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Impact of Hydraulic Interventions on Chronic and Acute Material Loading and Discolouration Risk in Drinking Water Distribution Systems

Sunny I[1], Husband PS[2], Boxall JB[2]

[1]AECOM, UK

[2]University of Sheffield, UK

Abstract

This paper presents results from an intensive long term investigation in three comparable trunk mains and downstream impact of non-invasive, in-service flow conditioning to manage discolouration risk. Findings show that flow conditioning, the careful regular increase in flows to mobilise small amounts of material from cohesive layers formed at the pipe wall, provides immediate risk mitigation and system resilience benefits. Evidence is presented showing longer term risk reduction in the trunk mains and a 25% discolouration risk reduction in the downstream networks. Whilst the flow conditioning produced an acute but short duration controlled mobilisation of material from the trunk main, longer term downstream monitoring showed reduced chronic or background material loading. It is proposed this change is due to altering the material exchange behaviour and volumes bound within cohesive layers that develop on bulk water / infrastructure interfaces. The paper provides evidence that flow conditioning is an efficient strategy to manage discolouration risk and improve consumer water quality throughout water distribution systems.

Keywords: Flow conditioning, shear stress, discolouration, accumulation, mobilisation

Introduction

Drinking water distribution systems (DWDS) are high surface area reactors where a complex set of physical, chemical and biological interactions occur simultaneously in both the bulk water and at the pipe wall. A resulting outcome may include discolouration, a key factor affecting customer satisfaction and acceptability of drinking water. Discolouration has been identified as being primarily due to the mobilisation of particulate material that has accumulated on the pipe walls. Discolouration events are often short in duration and associated with hydraulic disturbances. In addition to generating unacceptable customer contacts and failing turbidity standards, discolouration samples can breach other water quality regulatory limits, such as for metal concentrations including iron, manganese and lead (Cook, 2007). Customer contacts are associated with individual properties and hence discolouration often attributed to local network effects, however through spatial and temporal clustering analysis 30-50% of discolouration events have been identified as originating from upstream, including trunk mains (Husband et al 2010 and Cook et al., 2015).

Trunk mains are large diameter pipes that are critical water distribution infrastructure from which the consequences of discolouration are high due to the population exposed. With such risk associated to trunk mains, water companies are understandably cautious and often reluctant to undertake operational activities allied with them. Yet to manage and deliver consistently the highest water quality to customers, interventions are becoming inevitable as infrastructure deteriorates and expectations rise. As a result, water utilities are required to invest in the removal of accumulated materials from trunk mains with the aim of improving water quantity and quality issues as part of rehabilitation programs. An option to clean wall-bound material legacy is through expensive invasive cleaning strategies, e.g. air scouring, ice pigging or swabbing (AWWA, 2014). These strategies may deliver water quality benefits, yet they are often difficult to implement, expensive and require specialist resource-oriented strategies and includes the often very considerable challenge of taking mains out of service without interrupting supply. Studies have also highlighted that discolouration material returns to the pipe wall (Boxall et al., 2003a, Cook and Boxall, 2011) and water quality contacts return, raising questions regarding the long-term benefits of such invasive strategies. Some non-invasive and in-service hydraulic driven maintenance strategies have been implemented successfully in distribution systems, e.g. flow conditioning (Husband and Boxall, 2015) and self-cleaning velocity techniques (Van Den Boomen et al., 2004; Vreeburg et al., 2009). However, the long-term impact on discolouration risk of flow conditioning has never been assessed or the impact of different material loading regimes as water travels from the water treatment works (WTW) to the downstream distribution network. Concerns remain therefore over how these interventions influence long-term discolouration risk and if they provide water quality benefits.

Background

Discolouration processes

Discolouration has historically been conceived as the re-suspension of gravity deposit sediments, yet the microscopic size (2-50 μm) of analysed discolouration material suggests self-weight driven settling is unlikely to dominate behaviour other than in quiescent conditions (Boxall et al., 2001; Ryan et al., 2008).

Discolouration particles are typically observed during hydraulic disturbances where flow, and hence shear stress, the force perpendicular to the pipe wall, mobilises bound material. Further discolouration is observed with sequential flow increases, indicating particles are held in cohesive layers with a range of shear strengths, with the weakest of these layers dictated by the typical daily peak shear stress during normal operation (Boxall et al., 2003b; Husband and Boxall, 2011). This cohesive layer theory for particle accumulation in a DWDS has been validated under temperature controlled full representative laboratory conditions (Husband et al., 2008) and for operational systems (Husband and Boxall, 2011, 2016). Other research has also demonstrated that particles do not accumulate in a non-cohesive manner unless the hydraulic forces are very low (Vreeburg and Boxall, 2007; Pothof and Blokker, 2012).

Multiple studies have shown that discolouration material in DWDS re-accumulates on pipe walls following flushing (Husband et al., 2010; Cook and Boxall, 2011; Husband and Boxall, 2011; Blokker and Schaap, 2015). Repeated flushing studies conducted in the same DWDS pipes after periodic intervals (Husband and Boxall, 2011), showed that turbidity responses to each shear stress step increase was similar to initial trials. Their findings suggest that material regenerates at varying shear strengths simultaneously and this has been supported by controlled full-scale laboratory investigations by Sharpe et al., (2017). While the simultaneous accumulation of varying strength material has been well reported for small diameter pipes, this is not the case for large diameter trunk main systems.

Quantifying discolouration risk

Several studies quantified discolouration risk in DWDS by assessing the rate at which material accumulates on pipe walls. Those studies compared volumetric material loading (flow and associated turbidity response) from repeated controlled hydraulic events, e.g. flushing, over a specified period (Vreeburg et al., 2008; Blokker et al., 2011; Cook and Boxall, 2011; Husband and Boxall, 2011; Blokker and Schaap, 2015). The material accumulation return interval found in these studies ranged between 1.5 and 4.0 years. However, measuring accumulation rates or return interval in trunk mains using hydraulic events is complicated due to their layout and the volumes of water required.

Several studies have proposed the importance of continuous turbidity measurement as part of a water quality monitoring program (Frey and Sullivan, 2005; Storey et al., 2011; Kara et al., 2016). Van den Hoven et al. (1994) suggested that continuous turbidity measurement is an indicator of aesthetic issues. Previous studies have used high temporal turbidity to assess mass flux into the downstream DWDS and to identify spatial and localised material accumulation, suggesting its importance (Gaffney and Boult, 2012; Starczewska et al., 2017). By applying the CANARY event detection system (USEPA, 2010) to the turbidity data collected by Gaffney and Boult (2012), Mounce et al. (2015) showed that continuous turbidity can be used with hydraulic data for an event detection indicator. No studies have yet investigated continuous turbidity from trunk mains, to understand the risks they pose or to quantify material loading from them into downstream zones.

Hydraulic based discolouration management strategy in trunk mains

A non-invasive trunk main maintenance strategy termed "*flow conditioning*" (Husband and Boxall, 2015) was developed based on the concept of a cohesive transport turbidity modelling approach (Boxall and Saul, 2005). This strategy was developed and implemented by the University of Sheffield in collaboration with several UK water companies. Flow conditioning is considered as "controlled in-service flushing" by imposing managed excess shear stress to mobilise controlled amounts of material from pipe boundary surfaces yet keeping the response within defined limits, such as targeting 1 NTU (Nephelometric Turbidity Units) that retains a safety margin below the current UK regulatory limit of 4 NTU. To implement successful flow conditioning requires a knowledge of pipe hydraulic properties, the ability to control system hydraulics and knowledge of the hydraulic history so appropriate sized changes may be imposed. The method is designed to operate under normal network conditions without interrupting supply with mobilised material entrained in the bulk flow as wash load and transported through the downstream network. Material with cohesive strengths higher than the imposed shear stress remain on the pipe wall and hence flow conditioning reduces discolouration risk by selectively removing the weaker material proactively that otherwise could be rapidly mobilised from unplanned or inadvertent changes in system hydraulics. In addition, flow conditioning may be used to achieve network hydraulic resilience by facilitating higher flows, either in single or multiple stages depending on required resilience targets, such that operators have confidence that in the short-term the same flows can be repeated without fear of discolouration events. This allows network planning for changes including rezoning or valving operations, seasonal fluctuations or burst mitigation.

Flow conditioning interventions have been successfully implemented in several trunk main systems with verified short term reductions in discolouration risk (Husband and Boxall, 2015). However, the long-term impact on the trunk main and downstream network has not been studied. There is concern that the periodic mobilisation and subsequent transport of acute material loads (i.e. higher than typical turbidity values), could directly impact customers and accelerate accumulation rates in the downstream network. It may however be that much of the planned low level but acute loading remains as wash load and exits via consumer connections with insufficient contact time to accumulate downstream.

This study aimed to explore the impact of trunk main flow conditioning interventions on long-term discolouration risk by investigating the change in material loading from trunk mains and the effects on downstream network accumulation return periods.

Methods and Materials

Methodology

To assess the long term impacts of flow conditioning, three independent trunk mains with a single source and common physical attributes were identified and intensively monitored. Different flow conditioning strategies were implemented on two of the trunk mains over a 12-month period, while the third was used as a control. With the main focus of the work to differentiate the impact and effects of flow conditioning interventions, the selection of comparable and hydraulically similar mains allowed variables such as shear stress and pipe material to be effectively eliminated as experimental variables. To further investigate the impact, the networks downstream of each trunk main were also studied.

Hydraulic and turbidity time series data was collected for each trunk main, quantifying the interventions imposed, as well as any natural events, and enabling assessment of their resulting performance. To assess the impact of the different material loading regimes on the downstream networks, material mass fluxes resulting from repeated hydraulic flushing operations were compared. Customer contact data was also assessed. Although discolouration customer contacts are regarded as non-scientific, clustering analysis of data from within a time frame and across multple locations can be used to identify events linked to upstream mains from pre and during the trials.

To provide different risk management and material loading scenarios, two periodic flow conditioning interventions were designed and implemented. One with higher regular applied shear stress termed ‘normal flow conditioning’ and the other with lower imposed shear stress events termed ‘passive flow conditioning’. Both flow conditioning interventions were implemented quarterly, a period considered sufficient for material accumulation to allow a measurable mobilisation response. The third, control trunk main, had no periodic interventions, just pre and post assessment. All three trunk mains underwent high shear stress flow conditioning at time zero and after 12 months. This was to achieve consistent starting conditions and to assess final levels of discolouration risk due to the different imposed strategies. Figure 1 presents the different magnitudes and timeline of flow conditioning interventions applied to the trunk mains. Selected pipes, with similar attributes (e.g. hydraulic conditions, material and location in the network) in the networks downstream of each trunk main were also flushed pre and post the 12 month period. Data from the District Metered Areas (DMA, a system of distribution system discretisation applied in the UK) flushing trials enabled assessment of material accumulation periods using mass flux analysis.

Both hydraulic and water quality data were essential for this study. Trunk main flow data was necessary both as an investigative record and also to manage flow conditioning events. Combining turbidity and flow data enabled assessment of material loading and determination of material flux from the common inlet to the three study trunk mains and at a downstream location for each trunk main. Monitoring at high temporal resolution was necessary to accurately capture material loading to account for the temporal variations observed in operational networks.

Site details and network characteristics

To fulfil and ensure sound experimental design, a single source water treatment outlet was selected that supplied three otherwise independent but similar trunk mains from an operational network in the UK. Each trunk main had similar pipe material and hydraulic profiles shown in Table 1. This was to establish comparable physical, chemical and microbiological water quality conditions and hence, as much as possible within operational systems, similar discolouration risk generating conditions. Thus, any differences in discolouration behaviour should be dominated by the different interventions imposed. Figure 2 presents a network schematic and location of monitoring instruments. While the choice of inlet point defined the incoming loading from treated water, the outlet point recorded the change in discolouration risk by monitoring the response to interventions and provided material loading concentrations supplying the downstream DMAs.

The raw water was supplied from an upland surface water source and treated with a ferric coagulation process and chlorinated prior to supplying the trunk mains. Table 2 presents the treated water quality parameters from discrete samples collected for regulatory purposes over four years up to and including the period of study. Discrete samples were collected and analysed by UK industry standard laboratory. All mains were gravity fed from the treatment works.

Selected DMA pipe characteristics

Five pipes with similar characteristics were chosen from each of the selected DMAs for repeated flushing. Priority was given to non-corroding pipes, such that the dominant potential contribution to discolouration risk could be assigned to accumulation from the bulk water, rather than localised corrosion of the pipes. All pipes were located near to the DMA inlet and operated as effectively dead end sections serving residential areas, thereby likely to have similar demand patterns. Without detailed monitoring of DMA flows, this would allow comparison of results, as opposed to pipes serving different sized downstream areas and therefore subjected to very different hydraulic demands. Table 3 presents the properties of the pipes selected for flushing analysis fed from the three trunk mains.

Fieldwork procedure and timeline

The flow conditioning strategies were designed using the validated PODDS model (Husband and Boxall, 2015) and set to limit turbidity response to a maximum of 1.0 NTU during the trial period. To achieve repeatable and accurate managed flow increases, hydrant standpipes fitted with ABB Aquamaster flow meters to which twin independent ATI Nephnet turbidity monitors were connected. TM-1 normal flow conditioning trials were designed with a maximum 40% step shear stress increase addition to the typical historical (12 month) peak shear stress, TM-2 passive flow conditioning was with a maximum 16% addition to the peak shear stress and TM-3 was the control main. The 40% additional peak shear stress increase was used in all TM's for time zero and after +12months. The fieldwork timeline and flow conditioning strategy applied to each trunk main is shown in Figure 1. Target shear stresses were selected based on the WTW hydraulic capacity and local drainage conditions. All flow conditioning trials were operated under similar conditions, i.e. same time of the day, equipment and monitoring sections, to standardise the trials. Since the trunk main flow profiles were demand driven and diurnal in nature, target excess shear stress was achieved during the morning peak when the network demand was highest. This was selected as it requires the lowest additional discharge flow to achieve the conditioning target.

To pre-set the DMA pipes to a known level of cleanliness prior to trial commencement, initial flushing was undertaken at time zero. Repeat flushing was undertaken after the completion of all flow conditioning trials to determine the impact of the different conditioning strategies on material accumulation (Figure 1). Both initial and repeat DMA pipe flushing was conducted with similar conditions to the initial trial, e.g. flow rate, flow step increase, flushing duration, time of the day and same equipment to maintain consistency.

Flow conditioning and DMA flushing monitoring

The turnover time for the three trunk mains during highest hydrant flow whilst conditioning was approximately 3.5 hours. Given the expected propagation effects of material mobilisation following the change of imposed shear stress and the limited duration of the highest flow combined with peak demand, a turbidity and trunk main flow sampling resolution of 15 minutes was identified as providing sufficient definition of the material mobilisation response. Since the turnover time for the typical DMA pipe (100mm diameter) with average pipe length of 150m and a flushing velocity of 1.0 m/s (approximately 8 l/s) was just over 2 minutes, sampling was at 1 second to ensure sufficient data points to accurately describe the response. To collect flow data during flow conditioning and DMA flushing trials, an ABB Aquamaster flow meter attached to a Langham UK hydrant instrumented standpipe was used. The ABB flow meter used in this work measured flow with an accuracy of ±5% of reading and maximum working pressure of 12 bar. Flow and therefore shear stress were increased carefully via a gate valve connected to the standpipe discharge point. ATI Nephnet instruments with Infrared (IR) Nephelometric measurement processing were used to measure turbidity responses during flow conditioning (acute loading) and DMA flushing. The ATI Nephnet logger functioning range was set to 0 - 4 NTU for flow conditioning trials and 0 - 400 NTU for DMA flushing. Instruments were calibrated with formazin standards under laboratory conditions and dual validated by duplication of units during trials. Turbidity data was also spot checked regularly by a 2100Q Hach handheld logger which was also calibrated with formazin standard dilutions. The handheld turbidity meter was calibrated for 0 - 800 NTU with an accuracy of ±2% of reading. A one-off 24-hour pressure recording at the trunk main downstream point was measured using Syrinix Transientminder, to calibrate the pipe roughness and therefore to calculate shear stress for all three trunk mains. The pressure logger range was set for 0 - 20 bar with an accuracy of 0.1% of full-scale output.

Long-term data monitoring

Data from ABB Aquamaster flow meters at the inlet of each trunk main and DMAs were available prior to and through out the study period. To measure the treated water turbidity, a Sigrist Aquascat 2 turbidity instrument was available at the WTW outlet. The turbidity instrument range was set to 0-4.0 NTU with an accuracy of ±0.001 NTU using the IR Nephelometric measurement process. To determine the downstream chronic loading, continuous turbidity data at 15-minute intervals was measured at the trunk main monitoring point initially with an ATI Nephnet instrument from October to February. After this Evoqua Hydraclam loggers were deployed. Like the ATI and Sigrist logger, Hydraclam uses IR Nephelometric measurements with a range set for 0 - 10 NTU with an accuracy of ±5% reading. Spot checks were made bi-weekly using Hach handheld turbidity instruments.

Due to discolouration particles known cohesive nature (Boxall et al., 2001), turbidity instrument drift was anticipated with optic lens fouling during long term monitoring (Gaffney and Boult, 2012). To minimise drift, the ATI Nephnet logger lenses were cleaned on site bi-weekly during its deployment period (October to February), although little or no drift was observed and consistently good agreement shown with spot checks. After February the Hydraclam logger was deployed in which turbidity drift was corrected through a proprietary post-processing algorithm which returned good agreement with handheld spot checks. The Sigrist logger was serviced as part of the regular WTW maintenance.

Data processing and analysis

Hydraclam turbidity data returned a higher standard deviation (SD) of 0.38 (sample size, n≥5800) compared to the ATI Nephnet unit (SD=0.03, n≥5800). A potential reason for the lower variation with the ATI logger is that it used a continuous flow of 0.02 l/s (~1.2 l/m) for the sampling process. The Hydraclam logger used a purging system, running 6 litres of water at a flow rate of 0.1 l/s to waste prior to sampling each 15-minute interval. While the total discharged volume (>6 litres) can be increased, it was limited due to local drainage constraints. This is considered to produce additional noise in the data due to only partial purging of the hydrant riser and connecting pipework. To minimise the noise from the measured signal, different rolling means were explored with 1-hour selected based on minimising the signal to noise yet retaining measured behaviour. Figure 3 shows a moving average sensitivity study comparing measured turbidity response of treated water and the three trunk mains. Note that turbidity responses produced during flow conditioning trials are not included in the smoothing process as the higher flows through the hydrant negated the riser turnover effect and non-smoothed data was used from these periods.

Due to operational constraints and background flow demands, applied shear stresses were not constant over the duration of each flow conditioning operation (and not entirely consistent between pipes and operations), therefore volumetric turbidity responses (flow and turbidity) were not directly comparable. Flow conditioning trials were therefore assessed and compared via a material release rate. To compare the responses with a single metric, measured flow and turbidity was calculated by integrating the turbidity time series with the volume of water used and dividing by the sum of the imposed excess shear stress and effective pipe wall area. This is shown in equation 1.

$$Material\ release\ rate\ per\ excess\ shear\ stress\ \ per\ unit\ area = \frac{\int_0^t T_{ds}(t).Q(t)dt}{\frac{\pi}{4}D^2 \int_0^t \tau(t)} \tag{1}$$

Where $\mathrm{T_{ds}}$ is the turbidity in NTU, t is the trial duration in seconds, Q is the volume of water in m^3/s, τ is the applied excess shear during the trial period in N/m^2, and D is the internal pipe diameter in m. The excess shear stress was determined by average daily shear stress minus the additional shear stress imposed during the trial period. The imposed shear stress was calculated using equation 2.

$$Applied\ shear\ stress,\ \tau = \rho g R S_0 \tag{2}$$

Where, ρ = discolouration material density in kg/m^3, g = gravitational force in m/s^2, R = hydraulic radius in m and $\mathrm{S_0}$ = hydraulic gradient unit less. In this calculations, ρ and g were used at 1000 kg/m^3 and 9.81 m/s^2. Hydraulic gradient was calculated for the entire pipe length using Darcy-Weisbach formula integrating Swamee-Jain Colebrook-white approximation (Swamee and Jain, 1976) and network hydraulic properties stated in table 1.

While the flow conditioning data was compared using material release rate, the same calculation was not required for DMA pipe flushing data as the flow rate and hence shear stress was consistent for each flushing. Flushing data was therefore compared using volumetric material loading ($NTU.m^3$) which integrated the turbidity time series in NTUs and multiplied by flushing water volume in m^3/s, equation 3. This volumetric loading calculation was done at initial flushing (time zero) and repeated flushing (+12 months). From this it was possible to estimate complete regeneration period; how long it would take to acheive the initial amount based on how much of the initial response was seen after 12 months. This assumed a linear accumulation process over 12 months and the initial state represented undisturbed and fully developed material layers (Boxall et al., 2003a; Cook and Boxall, 2011).

$$Volumetric\ loading = \int_0^t T_{ds}(t).\,Q(t)dt \tag{3}$$

To investigate the significance of intervention impact on downstream network material accumulation rates, samples were statistically analysed by IBM SPSS v22.0 software. Due to the small sample size and assuming samples were not necessarily normally distributed, nonparametric testing was chosen to investigate the difference between the chronic and acute material loading rate with a significance level (α) of .05. For multivariate analysis, the Kruskal-Wallis H test was chosen, and Mann-Whitney U test was used for bivariate sample analysis.

Results

Flow conditioning and burst event trunk main data

Figure 4 presents the WTW final turbidity and flow and turbidity profiles for each of the three trunk mains over a 17-month period; note that due to practical constraints the 12-month period of the control main lagged that of the other two. One major unplanned burst event affected flows in TM-1, occurring between conditioning trials 2 and 3. Four burst events were recorded by the TM-2 flow meter during the measured period. Two burst events were observed in TM-3 data. All these hydraulic events occured in the downstream networks except a burst event in June in TM-3 which occurred approximately 1.3 km from the WTW outlet. During the repair process, TM-3 demand was rerouted via parallel TM-2 at 1.7 km from the WTW outlet. This then initiated the burst event in TM-2 at the same time. The burst in December in TM-3 was a small event that caused 6 l/s additional flow and was located approximately 2.0 km from the WTW outlet. No turbidity response was observed from this event at the downstream turbidity measurement point.

Figure 5 presents the three trunk main flow conditioning and burst event measured flow and turbidity responses. Each plot shows a 72 hour (3 day) period with zero at midnight (12:00 am) of the day in which the conditioning or burst commenced. A three day (72 hour) period was chosen as the final target shear stress was often achieved by imposing staged increases over several days to ensure turbidity remained below 1 NTU, and to show the key aspects of each of the bursts that continued up to a maximum of 72 hours. TM-1 in Figure 5(a) shows that notable material (>average turbidity) was mobilised from all planned and unplanned trials, with turbidity observed from each additional shear stress increase. A peak turbidity of about 10 NTU was recorded during the burst in March 2016. While relatively greater strength material will have been released from this burst, enough material accumulated in the following two months to have a turbidity response higher than average values (≤0.5 NTU) from trial 3. Figure 5(b) presents TM-2 flow conditioning and burst event flow and turbidity data. No notable turbidity was observed from any TM-2 flow conditioning trials, potentially an effect of multiple burst events during the monitoring period. However, material was released from each burst event under varying imposed shear stress conditions. For TM-3, only trial 1 and the burst in May 2016 had observable turbidity responses, as shown in Figure 5(c). In all three trunk mains cases, these events were separated by a period that allowed material to accumulate resulting in further discolouration responses across the range of imposed hydraulic events. Material release in successive trials indicates accumulation occurring throughout the year and simultaneously across the range of imposed shear stresses.

Figure 6 presents the flow conditioning trials and burst event responses as material release per unit excess shear stress per unit wall area. From Figure 6, the material release from TM-1 was lowest in trial 2 and 3 and the highest value was recorded during trial 5. Since similar imposed shear stress was implemented for all trials in TM-1, it was anticipated, yet not observed, that similar amounts of material would be mobilised. The relatively lower amount of material mobilised during trial 2, could indicate a seasonal effect with lower rate of material accumulation over a colder winter period although the limited data prevents detailed statistical analysis. A significant correlation was however observed between seasonal treated water temperature and turbidity behaviour for the same dataset (Sunny et al. 2018). Unfortunately, any further seasonal effects, in TM-1 (and TM-2) are also masked by the occurrence of burst events. The burst event in February resulted in a high release of material, likely due to imposing flow rates higher than had been observed in the trunk main for considerable time and hence material had been able to accumulate over a long period. The lower amount of material seen in response to trial 3 is probably due to the impact of the burst on material layers in February and the relatively shorter accumulation period since the burst event. Relatively less material was mobilised from TM-2 during the passive flow conditioning trials compared to TM-1, which was anticipated due to the lower imposed shear stress conditions. A high amount of material was released from the two larger magnitude burst events, a result of mobilising previously undisturbed (higher shear strength) material, and these will also have impacted flow conditioning trials 3 and 4 by shortening the period over which material could accumulate. Similar amounts of material were released from the two planned trials from the control main (TM-3) with a 12-month interval. Similar to TM-2, a burst in May 2016 released high amounts of material with potential impact on the trial 2 response. However, due to the long interval period between the bursts in May and trial 2 in TM-3, it is difficult to quantify the impact.

Long-term trunk main data shown in Figure 7 presents the measured turbidity of the treated water and at the downstream ends of the three trunk mains for May. This period was chosen for turbidity comparisons as it was just after trial 3 of TM-1 and TM-2, before the May burst event in TM-2 and TM-3, and approximately in the middle of the investigation period with all monitors functioning. Visual comparison between treated water turbidity and the three trunk mains indicates turbidity increased during transit through each of the trunk mains, particularly evident in TM-3. The downstream turbidity also exhibits a regular diurnal pattern, associating particle mobilisation and bulk water loading with diurnal variations in flow.

To further assess how bulk water turbidity varied during transit and to quantify the impact of hydraulic events on turbidity responses, turbidity data of treated water and the three trunk mains is shown in box-whisker plots, Figure 8. Box-whisker plots were processed in monthly periods and show the median, 25th, 75th and 99th percentile range of turbidity data excluding flow conditioning trials and burst events. Monthly periods were chosen as providing sufficient data in each period but still allowing identification of possible seasonal trends and the impacts of bursts and flow conditioning. Figure 8(a) shows the treated water turbidity median lies between 0.07 and 0.15 NTU with no abrupt variations, suggesting consistent supply of low turbid water. TM-1, subjected to normal flow conditioning, shows that additional particles were generated compared to treated water responses as shown in Figure 8(b). The initial turbidity response of TM-1 (October) was relatively higher than the WTW. From Figure 8(b), median turbidity response was improved post flow conditioning trials that started in November and after that median turbidity was closer to the WTW baseline. This suggests that flow conditioning is influencing material loading and hence turbidity behaviour. The only exception was observed in the final October, where relatively higher turbidity responses were measured than in the other months. This could be related to the change from summer to autumn cyclic seasonal loading, although TM-2 data did not show similar behaviour. However, following trial 5 in TM-1 (implemented at the end of October), notable improvement in turbidity was observed from October (median=0.27 NTU) to November (median=0.075 NTU) and December (median=0.10 NTU).

Similar to the TM-1 monthly turbidity response, Figure 8(c) shows that the TM-2 (passive flow conditioning) median responses was nearer to the treated water responses post flow conditioning commencement, suggesting this improvement was due to the maintenance effect from this managed application of hydraulic events. Figure 8(c) also shows that following the bursts in May, median turbidity was again improved. Figure 8(d) shows that TM-3, the control main, has increasing turbidity over time, indicating that post the primary trial, turbidity contribution from the trunk main increases with no maintenance. No immediate impact on turbidity response was observed from the burst in May; however, a little improvement was measured from July onwards, with a slight improvement after the December burst.

Figure 9 presents single box-whisker plot for over 12 months of turbidity data from the treated water and the three trunk mains. The WTW baseline is between 0.08 and 0.15 NTU for 25th to 75th centiles with a median of 0.1 NTU. Amongst the three trunk mains, TM-2 had the lowest response, with a median of 0.095 NTU which was lower than the treated water median value. TM-1 measured data is a little higher than TM-2 with median 0.12 NTU, just greater than the treated water median value. The maximum turbidity was recorded for TM-3, with a median of 0.260 NTU, roughly 240% higher than treated water response. These results indicate the material loading behaviour of the trunk mains are significantly impacted by the regular flow conditioning interventions. The two flow conditioned trunk mains transmit lower long term chronic material loading to the downstream network, whilst the control trunk main with no interventions has a detrimental effect on water quality with higher chronic loading.

Customer contacts

The effects of the trunk main flow conditioning were also investigated by clustering analysis of customer contacts. Although not regarded as scientifically precise, customer contacts are used as a primary measure for UK and many other countries to assess overall levels of performance and customer satsifaction. Clustering of data from within a rolling time frame (3 days in this case) and across multple locations can be used to identify upstream events. Figure 10 presents the clustered contact analysis for the DMAs downstream of each trunk main, showing the percentage of customer contacts in each area that could be attributed to upstream events, for periods pre and during the interventions. Average discolouration contacts were similar for all trunk mains pre-intervention period. No clustered contacts were found in TM-1 during the monitoring period, indicating that flow conditioning had no immediate detrimental effect on customers. Both TM-2 and TM-3 contact numbers were affected by a burst event in June, with 90% of contacts in the monitoring year attributable to this in TM-2 and 65% for TM-3. This suggests TM-2 fed DMA performance was good compared to TM-3 and overall flow conditioning is beneficial in reducing trunk main associated events.

DMA flushing results

Figure 11 shows initial and repeat flushing turbidity data along with the stepwise demand increase in flow used to produce target shear stress values exceeding a design 1.2 N/m^2. This value was selected based on recommendations from UK trials by Husband & Boxall (2010) to remove material layers for smooth walled pipes and diameter less than 150 mm / 6". The patterns shown are consistent with those observed from all flushing trials and show that for each increase in flow (and therefore shear stress), additional material is released from the pipe walls. Pipes had been selected based on company records indicating long term undisturbed conditions. As a result, material accumulated on pipe walls pre-trial were assumed to have achieved an equilibrium state representing an effective maximum discolouration risk for each specific section. Figure 11 supports this as each pre-flush produced a greater turbidity response than the post-flush 12 months later. This indicates that material layers had not fully regenerated during the 12 months between flushing exercises. By integrating the turbidity responses during the trial period as shown in Figure 11, a volumetric turbidity was calculated for pre and post flushing. Assuming a linear accumulation rate, a predicted return period to achieve the initial or maximum discolouration risk could then be determined.

Table 4 presents the DMA pipes pre and post volumetric turbidity with accumulation during the 12 month trial period shown as a percentage of initial trial results and a predicted return period for maximum discolouration risk. For each DMA, results were relatively consistent and indicate no significant variations between pipe materials (or possible unrecorded disturbances during the trial period), with the possible exception of pipe B in DMA_A. Taking all the results from DMA-A pipes (supplied from TM-1, normal flow conditioning), the average time to reach the maximum discolouration risk would be 2.7 years (excluding pipe B returns 2.5 years), with 2.5 years for DMA-B (TM-2, passive flow conditioning) and 2.0 years for DMA-C (TM-3, control). This analysis indicates that the pipes in DMA's fed by flow conditioned mains experience at least a half years increase on the 2 year accumulation return period measured in the control zone, representing a 25% improvement.

The Kruskal-Wallis (K-W) H test demonstrated a statistically significant difference in the DMA pipes accumulation return period between all three test groups with $X^2 = 8.398$, $p = .015$. A similar statistical difference in downstream accumulation return periods was found between the control group (TM-3) and normal flow conditioning (TM-1) group using Mann–Whitney (M-W) U test (U=.15, $p = .016$). However, for DMA pipes supplied from the two flow conditioned trunk mains (TM-1 and TM-2), the accumulation return period did not differ significantly according to the M-W U test (U=6.5, $p = .22$). These statistical significance tests suggest that there was no adverse effect on downstream accumulation return period from the acute loading of quarterly flow conditioning interventions. Rather it seems that the reduced chronic loading due to the periodic flow conditioning intervention, evident from Figure 9, has a significant and beneficial effect on downstream discolouration risk.

Discussion

Trunk main turbidity time-series data and diurnal profile

Long term (>12 months) trunk main turbidity monitoring showed that transmitted water quality deteriorated in the control main (TM-3), Figure 9, with elevated downstream turbidity concentrations. The measured higher turbidity could be due to varying interactions, e.g. iron corrosion as the test mains were unlined CI (Carriere et al., 2005; Sarin et al., 2002, 2003), chemical reactions (Kirmeyer, 2000; Sly et al., 1990) and biological growth (LeChevallier et al., 1987; Gauthier et al., 2001; Meckes, 2001). This study was not however designed to investigate independent factors that contribute to degradation, rather to focus on the combined effects and flow conditioning impacts. Daily patterns in turbidity at the downstream end of each trunk main were not observed in the water treatment outlet data, indicating in-pipe processes. Lower turbidity was observed during night time low flows suggesting accumulation during this period, with subsequent mobilisation as flows increase, primarily during the morning peak. This field evidence suggests that a continuous daily material mobilisation-accumulation process cycle exists in the trunk mains. Similar turbidity correlations to diurnal flow patterns have also been observed by Cook, (2007) and Machell and Boxall, (2014) in local distribution systems. Mounce et al. (2015) used semblance techniques to correlate long-term continuous measured flow and turbidity data and suggested that as the correlation gets stronger there is a greater risk of discolouration due to increasing accumulations of pipe wall bound materials. The diurnal turbidity behaviour observed here was most apparent in TM-3 (control) main (Figure 7) compared to the other two flow conditioned mains, suggesting greater material accumulation / mobilising behaviour and therefore higher discolouration risk from this non-flow managed pipe.

Material mobilisation and accumulation processes

The trunk main flow conditioning trials (Figure 5) and DMA flushing data (Figure 11) showed that during each mobilisation phase there was a release of material for each increase in shear stress, evidencing that the material at the pipe wall was bound with a range of shear strengths. This confirms what has been observed previously mainly for small diameter pipes (Boxall et al., 2003b; Cook and Boxall, 2011; Husband and Boxall, 2011, 2016). Both the trunk mains and small diameter pipes were also observed to exhibit ongoing material accumulation (Figure 6 and Table 4), supporting previous work and demonstrating periodic maintenance is essential to manage discolouration risk (Boxall et al. 2003b, Cook and Boxall 2011). Of particular note is the novel finding that the accumulation within trunk mains occurs simultaneously across the shear strength range as evidenced by turbidity responses whenever an above normal flow event occurred, irrespective of magnitude. Previously work had observed this behaviour for small diameter pipes, both at controlled laboratory (Sharpe et al., 2017) and operationally (Husband and Boxall, 2011; Husband et al., 2010). This improved understanding of accumulation processes in trunk mains is critical to understand how discolouration risk develops and therefore for designing management strategies with appropriate maintenance periods and applied shear stress interventions to avert risk-promoting accumulations of discolouration causing material.

Impacts of shear stress on continuous turbidity profiles

The experimental design used here stipulated that the three trunk mains had similar physical, chemical and biological attributes, including the same source water and similar hydraulic behaviour. This was to ensure that differences observed in the turbidity responses of the trunk mains was dominated by the imposed interventions. Long-term turbidity assessment (Figure 9) shows that background, or chronic turbidity loading, was improved by imposing periodic flow conditioning interventions compared to no interventions (TM1 and TM2 turbidities less than TM3). Although appearing to contradict initial findings of Gaffney and Boult (2012), when the same data set was analysed by Mounce et al. (2015) it also showed a corresponding turbidity improvement after flushing. A concept to explain the improvement in chronic loading is shown in Figure 12. During normal operation, without any hydraulic disturbances, cohesive layers are in an equilibrium state (Boxall et al., 2001) and a continuous daily material mobilisation-accumulation process cycle exists (Husband and Boxall, 2011). From TM3 in Figure 9 it is apparent that this equilibrium state results in a net increase in turbidity over the pipe length and this is captured by image 1 in Figure 12. In this state, in these pipes material is being sequestered from the bulk water and from corrosion of the cast iron pipes resulting in net increase over the pipe length. Image 2 captures the effects of flow conditioning with removal of wall bound material resulting in a short term increase in downstream turbidity. Image 3 captures the post flow conditioning state where accumulation processes are again occurring as well as mobilisation, but because the layers are net accumulating, the net effect in this case is no or little change in turbidity over the pipe length. It is worth noting that if these were not cast iron pipes with corrosion of the pipe wall as a material source, this concept suggests that there might be negligible or very little net effect on turbidity under equilibrium conditions and reduced turbidity following flow conditioning.

Normal and passive flow conditioning

By designing the passive and normal flow conditioning strategies with different target flows, different levels of resilience were achieved, that is the additional in-service flow that could be imposed without generating discolouration. Selecting a target in operational situations may not be straightforward with justification possibly based on anticipated future flows such as seasonal variations, planned operational changes such as re-zoning, unplanned but potential burst risks, and consideration of the ease or complexity required to regularly achieve the increased flow in a controlled manner. This study found similar long term chronic loading benefits from passive and normal flow conditioning, suggesting this should not influence the target selection. It is unknown however if the long term benefits would endure equally for the two conditioning strategies, but it seems reasonable to expect not. With more (and stronger bound) material removed by normal conditioning (Figure 5), it is likely to take longer to return to the equilibrium conditions where the trunk main is a net contributor of material into the bulk water. The results however show that even if desired target flows may not be obtainable, water quality benefits are still generated from passive flow conditioning.

Effects of acute and chronic material loading on downstream networks

Prior to these investigations a concern was that the short duration acute loading from flow conditioning of trunk mains would increase discolouration risk in the downstream network. This is shown not to be the case with results from the DMA flushing showing 25% lower material return intervals (table 4) in the networks downstream of the trunk mains where flow conditioning was imposed. Non clustered contact data was also investigated, but no statistical significant findings were identified with the limited data over the short period investigated so is not included. This change in performance is attributed to the fact that while there was occasional acute material loading (in this case ≤1.0 NTU) generated from the flow conditioning, there was the reduction in chronic loading as seen in Figure 9 and explained by Figure 12. The flow conditioning, by effectively changing the behaviour of the material layers within the trunk mains therefore yielded both a beneficial reduction in discolouration risk from the trunk main itself and the downstream networks. This suggests the benefits from the reduced chronic material loading post conditioning, in addition to the immediate resilience benefits, outweighs concerns around short-term acute loading. It is possible the acute loading may increase accumulation rates temporarily, but the overall reduction in risk suggests more material remains entrained in the flow and passes out of the system supporting the value of network cleaning.

The impact on accumulation return periods from higher chronic loading indicates that improving treated water quality will also reduce discolouration risk and lengthen maintenance return intervals. A similar conclusion was found by Vreeburg et al., (2008) by changing treated water quality, whereas this study evidences the significance of bulk water on discolouration risk by managed hydraulic interventions. This improved understanding of discolouration risk management opens up the opportunity to assess the synergy between treated water improvements and network maintenance. Such assessments can be undertaken by analysing the trade-off between cost of improved treatment and cost of network interventions such that optimal discolouration management conditions can be designed encompassing a source to tap approach.

Conclusions

This study assessed the impacts of trunk main flow conditioning, using knowledge of network hydraulics and then manipulating flows as part of simple, pro-active and in-service operation for discolouration risk. The findings show that flow conditioning provides immediate trunk main risk mitigation and resilience benefits, as well as effective long term risk reduction in both trunk mains and downstream networks. In this study a 25% reduction in rates of material accumulation in the downstream networks where observed. This is attributed to changing the material exchange behaviour within the trunk mains, effectively managing the amount of material bound within cohesive layers at the bulk water / asset interfaces and how this interacts with the bulk water.

Specific findings indicate:

- The chronic, or long term, low concentration material loading from the bulk water is more significant in terms of rates of material accumulation at pipe walls and hence discolouration risk than acute, or short duration, high concentration loading.
- Hydraulic interventions (such as flow conditioning) in trunk mains reduces downstream chronic material loading and thereby asset deterioration rates and discolouration risk.
- The direct and downstream benefits of flow conditioning in trunk mains, combined with low-enabling requirements and in-service application, make it a highly cost-effective option to effectively and efficiently manage discolouration risk in drinking water distribution systems.

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