dominant metals composition in the sediment were iron and aluminium, with smaller amounts of manganese and copper (Table 3). While detection of aluminium can be attributed to treated water, representing either unremoved colloidal material from source water or from the treatment process (aluminium is used as the primary coagulant at all Adelaide WTPs), iron may originate not only from source/treated water, but also corrosion of metallic network infrastructure. As iron was the dominant metal at nearly all sites tested, it was of interest to identify which mechanism was responsible for the deposition. In several sites, manganese was also present in the resuspended sediments. The key source of manganese in pipe sediments is expected to be due to input/accumulation over time from source water (Sly *et al.* 1990). As a result, the covariance between aluminium and manganese in pipe sediment samples should be considerable. Data plotted from the investigated sites strongly supported the contention that these metals are depositing via similar mechanisms (Figure 2(a)). Conversely, the relationship between aluminium and iron in pipe sediments is poor, suggesting that they deposit by different, unrelated mechanisms (Figure 2(b)). The relationship between iron and other metals (such as Mn) in other systems has also been variable, which may similarly indicate different input sources. In Seth *et al.* (2004), the ratio of Fe to Mn in pipe sediments varied by between 1 to 3 orders of magnitude.

Therefore, while it is possible that a portion of the iron in the pipe sediment is derived from the treated water, it is likely that the majority of particulate iron is actually the product of corrosion of network infrastructure. Approximately 31.9% of mains in the Adelaide DWDS are pipes containing iron; although only a small proportion of these are unlined cast iron (2.4%). Other sources of corrodible iron also exist, including treated water storages, isolation valves and fireplugs. The latter has previously not been closely considered in relation to corrodible iron input to pipes; however, sampling of water sitting in the tapping pipe below these structures suggests they could be a significant source (see Blackwater section below).

Iron has been shown to be a key component of loose deposits in other distribution networks (Li *et al.* 2016). Seth *et al.* (2004) found iron to be the dominant material mobilised during flushing of mains, regardless of pipe material and pipe section being flushed. Significant increases in iron were also noted following particle characterisation in Dutch distribution systems (Gauthier *et al.* 2001a; Verberk *et al.* 2006, 2009). In Verberk *et al.* (2006), iron concentration in suspended deposits, measured by large volume filtration of distributed water, were up to 40 times higher than the water leaving the treatment plant. In some of these systems, unlined pipes also made up a negligible amount of distribution system infrastructure. Only 2.4% of the Adelaide DWDS is comprised of unlined cast iron main; however, given the age of lined cast iron pipes in the system, it is highly probable that these also contribute iron particles.

Particle deposition

Comparison of particulate volumes leaving the treatment plants to that of bulk water in the distribution system (post flush samples) shows that particulate content of water increases during distribution transport. This trend has similarly been observed in Dutch distribution systems (Verberk *et al.* 2006). Possible sources of particles in distribution systems are through precipitation of dissolved components,

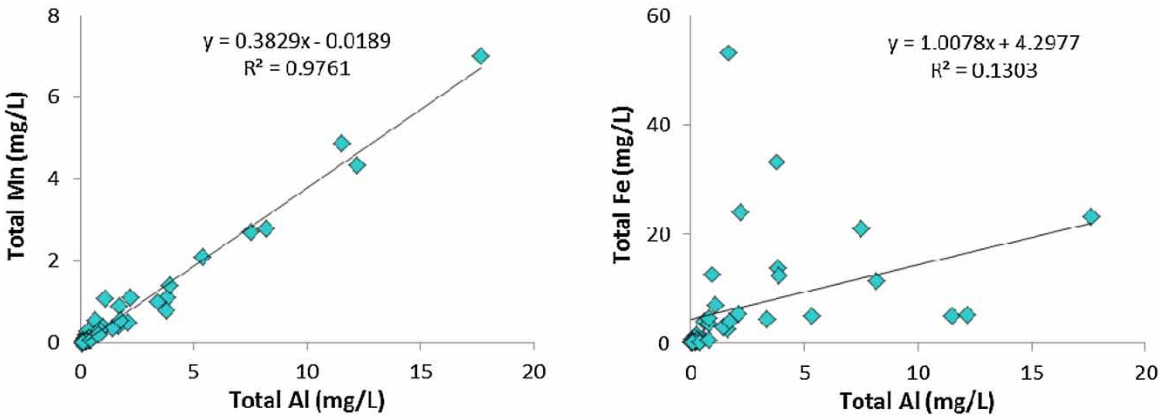

Figure 2 | Correlation between (a) Al and Mn and (b) Al and Fe during RPM events (early and late flush samples).

resuspension of previously deposited sediment, microbial growth (biofilm) or corrosion of network infrastructure.

Particle volume concentrations measured on water sampled during RPM resuspensions revealed three distinct patterns of sediment redeposition over a six month period (Figure 3). At some sites, such as S9 and S10 (S10 shown as an example, Figure 3), redeposition of sediment was evident but appeared to occur at a relatively slow rate. At others, like S1 (shown), S2, S5 and S6, redeposition of larger particles was noticeably higher. Sites that possessed low volumes of particulate material initially (S3 and S7, pictured) had negligible rates of redeposition. It is proposed that these three patterns may be related to different mechanisms of sediment deposition at each site. Slow redeposition rates may indicate that the primary source of particle input is from distributed water components that would accumulate slowly over time. The higher proportion of aluminium at S10 initially, compared to other sites, supports this theory (Table 3). Conversely, fast redeposition of larger particles at sites like S1 may relate to input of large particles from local sources, like network corrosion that would supply particulates more rapidly. Further RPMs conducted around deposition hotspots like these would confirm the proximity and nature of these local sources. Sites with low levels of particles prior to the first RPM had low levels of redeposition and appear to be located in areas of the network where sediment deposition/accumulation does not occur, possibly due to localised hydraulic conditions which may be too low to transport particles to this site, or high enough to keep them suspended.

Microbiology

Despite a history of continuous chlorine residuals, culturable heterotrophic bacteria were present in the resuspended sediment of nearly all sites and were generally considerably higher than abundances found in the overlying water, represented by post-flush samples (Table 4). Attachment of bacteria to surfaces or sediment has previously been shown to increase protection of microbial cells from disinfection, either due to reduced exposed surface area for disinfectant attack or increased disinfectant demand created by the particle surface (Ridgway & Olson 1982; LeChevallier *et al.* 1988; Gauthier *et al.* 2001b; Liu *et al.* 2014). Particles may additionally be a source of nutrient rich media (Lehtola *et al.* 2004). In the Adelaide DWDS, attachment to particles appears to increase the survival of heterotrophic bacteria. As a large proportion of deposits are iron based particles, it is possible that these particles may create considerable localised chlorine demand, reducing chlorine penetration to attached microbial cells.

Higher abundances of microbial activity in sediment are relevant in the context of quantifying water quality risk of these sediments. Current Australian and New Zealand drinking water guidelines do not specify upper limits for culturable bacteria in water, but rather that unusual/significant increases in HPC should be investigated (NHMRC NRMMC 2011). However, as shown in this study, higher levels of culturable microorganisms could occur due to the resuspension of deposited sediment, rather than relating to changes in the overlying water

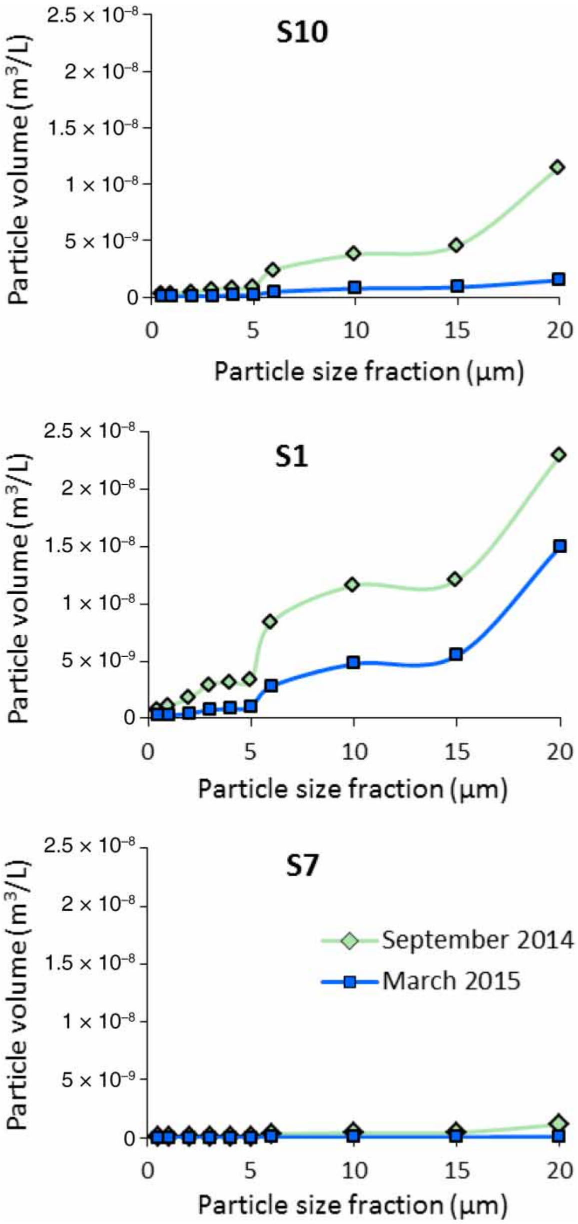

Figure 3 | Particle volume concentrations at three distribution system locations during September 2014 and March 2015 RPM events.

quality or treatment efficiency. Similarly, the microbiological health of distribution systems determined by examining HPC of overlying water will likely underestimate the true microbiological quality or potential microbiological loading available to be transferred to customers. It is recommended that this is examined further, with regular sampling of pipe sediments undertaken, in addition to regular water quality samples.

Table 4 | HPC (cfu/mL) in early, late and post flush samples during RPM

	Early flush		Late flush		Post flush water	
Site	Sep-14	Mar-15	Sep-14	Mar-15	Sep-14	Mar-15
S1	140,000	200	1,400	0	3,000	0
S2	430	190	15	110	1	11
S3	47	81	27	26	8	44
S4	42	180	20	38	0	140
S5	6	0	3	0	0	0
S6	94	0	87	0	1	0
S7	88	11	12	0	0	0
S8	1,200	5	8	1	1	0
S9	340	240	16	5,400	83	12,000
S10	1	400	0	14	0	4

At some sites (S3, S4, S5, S6, S7), microbial numbers found in Adelaide DWDS pipe sediments were lower than those found in comparable systems elsewhere. In a Finnish network supplied with water treated with coagulation/rapid sand filtration and chlorine disinfection, average HPC levels in loose deposits were between 100 and 400 CFU/mL (Lehtola *et al.* 2004). Conversely, at S1, S8 and S9, numbers were above the upper limit (≤500 CFU/mL) allowable in unchlorinated supplies by the US EPA (US EPA 1990, 2006). At one location (S9) HPC in post-flush water was several orders of magnitude higher than early-flush water (Table 4), which may be related to difficulties in dispersing bacterial biofilms to achieve sample homogeneity. The risk of higher active microbiology present in the pipe sediments to consumers may be low; however, testing to determine the presence or absence of pathogenic species would be required to confirm this. In a Finnish network sample (Lehtola *et al.* 2004), no Norwalk-like viruses or coliform bacteria were detected in loose deposits.

Blackwater

During the RPMs, it was identified that a pocket of stagnant water existed under all network fireplugs that required clearing prior to commencing the RPMs. This material is termed 'blackwater' due to being dark in colour, and was composed of particulate material from both above (dry) and below the hydrant valve (Figure 4(a)). Due to the potential connectivity between this blackwater and the underlying mains water, this material was sampled at all sites before RPMs to determine composition.

Water quality analysis revealed blackwaters to consist of mainly inorganic iron corrosion products (73–99% of total metals) originating from continual contact with the unlined cast iron hydrant valve. These suspended materials were capable of regenerating to similar or higher levels in the six months between RPM tests (Figure 4(b)). These iron-rich particulates are responsible for the highly coloured appearance, with the colour tone and intensity likely related to the presence or absence of chemical and biologically mediated reduction (anoxic) or oxidation reactions (Wang *et al.* 2014; Li *et al.* 2015). They also provide a focused example of the mechanisms through which high proportions of iron deposition may be detected throughout the network, even in the absence of iron-based pipe materials. Gravitational settling would be sufficient to allow the particles to transition from the hydrant body down into the main pipe and be transported downstream by normal flow velocities. Understanding the contribution of other, non-pipe iron sources like fireplugs in the distribution system may drive management strategies to address these, such as replacement of network infrastructure with non- or less

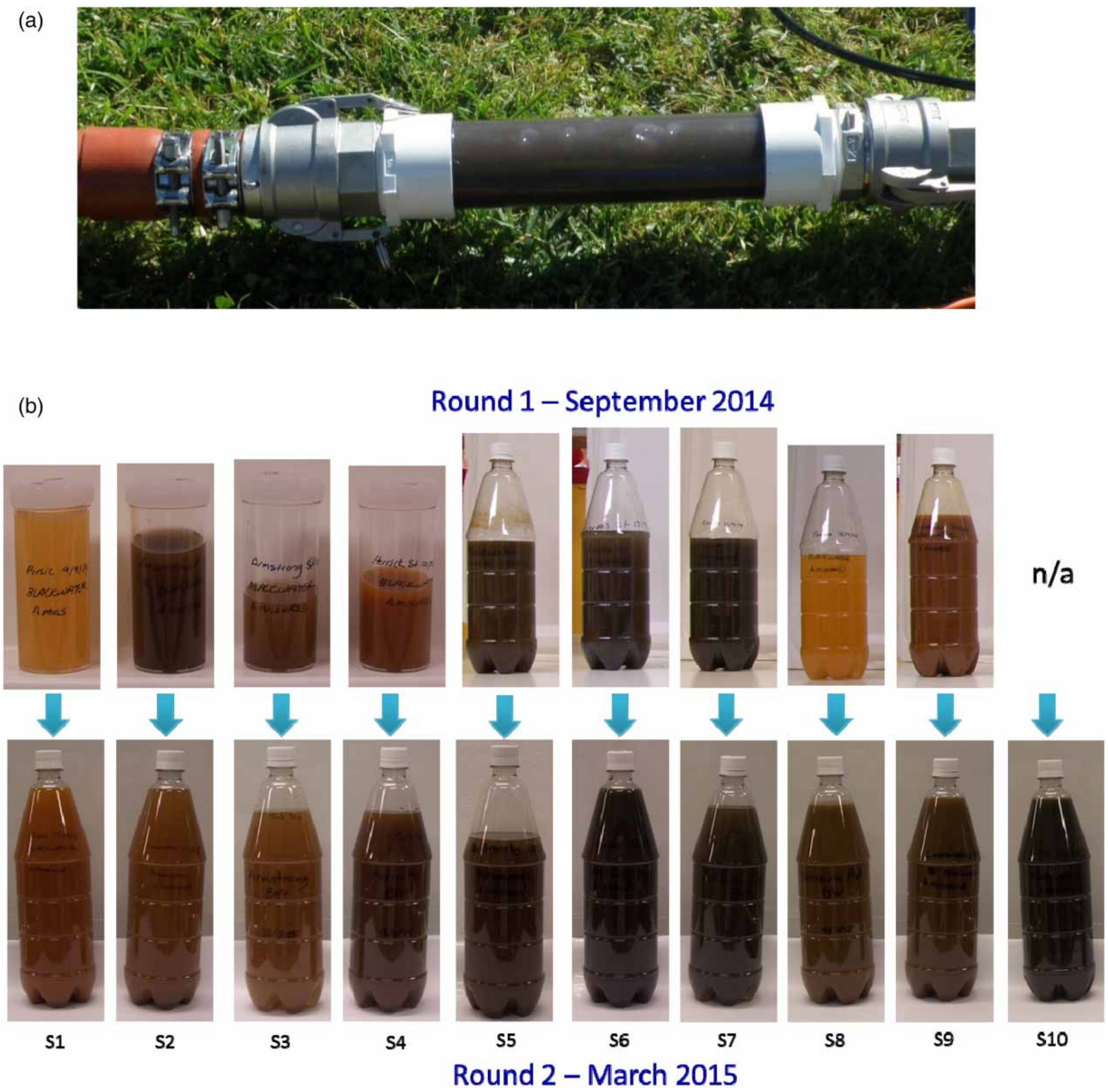

Figure 4 | Blackwater collected prior to RPM testing.

corrodible components, or proactive coating of legacy cast iron infrastructure.

Implications for network management

In this study, discolouration potential varied and appeared to be related to particle origin, as sites with the highest RPM scores were characterised by large amounts of iron-rich particles. The re-accumulation rate of iron at these sites generally exceeded the re-accumulation rate of other metals; consequently, the suspected origin of this iron is corrosion of metallic network infrastructure. Presence of iron pipes did not directly relate to sites of high iron deposition, suggesting alternate input sources for these corrosion products.

Particle size distribution was a useful technique for identifying different patterns of redeposition. Areas where re-deposition of larger particles was rapid suggested a nearby input source, such as corrosion particulates, rather than slower re-accumulation of particles transported from the treatment plant; this assertion was supported by metals data. Further observation of particulate accumulation patterns in conjunction with metals data may allow further diagnosis of particle source in the network and identify priority areas to address.

This work supported a link between microbial water quality and particulate presence, as has been observed in other systems. HPCs detected in distributed water, both before and after RPMs, were significantly lower than during sediment resuspension periods. Current checks of microbial water quality in distribution networks that measure microbial presence/activity only in distributed water may be underestimating risk. Conducting sampling of pipe sediments via RPM or other techniques may allow better overall risk quantification. Loose deposits may play a direct role in deteriorating microbial quality of DWDS, and increase the public health risk as customers may be exposed to higher levels of microbes during dirty water events.

Maintenance of a closed supply to protect distributed water is an ongoing challenge for network operators, as numerous points of ingress exist. Although identified black-water does not appear to mix fully with bulk water when pressurised, at the interface between the pipe sections, cross-contamination could occur. Further examination of the microbiological composition of this water, and its potential for input into water supply, should also be investigated.

This study has provided an initial investigation into the links between particulate source, discolouration potential and microbial water quality risk in the Adelaide DWDS. A key finding of this work is that the presence of loose deposits occurs to some extent throughout the network, making discolouration and customer complaints related to velocity increase events highly likely. The initial sample size measured in this study is limited; however, further RPM analysis of loose deposits and measurement of discolouration potential in the Adelaide DWDS will allow identification of problem areas and particle sources so that proactive management strategies can be developed. If iron deposits are confirmed to be the primary cause of discolouration in this network, longer-term management strategies to address previously overlooked iron sources like fireplugs could be implemented to significantly reduce discolouration potential.

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