Hydraulic conditioning to manage potable water discolouration

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Hydraulic conditioning to manage potable water discolouration

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Results are reported from studies conducted using a unique laboratory-based, full-scale, temperature-controlled pipe facility to examine the impact of conditioning shear stress on discolouration risk, as characterised by bulk water samples (turbidity, iron and manganese) and biofilm pipe wall measurements. The facility uniquely allowed for replication of the dynamics of an operational network but with rigorous control, thus yielding fully representative results overcoming the limitations of bench-scale or operational studies. The effect of the daily variation in flow (and boundary shear stress) was observed to be greater than the effect of the average daily flow rate at reducing discolouration risk. This is useful for informing operation and maintenance strategies, specifically that regularly imposing cycles of flow variation are more effective than increasing total average flow rates at limiting discolouration risk. The application of such knowledge aids the development of cost-effective, proactive, operational interventions to manage discolouration.

1. Introduction

1.1 Background

Discoloured water is the dominant water-quality-related customer complaint within the UK water industry and is a significant issue internationally. Although termed discolouration, the regulated parameter is turbidity because the aesthetic impact is due to suspension of fine particulate material (Boxall *et al.*, 2001). The Drinking Water Inspectorate (DWI) regulates the UK water industry for drinking water quality and has set turbidity standard at customers' taps at 4 NTU (nephelometric turbidity units) (DWI, 2000). Water leaving treatment works is regulated at 1 NTU, but by the time it reaches the customer it can fail to reach the distribution standard (Bristol Water, 2008). Even if one considers external particle sources, such as source water and ingress due to negative pressures (Fox *et al.*, 2015), it is clear that processes within the network contribute considerably to increased turbidity by the time the water reaches taps. The main cause of this is thought to be the mobilisation of material layers from pipe walls due to changes in hydraulic conditions, such as increases in flow, which increase shear stress and thus the forces acting to mobilise accumulated material (Boxall *et al.*, 2001). Hydraulic conditions within operational systems are complex, commonly exhibiting a diurnal pattern in flow driven by consumption, but also due to events and incidents such as bursts. Processes leading to particle accumulation include physical, chemical and biological factors (Vreeburg and Boxall, 2007). Previous knowledge and understanding of the processes that influence the accumulation and mobilisation of material have been developed in experimental investigations through laboratory, pilot and field flushing studies (controlled increase of the pipe flow rate intended to mobilise material (Husband *et al.*, 2008)) and by way of model theories (Boxall *et al.*, 2001). However, due to the limitations of such approaches, there remains significant uncertainty, including the exact nature of the influence of normal (daily) hydraulic conditions within operational networks.

1.2 Discolouration experimental research

Conditions in operational distribution networks are complex, uncertain and inadequately understood or quantified. Network conditions vary considerably and are sensitive to physico-chemical and biological conditions (Block, 1992). Discolouration events, resulting in customer contacts, are unpredictable and happen over a short time period, making them difficult to study in operational networks (Vreeburg and Boxall, 2007). Controlled discolouration events (flushing) are possible and these have shown strong correlations between increased turbidity and iron (Fe) and manganese (Mn) levels (Seth *et al.*, 2004). In particular, the long-term network conditions prior to flushing are also often unknown, varied and uncontrolled. It is therefore very difficult to conduct detailed investigations into the build-up of accumulates and discolouration risk in operational networks.

Bench-scale testing devices such as Propella and annular reactors like the Robbins device (Kharazmi *et al.*, 1999) and Rototorque provide alternatives to field studies, providing potential for the control of influential factors such as nutrient supply. Many of these devices include plugs inserted into the surface so that accumulates can be analysed (Flemming, 2002). Donlan (2002) developed a reactor that incorporated removable 'biofilm growth surfaces' allowing formation under different shear stress conditions. Although these have been very useful in providing continuous non-destructive sets of information, the conditions do not effectively replicate some important aspects of a drinking water distribution system (DWDS). Bench-scale tests do not recreate the DWDS boundary layer hydraulics and turbulence, or the correct ratio of bulk water to surface area and transfer between these. Hydraulic conditions in bench-scale tests are often simply defined by reference to, and control of, the speed of rotation. The hydraulic conditions generated are complex and poorly represent pipeline hydraulic conditions. Most bench-scale investigations assess material accumulation and detachment under steady-state hydraulic conditions, which never occur in operational distribution systems. Furthermore, most bench-scale research studies have only investigated accumulation (e.g. Batte *et al.*, 2003; Murga *et al.*, 2001; Schwartz *et al.*, 1998). Few bench-scale studies have attempted to simulate mobilisation due to hydraulic changes; those that have, crudely increased the speed of rotation (Abe *et al.*, 2011, 2012). Such studies can only observe the loss from the wall, not the bulk water response. A recent investigation by Luo *et al.* (2015) confirmed such limitations, finding that bioreactors provide an unrealistic representation of biofilm growth in operational systems.

The investigations reported by Husband *et al.* (2008) provide a compromise between bench-scale and operational networks by using a 90 m long recirculating high-density polyethylene (HDPE) pipe facility within a controlled laboratory environment. Week-long investigations were completed at a constant conditioning flow rate of 0·3 l/s, before being flushed by small flow increments (15 min each). The data generated demonstrated a positive relationship between shear stress and turbidity, validating the basis of the prediction and control of discolouration in distribution systems (Podds) model (Boxall *et al.*, 2001). A second experiment involving four month-long studies measured the impact of constant and varied flow on turbidity. During the first flushing step more material was mobilised during the constant-flow trials than during variable flow. It was therefore concluded that, during steady-state flow, weaker particle layers develop than during variable flow. The variability in flow was hence deemed a significant factor in determining the risk of discolouration. However, there were several limitations to the experiment. Firstly, there was no temperature control and variable elevated temperatures are likely to influence chemical and biological processes. In addition, the experiment only recorded turbidity and so provided no further insight into the material mobilised or the processes involved. Furthermore, while the length of the facility was significant, it was not sufficient to be certain that pipe surface effects entirely dominated the effects of the tank and ancillary fittings and fixtures. Finally, the facility was a single loop, offering no simultaneous replication, and there may have been variations in the source water between repeats with different hydraulic conditions.

Other pilot-scale research studies have been conducted, but these too have significant limitations. Martiny *et al.* (2003) sampled biofilm and bulk water from a model water distribution system supplied with untreated groundwater. The experiment solely investigated steady-state hydraulic conditions. Steel plugs were inserted in a 12·2 m loop for biofilm sampling, but were not designed flush to the pipe wall, so would have produced locally significant distortion of the boundary layer and turbulence regime. Lehtola *et al.* (2005) investigated the differences in water quality and the formation of biofilms in a pilot-scale distribution system comparing copper and plastic (polyethylene) pipes. Research design limitations included the size of the network, which did not effectively recreate the boundary layer hydraulics and the turbulence regime of operational systems, and hence the exchange with bulk water for the correct ratio of bulk water to pipe surface area.

1.3 Hydraulic conditioning and discolouration risk

Hydraulic conditioning has been suggested as a management strategy to reduce discolouration risk. The 'self-cleaning' method employed in the Netherlands constitutes keeping the velocity higher than 0·4 m/s in order to reduce build-up (Van den Boomen *et al.*, 2004). It was suggested that, due to low velocity, particles can accumulate in areas such as redundant loops and oversized pipes, and 0·4 m/s was shown to be a pragmatically effective value for the Netherlands. Alternatively, Boxall *et al.* (2001) assumed the existence of cohesive material layers accumulated within the DWDS and that layers formed during conditions of high average flow were stronger than layers formed during lower average flow. This approach has been supported by UK (Husband and Boxall, 2010) and international (Boxall and Prince, 2006) DWDS field trials. In further support, Cook (2010) found a correlation between decreased conditioning shear stress and increased frequency of customer contacts regarding discolouration. Such investigations were based on field studies and therefore the previous conditioning hydraulic demand profiles, water chemistry and biology were uncertain. For example, work by Blokker *et al.* (2010), which considered stochastic demand prediction, suggested that the Dutch threshold should be increased by 0·2–0·25 m/s.

While such works clearly show the influence of hydraulic conditions, there is uncertainty over whether the peak or average hydraulic conditions are important, or some combination of the two. This ambiguity is attributable to the uncertainty of flow in individual pipes of operation networks, which is only available from one-dimensional hydraulic models that attempt to simulate an idealised 24 h period. Further work, such as that conducted by Smith *et al*. (1999) using a pipe test facility, has suggested that the interactions that occur during low-flow or night-time stagnation conditions are important in processes leading to aesthetic water-quality issues. However, this study was conducted for cast-iron pipes and was likely dominated by ion release and accumulation in the bulk water during the low-flow period.

In summary, while modelling and bench-top experiments can help predict system responses to events, studies in operation systems have too many uncontrolled factors and uncertainties and do not allow for deeper understandings of controlling environmental factors. Research in a controlled laboratory is required to determine the impact of different shear stress profiles and whether it is the peak, average or variability of the flow pattern that is the most important factor in discolouration risk.

2. Research aims

The aim of this research was to investigate the impact of hydraulic conditions on material accumulation on pipe walls within a DWDS and the subsequent mobilisation (discolouration) response of this material due to flushing. Specifically, the impact of different net flow rates and diurnal patterns was studied. A key advance of the research was ensuring that hydraulic and temperature conditions were fully representative of operational systems, but with the control and replication of a laboratory environment. The value of this research is to help to inform intervention strategies to best manipulate hydraulic conditions to manage discolouration risk.

3. Materials and methods

3.1 Experimental pipe facility

An internationally unique, large-scale, experimental pipe loop facility housed in a temperature-controlled room was used for the experiments (Figure 1). The use of a pipeline fundamentally addresses the issues with bench-top systems (as set out in Section 1.2) while providing the control and repetition not possible in operational systems (Section 1.3).

The facility comprises three loops, controllable to represent different hydraulic regimes. The loops are exact replicates, providing confidence in the results. The laboratory temperature was controlled by means of cooling units (±1°C), with the water temperature monitored for confirmation. The length of the pipe loop ensured that pipe surface effects were dominant over others (e.g. the effects of ancillary fittings and fixtures). HDPE pipes were chosen to correspond to the design of a modern DWDS. Each coil had a final straight section for hydraulic control and flow measurement. The pipe diameter was selected to be representative of the dominant pipe diameter by length of UK DWDSs (based on data reported by UK Water Industry Research (UKWIR, 2003)). Unlike bench-scale experiments, the realistic volume to area ratio and turbulence regime of the test loop facility fully replicated the exchange processes and interactions between the bulk fluid and the pipe wall of operational systems (e.g. nutrient and particle exchange). The full-scale nature of the facility, including hydraulic and turbulence regimes, also meant that the boundary layer conditions and hence surface forces were fully representative.

The system was supplied with water from the local distribution system, characterised by a peat upland source, a treatment system based on iron coagulation, high standard final filters and free chlorine disinfection and residual. There was ~10 km of predominantly cast-iron trunk main and one service reservoir before the water reached the laboratory, with no local distribution systems and minimal pipe connectivity prior to the laboratory. Once filled from this source, the system was operated with a trickle turnover to achieve the desired water age, providing a renewal of bulk water material including chlorine residual. Bulk and incoming water quality were sampled throughout.

The facility was operated in a recirculating manner with a single enclosed tank. Water was transferred to the loops by a single variable-speed pump and then a three-way manifold. Overall system pressure was computer-controlled by the pump speed, with flow rates through each of the loops independently computer-controlled by valves at the end of each loop, before being returned to the tank. Each loop thus had a residence time as a function of the hydraulic conditions created within it, and this was independent of the system residence time controlled by the overall trickle feed and drain. A single tank was selected such that the loops shared the same bulk water, allowing for seeding and mixing between the loops. This is representative of a complex, looped operational network where interacting pipe conditions occur upstream of any given pipe length, and ensured that any difference between the loops was purely a function of the hydraulic conditions created within that loop.

To achieve the study aims, coupons were required to investigate the amount of material accumulation on the pipe wall. Pennine Water Group coupons (Deines *et al*., 2010) were used, allowing for direct observation of material on the pipe wall. These coupons consist of an HDPE disc, which follows the pipe curvature, with a removable flat section for microscopy (Figure 1(e)). The flat microscope section is only 4·5 mm wide, such that the deviation from pipe curvature approaches that of roughness heights used to represent plastic pipes in hydraulic

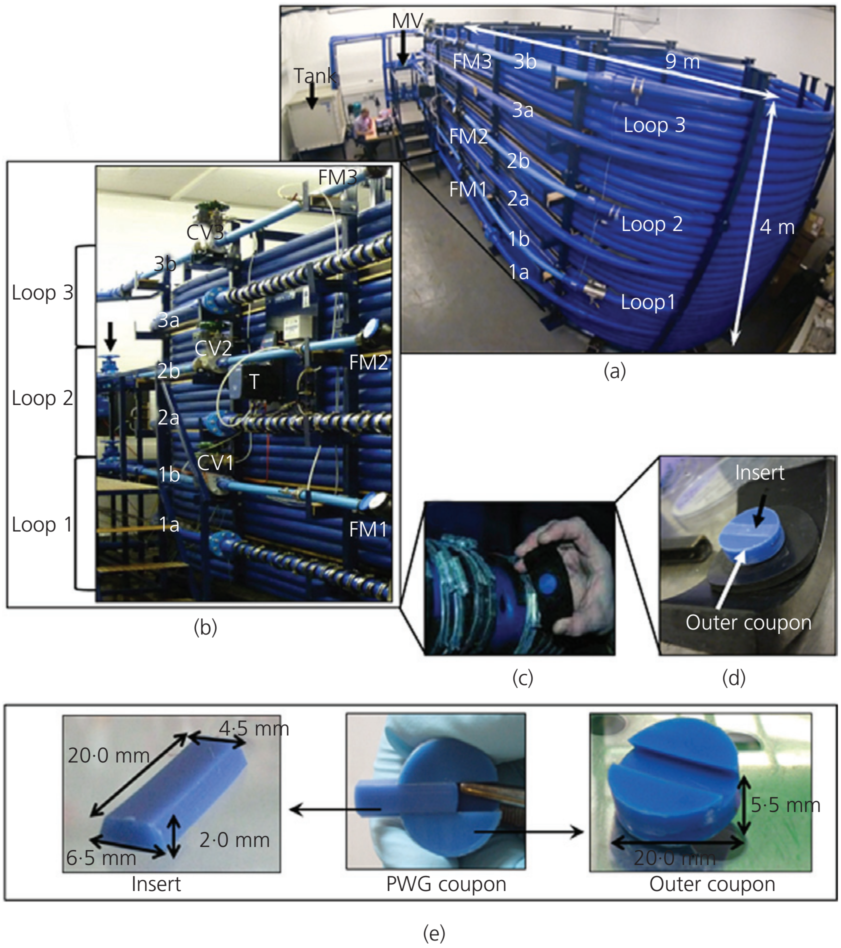

Figure 1. DWDS simulation pipe facility and Pennine Water Group (PWG) coupon. (a) Test facility: total volume (tank and loops), 4·5 m^3; tank volume, 1·53 m^3; each loop comprised nine and a half 21·4 m long coils of 79·3 mm internal diameter HDPE, with a total length of ~200 m; MV = manual valves used to separate the three loops; 1a, 2a and 3a indicate the fifth coil of each loop into which PWG coupons were inserted; 1b, 2b and 3b indicate the 50 mm internal diameter pipes containing flowmeters (FM) and control valves. (b) Detail of loop arrangement: T = turbidity meter (measured using a Chemtrac TM2200 turbidity instrument (Chemtrac Inc., USA)); CV = control valve. (c) Coupons secured in the apertures. (d) HDPE PWG coupon and rubber gasket to ensure a watertight fit. (e) PWG coupon components (insert for microscopy and outer coupon for molecular analyses) and dimensions (reproduced from Fish *et al.*, 2015)

modelling, thus minimising distortion of the boundary layer flow (Douterelo *et al.*, 2014).

3.2 Experiment design

3.2.1 Experimental design overview

Using the unique facility, two experiments were conducted consisting of a 28 d accumulation phase followed by short-duration flushing (substantially increased flow) phases for material mobilisation. The experiments were conducted to determine the impact of hydraulic conditions on discolouration risk, defined here as the quantity of material accumulated on the pipe wall and the amount mobilised into the bulk water after imposed flushing. The environmental variable controlled and studied was hydraulic conditions during the accumulation phase. One experiment investigated the impact of steady-state conditioning shear stress on material behaviour; the other compared this with, and explored the effect of, diurnal flow patterns.

Figure 2 shows the 24 h hydraulic patterns used during the accumulation phases. These patterns, the range of system pressures, flow rates and hydraulic retention times used in this research were determined by reviewing and averaging the outputs from UK pressure-calibrated hydraulic models, with demand patterns extrapolated from flowmeters of several networks, as also done by Husband *et al.* (2008). Average values of pressure, flow and hydraulic retention times used were based around 40 m, 0·3 l/s (0·06 m/s, Re = 4200) and 1 d, respectively. Flow patterns were offset within the day, such that night-time minimum conditions occurred in early afternoon to enable sampling or checks to be made during low-flow

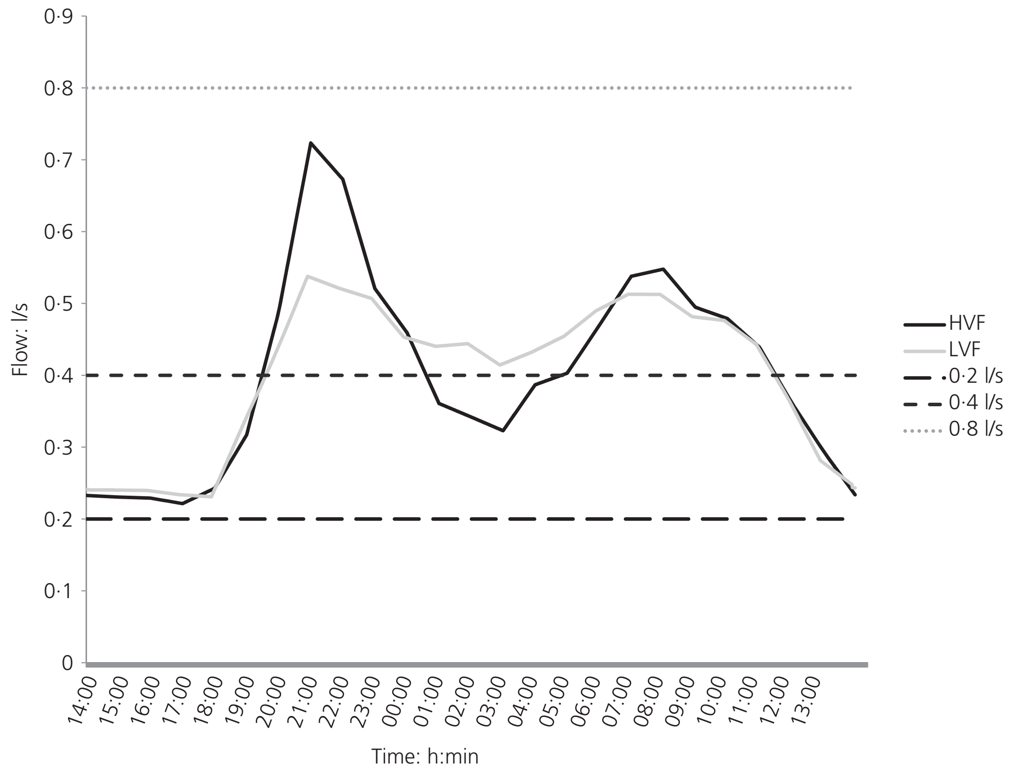

Figure 2. Accumulation-phase daily experimental flow profile (HVF refers to high varied flow and LVF indicates low varied flow). Reynolds number for these flow rates ranged from 3500 to 10 500 (Husband *et al*., 2008); flow was thus either just transitional or fully turbulent

conditions and hence minimising any impacts. All experiments were performed in winter. In order to mitigate for any temperature change effects (i.e. chemical or microbial processes and interactions), the laboratory temperature was matched to the incoming winter water temperature (8°C). The test loop facility was cleaned before each set of experiments to achieve consistent starting conditions. This was achieved by disinfection with a 20 mg/l sodium hypochlorite solution (<16% free chlorine), recirculated within the facility for 24 h, at the maximum attainable flow rate (4·5 l/s). Afterwards, the test loops were flushed recurrently with fresh water until the chlorine and turbidity levels stabilised to those of the inlet water.

3.2.2 Accumulation

The first set of experiments investigated the impact of three different steady-state flow rates, or conditioning shear stresses, on material behaviour. Steady-state experiments were conducted to determine the controlled effect of 0·1, 0·2 and 0·5 N/m^2 conditioning shear stress on discolouration risk, thus improving on bench-scale tests by providing controlled definitive knowledge and understanding of the amount of material accumulation and mobilisation. The chosen conditioning shear stresses relate to typical low, medium and high values experienced within UK DWDSs (Husband *et al*., 2008). Although research into steady-state shear stresses usefully demonstrates the different impacts of net flow effects and conditioning shear stress, it is not realistic of demand-induced diurnal flow patterns experienced in operational distribution networks. Hence the second set of experiments explored the effects of diurnal flow patterns. Profiles were chosen based on typical flow profiles from a UK network (Husband and Boxall, 2010). An average double-peak residential pattern, taken from flow in a 75 mm pipe, was used as the basic flow pattern to define two varied flow patterns (Figure 2). The second set of experiments also repeated the medium flow rate of the steady-state trials as a control and to allow for direct comparison and repeatability checks. Each of these (two varied flow patterns, and medium steady-state) had the same total flow in 24 h, removing net flow effects from comparison between them. The two varied, daily, flow patterns were designed to achieve different peak conditions such that the effect of these could be studied. The patterns were also designed to have the same night-time minimum conditions. Thus, if different results were obtained for varied patterns, the peak effect is important. If similar results occurred for the two varied flow patterns, and these tended to be the results from the lowest steady-state conditioning experiment, then the night-time minimum is important.

3.2.3 Mobilisation

Following the 28 d accumulation phase, a simulated flushing mobilisation phase was performed in each loop sequentially. The selected loop was flushed by increasing the shear stress in

Table 1. Mobilisation-phase flow rate conversion table

Conditioning flow: l/s	Velocity: m/s	Conditioning shear stress: N/m^2
0·8	0·16	0·5
1·2	0·24	0·73
1·75	0·35	1·07
3·2	0·65	2
4	0·81	2·5
4·5	0·91	3

small increments, designed to generate detailed data about the strength profiles of the developed layers. In order to avoid acceleration or transient dynamic force effects, flushing increments were controlled by smooth transitions rather than step changes. Hence all mobilisation was by pseudo steady-state shear stress, not dynamic force or shock loading. Each flushing increase lasted for three turnovers to allow enough time for turbidity to stabilise and for the water quality to become well mixed. Flushing rates are provided in Table 1 for flow, velocity and shear stress.

Discolouration was quantified as a measure of continuous bulk water turbidity, discrete samples of iron and manganese, and coupons for the direct quantification of material on the pipe wall surface. Three replicate discrete water-quality samples were taken at each sampling point. Samples were collected straight after each other into different containers. Samples were stored in 100 ml vials containing 5 M of nitric acid and sent for inductively coupled plasma mass spectrometry (ICP-MS) analysis at an accredited laboratory using water industry standard methods (ALcontrol Laboratories, Rotherham, UK).

3.3 Pipe wall investigations

Coupons were used to determine the amount of material accumulated, in the form of cells. To test the impact of different conditioning flow profiles on material accumulation and mobilisation, coupons were removed on day zero, day 28 and the start and end of flushing. Three replicate coupons were removed at each sampling point, from random points along the coupon pipe length. The flat insert section was then separated from the coupon and fixed in 5% formaldehyde before storage at 4°C. After fixing, the inserts were stained with 20 μM Syto 63 for 30 min. Syto 63 is a cell-permeative nucleic acid stain, which was used to visualise the cells (McSwain *et al.*, 2005). The samples were then washed three times in sterile water, air dried for 10 min then stored in darkness at 4°C (<1 month). A Zeiss LSM 510 meta confocal fluorescent microscope was used for fluorescent microscopy and imaging. Images were taken using a ×20 EC Plan Neoflaur objective (0·5 NA), a 31·54 μ/pixel speed, pin hole set to an optical slice of 4·7 μm, resolution of 832 × 832 pixels and a frame size of 420 × 420 μm. LSM510 Image Examiner software was used to visualise the images. Each insert was imaged for seven random fields of view to provide an accurate representation of cell coverage.

4. Data processing

4.1 Turbidity data

Although continuous turbidity data were collected, the recirculating nature of the facility leads to complex time series results. The net change in bulk water due to flushing is of interest, hence (and in order to simplify the time series) it was averaged to yield a single value with the change in this average value then interpreted. As these baseline values varied between experiments and because the effect of interest was the change due to flushing, all values were normalised by subtracting the loop-specific baseline value after the tank and loop water had been mixed.

4.2 Discrete metal water-quality data

Discrete metal water-quality data refer to measurements of iron and manganese sampled at three turnovers of the system for each flushing step. Three turnovers were selected as all material should have been mobilised and well mixed with the bulk water. Metal water-quality data are presented here as averages of three readings with one standard deviation error bars. As with the turbidity data, the metal water-quality data were normalised for concentrations at the end of mixing phase.

4.3 Pipe wall investigations

After preparation, coupon samples were studied under the microscope for seven random fields of view to account for any spatial variability of cells. A z-stack for each field of view was produced, allowing a cross-sectional picture from top to bottom of the layer. To analyse and quantify the data, separation of the different fluorescence signature was required (un-mixing). In order for the cell stain to be isolated disregarding any background noise, the data were separated between different fluorescence signatures against a spectral database. Digital image analysis was applied to the images to calculate the pixels associated with the Syto 63 stain. The volume of material was calculated based on the area covered in each slice of the z-stack images and then multiplication with respect to the spacing of the slices.

5. Results

5.1 Bulk water results

Water-quality data (Table 2) collected during the accumulation phase indicated that there was no significant change during or between each 28 d accumulation phase. All measurements recorded were below World Health Organization (WHO) standards (Frisbie *et al.*, 2012).

Figures 3 and 4 present the results after data processing, comparing the impact of conditioning shear stress on bulk water turbidity, iron and manganese; the ±1 standard deviation error bars are presented as a combined error based on the

Table 2. Water-quality data collected during the accumulation phases (averages based on three replicates per weekly sample ($n = 12$))

Water quality parameter	Steady-state tests (mean)	Varied state test (mean)	WHO standard (Frisbie *et al.*, 2012)
Chlorine: mg/l	0·2	0·1	5
Iron: mg/l	0·02	0·03	0·02
Manganese: mg/l	0·002	0·005	0·005
Turbidity: NTU	0·011	0·019	4 NTU at customers' taps 1 NTU at water treatment works
Conductivity: µS/cm	542	580	2500 µS/cm at 20°C
pH	7·4	7·3	6·5–9·5

error from the initial value used to normalise the data and the actual recording.

The mobilisation data for steady-state shear stress trials at 8°C (Figure 3) depicted the general trend of less material mobilised into the bulk water in terms of turbidity, iron and manganese with increasing steady-state shear stress. The exception to this was observed for the turbidity value at a shear stress 2·5 N/m^2 for the highest steady-state shear stress (Figure 3(a)).

Despite the same 24 h total flow of each hydraulic regime, there was generally more material mobilised from the material accumulated under the steady-state conditioning shear stress of 0·2 N/m^2 compared with the varied conditioning shear stress experiments (Figure 4). This was especially pronounced for iron (Figure 4(b)) and manganese (Figure 4(c)) and after 2 N/m^2 for turbidity (Figure 4(a)). Little difference in the iron and manganese results was observed between the low and high varied hydraulic condition experiments.

Comparing the 0·2 N/m^2 steady-state results from the two sets of experiments (Figures 3 and 4), there was slight variability in the two repeats but, in general, the same trends and magnitudes of response are evident across the turbidity, iron and manganese parameters.

5.2 Pipe wall material results

Only just-measurable material was detected on the day zero coupons, and no difference was found between samples on day 28 and the start of flushing. Figure 5 shows the amounts of material on the coupons at the start and end of the flush programme for each of the conditioning daily shear stress values. The volume fraction is the amount of three-dimensional space occupied by material for the entire image and is a useful measurement of the overall amount of material per field of view.

The error bars on Figure 5 are considerable, with errors increasing as a function of average volume, suggesting that the volume of material was highly spatially heterogeneous. Despite this, general trends are visible. Initially considering the steady-state experiments, the results show the following trends: the lowest conditioning shear stress generated the highest levels of material accumulation and subsequent mobilisation, and the highest shear stress of 0·5 N/m^2 produced the least build-up and the smallest error bars. However, the spatial heterogeneity was such that the start and end flushing at 0·5 N/m^2 suggest an increase in material. Comparing the two sets of experiments reveals significant differences between the steady-state and varied flow experiments, with more material being accumulated and mobilised under steady-state conditions, even when the high steady-state flow rate was slightly greater than the peak in the high varied flow pattern (Figure 2). This corresponds with the bulk water data (Figures 3 and 4), which showed that more material was mobilised during steady-state conditions. For the higher steady-state shear stress and the varied shear stress experiments, the difference between the start and end data was small. More material was seen to accumulate and be mobilised in the high varied flow experiment compared with the low varied flow experiment.

6. Discussion

The results of these highly controlled yet physically fully representative experiments support the Podds assumptions (Boxall *et al.*, 2001) and previous less-controlled experimental results (Husband *et al.*, 2008) that the accumulation and mobilisation of cohesive layers with variable strength profiles within DWDSs are responsible for discolouration. This is evident in the sequential release of material with each increase in imposed boundary shear stress (Figures 3 and 4), rather than the threshold release of material when particle self-weight is overcome.

The authors contend that the normal daily hydraulic conditions within a pipe have a direct influence on the amount of material that accumulates on pipe walls within DWDSs and ultimately lead to discolouration risk. Under steady-state flow conditions it was observed that the amount of material accumulated on the pipe wall (cells) and mobilised (turbidity, iron and manganese) by subsequent flushing is directly related to the steady-state shear stress, with decreasing amounts of material with increasing shear stress.

It was also found that variable shear stress profiles were more effective at reducing discolouration risk than steady-state shear stress. Variable (daily profile) flow conditions were observed to

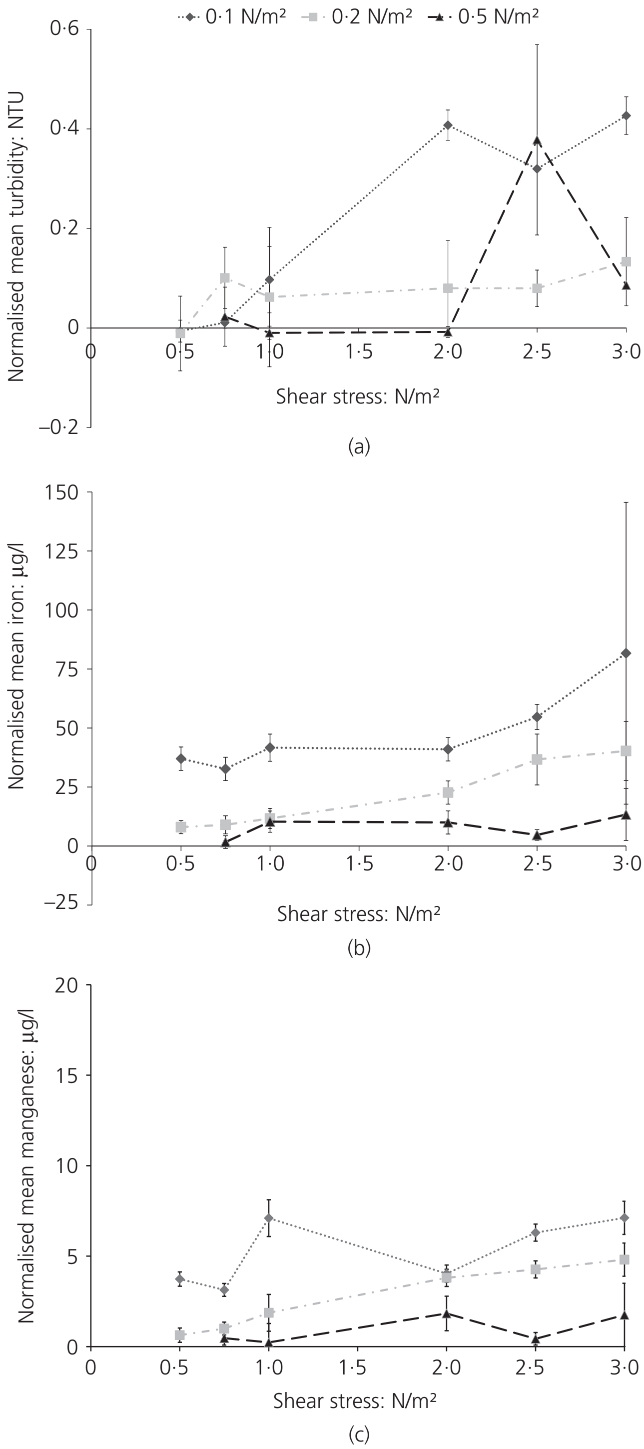

Figure 3. Comparison of normalised mean (a) turbidity, (b) iron and (c) manganese concentrations during the flushing phase for loops conditioned by steady-state hydraulic conditions of 0·1, 0·2 and 0·5 N/m^2

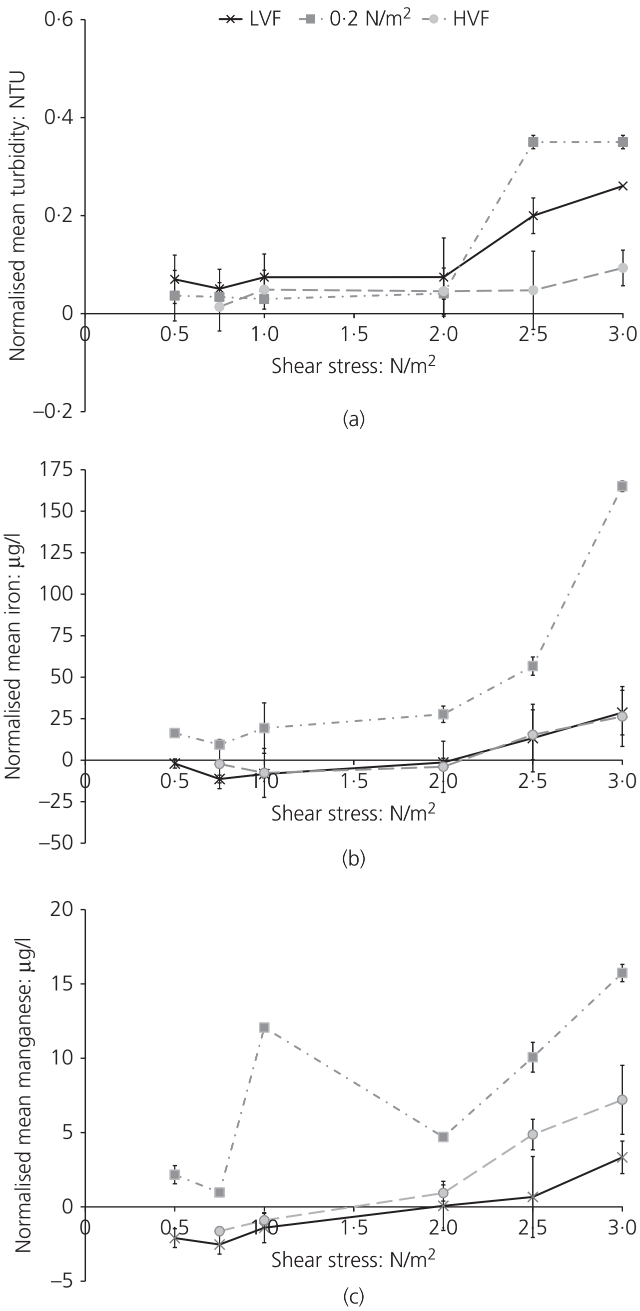

Figure 4. Comparison of normalised mean (a) turbidity, (b) iron and (c) manganese concentration during the flushing phase for loops conditioned by low varied, steady-state (0·2 N/m^2) and high varied hydraulic conditions

reduce the amounts of material accumulated on the pipe wall (Figure 5) and mobilised (Figures 3 and 4) compared with steady-state conditions for the same total daily flow. Indeed, the daily profile conditions were observed to supress material accumulation to levels below the highest steady-state profile, despite the peak in high varied daily flow being slightly less than the steady-state value, and the low varied shear stress being significantly less. Thus, despite experiencing a low night-time flow and the same average of 0·2 N/m^2 as all the medium steady-state experiments, the peak has a substantial influence

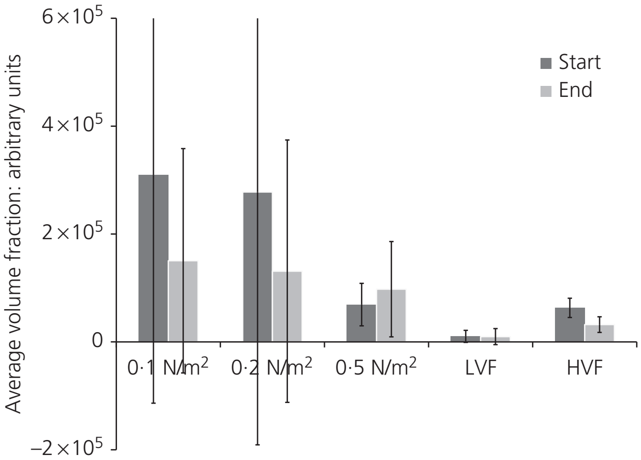

Figure 5. Average amount of material on the pipe wall at the start and end of mobilisation flushing. The results for 0·2 N/m^2 were based on the average of the two sets of experiments. HVF refers to high varied flow and LVF refers to low varied flow

in reducing discolouration material accumulation and is therefore an effective management strategy over average or net flow conditions.

The mobilisation results of the two varied flow profiles suggest that slightly more material was mobilised (turbidity, iron and manganese) for the high daily shear stress than for the low shear stress regime (Figure 4). However, the material accumulation data (Figure 5) suggest that less material was accumulated and mobilised under low varied conditions. These results are contradictory, preventing clear differentiation of the effects of daily peak versus night-time stagnation. This suggests that the additional 0·1 N/m^2 (0·2 l/s) increase associated with the peak in high varied flow compared with the low varied flow did not make much difference to the results. Further experiments are required to check these findings to test whether this was because the increase in shear stress was too small, because after a certain threshold there is no longer a further reduction or because the overnight stagnation period was the same. The dominance of daily flow profiles over total average flow rates is important for the interpretation of past data, in particular from bench-top reactors usually operated under steady-state hydraulic conditions.

Even after flushing at a shear stress of 3 N/m^2, material remained attached to the pipe wall (Figure 5) for all test conditions. Similarly, the rising trend of the majority of turbidity, iron and manganese results (Figures 3 and 4) shows that more material could potentially be mobilised by greater imposed shear stress. Conversely, previous field research has suggested that, above a certain threshold, only small amounts of additional material are mobilised for plastic pipes; Cook and Boxall (2011) recommended a value of 0·7 N/m^2 while Husband and Boxall (2010) recommended 1·2 N/m^2. If the results of the experiments reported here are correct for operational systems, cost-effective flushing or other cleaning operations need to be designed with respect to the maximum expected flow increase for any pipe length (risk-based approach) rather than by achieving a universal target value of flow, velocity or shear stress. While cleaning above such a target might remove more material, that material would be strongly bound and thus not necessarily pose a discolouration risk, unless the material layers were weakened, for example by major changes in the bulk water quality. However, it should be noted that the material layers in this investigation were only generated over 28 d at 8°C, while those occurring within operation systems have developed over the lifetime of the pipes. There may also be seasonal effects driven by changes in water temperature affecting the nature and rate of the chemical and biological processes. Further research may therefore be desirable to better understand the impact of a wider range of temperatures, although the central range experience in the UK was covered in this work. The results reported here are the product of a 28 d growth period; while it may be desirable to run longer experiments to provide further definitive evidence, such experiments are probably unnecessary due to evidence from operation systems that the processes of interest are linear functions of time (e.g. Cook and Boxall, 2011). Although the facility used provided conditions fully representative of operational networks, it also provided only one combination of the factors – specifically, only one source water quality (see Section 3.1 and Table 2) and only plastic pipe materials of 78 mm diameter. Previous work has suggested that the primary effect of different source water quality and pipe material is to change the rate of material accumulation on the pipe wall, not the ultimate risk level. Specifically, Husband and Boxall (2011) presented evidence that surface water sourced cast-iron pipes present a fully regenerated discolouration risk after 1·5 years, groundwater sourced cast-iron pipes present a fully regenerated discolouration risk after 3 years and, on average, plastic pipes present a fully regenerated discolouration risk after 4 years. Hence, the effect of these factors will be to change the frequency of regularly imposing cycles of flow variation recommended from this research. If this variation is achieved through daily flow variations, then according to data reported elsewhere (e.g. Husband and Boxall, 2011) the timescale of source water and pipe material effects makes them irrelevant. Alternatively, if the flow variation requires some valve operations or other intervention, these could either be automated and done at a high frequency relative to the above values or optimised based on the above and site-specific experience. The operation dataset reported by Husband and Boxall (2016) suggests that the approach of regularly increasing flows scales to trunk main diameter pipes, giving confidence in extrapolating the results reported here to other pipe diameters.

Overall, the most substantive finding of this work is that, following any cleaning strategy, subsequent material accumulation can be effectively minimised by the implementation of regular variations in the conditioning hydraulics, rather than implementing net flow increases, and thus the time to the next cleaning intervention can be extended or even avoided.

7. Conclusions

This paper has shown the importance of hydraulic conditions in controlling the accumulation and mobilisation of discolouration material within DWDSs. The main findings of this study are as follows.

There is an inverse relationship between steady-state hydraulic conditions during layer development and the amounts of material accumulated and mobilised. A daily cycle of hydraulics was found to have a dominant effect on limiting the accumulation of discolouration material and its subsequent release. The effect of a daily variation in flow (hence boundary shear stress) was far greater than the effect of the average daily flow rate. However, the results are inconclusive regarding the dominance of night-time stagnation compared with the magnitude of the morning peak on material accumulation and release.

Flushing at a level up to 3 N/m^2 was not sufficient to completely remove all the material accumulated on the pipe wall. The research evidences the importance of hydraulic conditions on in-pipe processes and the need to accurately recreate these for findings to have practical value; specifically, future studies should include demand-driven flow patterns as a key variable. The results from this study can be used to usefully inform those responsible for the operation and management of DWDSs to reduce discolouration risk. Firstly, control strategies that regularly impose flow variation cycles limit discolouration risk (in particular limiting accumulation) more effectively than increasing total average flow rates. Secondly, flushing only removes material up to the force imposed; if increases above the flush rate occur, further discolouration will result (even in plastic pipes) and hence flushing or other cleaning operations should be designed for the greatest flow rate expected for the pipe length, rather than for the unrealistic expectation of entirely clean pipes.

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