



Deposited via The University of Sheffield.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/id/eprint/152874/>

Version: Accepted Version

---

**Article:**

Sunny, I., Husband, P.S. and Boxall, J.B. (2020) Impact of hydraulic interventions on chronic and acute material loading and discolouration risk in drinking water distribution systems. *Water Research*, 169. 115224. ISSN: 0043-1354

<https://doi.org/10.1016/j.watres.2019.115224>

---

Article available under the terms of the CC-BY-NC-ND licence  
(<https://creativecommons.org/licenses/by-nc-nd/4.0/>).

**Reuse**

This article is distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs (CC BY-NC-ND) licence. This licence only allows you to download this work and share it with others as long as you credit the authors, but you can't change the article in any way or use it commercially. More information and the full terms of the licence here: <https://creativecommons.org/licenses/>

**Takedown**

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing [eprints@whiterose.ac.uk](mailto:eprints@whiterose.ac.uk) including the URL of the record and the reason for the withdrawal request.



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

3

4 **Sunny I<sup>1</sup>, Husband PS<sup>2</sup>, Boxall JB<sup>2</sup>**

5 <sup>1</sup>AECOM, UK

6 <sup>2</sup>University of Sheffield, UK

7

8 **Abstract**

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

21

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

23

## 24 Introduction

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

37 Trunk mains are large diameter pipes that are critical water distribution infrastructure from which the  
38 consequences of discolouration are high due to the population exposed. With such risk associated to  
39 trunk mains, water companies are understandably cautious and often reluctant to undertake  
40 operational activities allied with them. Yet to manage and deliver consistently the highest water quality  
41 to customers, interventions are becoming inevitable as infrastructure deteriorates and expectations  
42 rise. As a result, water utilities are required to invest in the removal of accumulated materials from  
43 trunk mains with the aim of improving water quantity and quality issues as part of rehabilitation  
44 programs. An option to clean wall-bound material legacy is through expensive invasive cleaning  
45 strategies, e.g. air scouring, ice pigging or swabbing (AWWA, 2014). These strategies may deliver  
46 water quality benefits, yet they are often difficult to implement, expensive and require specialist  
47 resource-oriented strategies and includes the often very considerable challenge of taking mains out  
48 of service without interrupting supply. Studies have also highlighted that discolouration material  
49 returns to the pipe wall (Boxall et al., 2003a, Cook and Boxall, 2011) and water quality contacts return,  
50 raising questions regarding the long-term benefits of such invasive strategies. Some non-invasive and

51 in-service hydraulic driven maintenance strategies have been implemented successfully in distribution  
52 systems, e.g. flow conditioning (Husband and Boxall, 2015) and self-cleaning velocity techniques  
53 (Van Den Boomen et al., 2004; Vreeburg et al., 2009). However, the long-term impact on  
54 discolouration risk of flow conditioning has never been assessed or the impact of different material  
55 loading regimes as water travels from the water treatment works (WTW) to the downstream  
56 distribution network. Concerns remain therefore over how these interventions influence long-term  
57 discolouration risk and if they provide water quality benefits.

58

## 59 **Background**

### 60 **Discolouration processes**

61

62 Discolouration has historically been conceived as the re-suspension of gravity deposit sediments, yet  
63 the microscopic size (2-50  $\mu\text{m}$ ) of analysed discolouration material suggests self-weight driven settling  
64 is unlikely to dominate behaviour other than in quiescent conditions (Boxall et al., 2001; Ryan et al.,  
65 2008).

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

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

### 85 **Quantifying discolouration risk**

86

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

94 Several studies have proposed the importance of continuous turbidity measurement as part of a water  
95 quality monitoring program (Frey and Sullivan, 2005; Storey et al., 2011; Kara et al., 2016). Van den  
96 Hoven et al. (1994) suggested that continuous turbidity measurement is an indicator of aesthetic  
97 issues. Previous studies have used high temporal turbidity to assess mass flux into the downstream  
98 DWDS and to identify spatial and localised material accumulation, suggesting its importance (Gaffney  
99 and Boulton, 2012; Starczewska et al., 2017). By applying the CANARY event detection system  
100 (USEPA, 2010) to the turbidity data collected by Gaffney and Boulton (2012), Mounce et al. (2015)  
101 showed that continuous turbidity can be used with hydraulic data for an event detection indicator. No

102 studies have yet investigated continuous turbidity from trunk mains, to understand the risks they pose  
103 or to quantify material loading from them into downstream zones.

#### 104 **Hydraulic based discolouration management strategy in trunk mains**

105

106 A non-invasive trunk main maintenance strategy termed “*flow conditioning*” (Husband and Boxall,  
107 2015) was developed based on the concept of a cohesive transport turbidity modelling approach  
108 (Boxall and Saul, 2005). This strategy was developed and implemented by the University of Sheffield  
109 in collaboration with several UK water companies. Flow conditioning is considered as “controlled in-  
110 service flushing” by imposing managed excess shear stress to mobilise controlled amounts of material  
111 from pipe boundary surfaces yet keeping the response within defined limits, such as targeting 1 NTU  
112 (Nephelometric Turbidity Units) that retains a safety margin below the current UK regulatory limit of 4  
113 NTU. To implement successful flow conditioning requires a knowledge of pipe hydraulic properties,  
114 the ability to control system hydraulics and knowledge of the hydraulic history so appropriate sized  
115 changes may be imposed. The method is designed to operate under normal network conditions  
116 without interrupting supply with mobilised material entrained in the bulk flow as wash load and  
117 transported through the downstream network. Material with cohesive strengths higher than the  
118 imposed shear stress remain on the pipe wall and hence flow conditioning reduces discolouration risk  
119 by selectively removing the weaker material proactively that otherwise could be rapidly mobilised from  
120 unplanned or inadvertent changes in system hydraulics. In addition, flow conditioning may be used to  
121 achieve network hydraulic resilience by facilitating higher flows, either in single or multiple stages  
122 depending on required resilience targets, such that operators have confidence that in the short-term  
123 the same flows can be repeated without fear of discolouration events. This allows network planning  
124 for changes including rezoning or valving operations, seasonal fluctuations or burst mitigation.

125 Flow conditioning interventions have been successfully implemented in several trunk main systems  
126 with verified short term reductions in discolouration risk (Husband and Boxall, 2015). However, the  
127 long-term impact on the trunk main and downstream network has not been studied. There is concern  
128 that the periodic mobilisation and subsequent transport of acute material loads (i.e. higher than typical

129 turbidity values), could directly impact customers and accelerate accumulation rates in the  
130 downstream network. It may however be that much of the planned low level but acute loading remains  
131 as wash load and exits via consumer connections with insufficient contact time to accumulate  
132 downstream.

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

## 136 **Methods and Materials**

### 137 **Methodology**

138

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

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

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

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

#### 174 **Site details and network characteristics**

175 To fulfil and ensure sound experimental design, a single source water treatment outlet was selected  
176 that supplied three otherwise independent but similar trunk mains from an operational network in the  
177 UK. Each trunk main had similar pipe material and hydraulic profiles shown in Table 1. This was to  
178 establish comparable physical, chemical and microbiological water quality conditions and hence, as  
179 much as possible within operational systems, similar discolouration risk generating conditions. Thus,  
180 any differences in discolouration behaviour should be dominated by the different interventions

181 imposed. Figure 2 presents a network schematic and location of monitoring instruments. While the  
182 choice of inlet point defined the incoming loading from treated water, the outlet point recorded the  
183 change in discolouration risk by monitoring the response to interventions and provided material  
184 loading concentrations supplying the downstream DMAs.

185

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

191

### 192 **Selected DMA pipe characteristics**

193 Five pipes with similar characteristics were chosen from each of the selected DMAs for repeated  
194 flushing. Priority was given to non-corroding pipes, such that the dominant potential contribution to  
195 discolouration risk could be assigned to accumulation from the bulk water, rather than localised  
196 corrosion of the pipes. All pipes were located near to the DMA inlet and operated as effectively dead  
197 end sections serving residential areas, thereby likely to have similar demand patterns. Without  
198 detailed monitoring of DMA flows, this would allow comparison of results, as opposed to pipes serving  
199 different sized downstream areas and therefore subjected to very different hydraulic demands. Table  
200 3 presents the properties of the pipes selected for flushing analysis fed from the three trunk mains.

### 201 **Fieldwork procedure and timeline**

202 The flow conditioning strategies were designed using the validated PODDS model (Husband and  
203 Boxall, 2015) and set to limit turbidity response to a maximum of 1.0 NTU during the trial period. To  
204 achieve repeatable and accurate managed flow increases, hydrant standpipes fitted with ABB  
205 Aquamaster flow meters to which twin independent ATI Nephnet turbidity monitors were connected.  
206 TM-1 normal flow conditioning trials were designed with a maximum 40% step shear stress increase  
207 addition to the typical historical (12 month) peak shear stress, TM-2 passive flow conditioning was

208 with a maximum 16% addition to the peak shear stress and TM-3 was the control main. The 40%  
209 additional peak shear stress increase was used in all TM's for time zero and after +12months. The  
210 fieldwork timeline and flow conditioning strategy applied to each trunk main is shown in Figure 1.  
211 Target shear stresses were selected based on the WTW hydraulic capacity and local drainage  
212 conditions. All flow conditioning trials were operated under similar conditions, i.e. same time of the  
213 day, equipment and monitoring sections, to standardise the trials. Since the trunk main flow profiles  
214 were demand driven and diurnal in nature, target excess shear stress was achieved during the  
215 morning peak when the network demand was highest. This was selected as it requires the lowest  
216 additional discharge flow to achieve the conditioning target.

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

223

#### 224 **Flow conditioning and DMA flushing monitoring**

225 The turnover time for the three trunk mains during highest hydrant flow whilst conditioning was  
226 approximately 3.5 hours. Given the expected propagation effects of material mobilisation following  
227 the change of imposed shear stress and the limited duration of the highest flow combined with peak  
228 demand, a turbidity and trunk main flow sampling resolution of 15 minutes was identified as providing  
229 sufficient definition of the material mobilisation response. Since the turnover time for the typical DMA  
230 pipe (100mm diameter) with average pipe length of 150m and a flushing velocity of 1.0 m/s  
231 (approximately 8 l/s) was just over 2 minutes, sampling was at 1 second to ensure sufficient data  
232 points to accurately describe the response. To collect flow data during flow conditioning and DMA  
233 flushing trials, an ABB Aquamaster flow meter attached to a Langham UK hydrant instrumented

234 standpipe was used. The ABB flow meter used in this work measured flow with an accuracy of  $\pm 5\%$   
235 of reading and maximum working pressure of 12 bar. Flow and therefore shear stress were increased  
236 carefully via a gate valve connected to the standpipe discharge point. ATI Nephnet instruments with  
237 Infrared (IR) Nephelometric measurement processing were used to measure turbidity responses  
238 during flow conditioning (acute loading) and DMA flushing. The ATI Nephnet logger functioning range  
239 was set to 0 - 4 NTU for flow conditioning trials and 0 - 400 NTU for DMA flushing. Instruments were  
240 calibrated with formazin standards under laboratory conditions and dual validated by duplication of  
241 units during trials. Turbidity data was also spot checked regularly by a 2100Q Hach handheld logger  
242 which was also calibrated with formazin standard dilutions. The handheld turbidity meter was  
243 calibrated for 0 - 800 NTU with an accuracy of  $\pm 2\%$  of reading. A one-off 24-hour pressure recording  
244 at the trunk main downstream point was measured using Syrinix Transientminder, to calibrate the  
245 pipe roughness and therefore to calculate shear stress for all three trunk mains. The pressure logger  
246 range was set for 0 - 20 bar with an accuracy of 0.1% of full-scale output.

247

#### 248 **Long-term data monitoring**

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

258 Due to discolouration particles known cohesive nature (Boxall et al., 2001), turbidity instrument drift  
259 was anticipated with optic lens fouling during long term monitoring (Gaffney and Boulton, 2012). To

260 minimise drift, the ATI Nephnet logger lenses were cleaned on site bi-weekly during its deployment  
261 period (October to February), although little or no drift was observed and consistently good agreement  
262 shown with spot checks. After February the Hydraclam logger was deployed in which turbidity drift  
263 was corrected through a proprietary post-processing algorithm which returned good agreement with  
264 handheld spot checks. The Sigrist logger was serviced as part of the regular WTW maintenance.

### 265 **Data processing and analysis**

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

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

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

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

291 *Applied shear stress,  $\tau = \rho g R S_0$*  (2)

292 Where,  $\rho$  = discolouration material density in  $kg/m^3$ ,  $g$  = gravitational force in  $m/s^2$ ,  $R$  = hydraulic radius  
 293 in m and  $S_0$  = hydraulic gradient unit less. In this calculations,  $\rho$  and  $g$  were used at  $1000 kg/m^3$  and  
 294  $9.81 m/s^2$ . Hydraulic gradient was calculated for the entire pipe length using Darcy-Weisbach formula  
 295 integrating Swamee-Jain Colebrook-white approximation (Swamee and Jain, 1976) and network  
 296 hydraulic properties stated in table 1.

297 While the flow conditioning data was compared using material release rate, the same calculation was  
 298 not required for DMA pipe flushing data as the flow rate and hence shear stress was consistent for  
 299 each flushing. Flushing data was therefore compared using volumetric material loading ( $NTU \cdot m^3$ )  
 300 which integrated the turbidity time series in NTUs and multiplied by flushing water volume in  $m^3/s$ ,  
 301 equation 3. This volumetric loading calculation was done at initial flushing (time zero) and repeated  
 302 flushing (+12 months). From this it was possible to estimate complete regeneration period; how long  
 303 it would take to achieve the initial amount based on how much of the initial response was seen after  
 304 12 months. This assumed a linear accumulation process over 12 months and the initial state  
 305 represented undisturbed and fully developed material layers (Boxall et al., 2003a; Cook and Boxall,  
 306 2011).

307 *Volumetric loading* =  $\int_0^t T_{ds}(t) \cdot Q(t) dt$  (3)

308 To investigate the significance of intervention impact on downstream network material accumulation  
 309 rates, samples were statistically analysed by IBM SPSS v22.0 software. Due to the small sample size

310 and assuming samples were not necessarily normally distributed, nonparametric testing was chosen  
311 to investigate the difference between the chronic and acute material loading rate with a significance  
312 level ( $\alpha$ ) of .05. For multivariate analysis, the Kruskal-Wallis H test was chosen, and Mann-Whitney  
313 U test was used for bivariate sample analysis.

314

## 315 **Results**

### 316 **Flow conditioning and burst event trunk main data**

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

328 Figure 5 presents the three trunk main flow conditioning and burst event measured flow and turbidity  
329 responses. Each plot shows a 72 hour (3 day) period with zero at midnight (12:00 am) of the day in  
330 which the conditioning or burst commenced. A three day (72 hour) period was chosen as the final  
331 target shear stress was often achieved by imposing staged increases over several days to ensure  
332 turbidity remained below 1 NTU, and to show the key aspects of each of the bursts that continued up  
333 to a maximum of 72 hours. TM-1 in Figure 5(a) shows that notable material (>average turbidity) was  
334 mobilised from all planned and unplanned trials, with turbidity observed from each additional shear  
335 stress increase. A peak turbidity of about 10 NTU was recorded during the burst in March 2016. While

336 relatively greater strength material will have been released from this burst, enough material  
337 accumulated in the following two months to have a turbidity response higher than average values  
338 ( $\leq 0.5$  NTU) from trial 3. Figure 5(b) presents TM-2 flow conditioning and burst event flow and turbidity  
339 data. No notable turbidity was observed from any TM-2 flow conditioning trials, potentially an effect  
340 of multiple burst events during the monitoring period. However, material was released from each burst  
341 event under varying imposed shear stress conditions. For TM-3, only trial 1 and the burst in May 2016  
342 had observable turbidity responses, as shown in Figure 5(c). In all three trunk mains cases, these  
343 events were separated by a period that allowed material to accumulate resulting in further  
344 discolouration responses across the range of imposed hydraulic events. Material release in  
345 successive trials indicates accumulation occurring throughout the year and simultaneously across the  
346 range of imposed shear stresses.

347 Figure 6 presents the flow conditioning trials and burst event responses as material release per unit  
348 excess shear stress per unit wall area. From Figure 6, the material release from TM-1 was lowest in  
349 trial 2 and 3 and the highest value was recorded during trial 5. Since similar imposed shear stress  
350 was implemented for all trials in TM-1, it was anticipated, yet not observed, that similar amounts of  
351 material would be mobilised. The relatively lower amount of material mobilised during trial 2, could  
352 indicate a seasonal effect with lower rate of material accumulation over a colder winter period although  
353 the limited data prevents detailed statistical analysis. A significant correlation was however observed  
354 between seasonal treated water temperature and turbidity behaviour for the same dataset (Sunny et  
355 al. 2018). Unfortunately, any further seasonal effects, in TM-1 (and TM-2) are also masked by the  
356 occurrence of burst events. The burst event in February resulted in a high release of material, likely  
357 due to imposing flow rates higher than had been observed in the trunk main for considerable time and  
358 hence material had been able to accumulate over a long period. The lower amount of material seen  
359 in response to trial 3 is probably due to the impact of the burst on material layers in February and the  
360 relatively shorter accumulation period since the burst event. Relatively less material was mobilised  
361 from TM-2 during the passive flow conditioning trials compared to TM-1, which was anticipated due  
362 to the lower imposed shear stress conditions. A high amount of material was released from the two

363 larger magnitude burst events, a result of mobilising previously undisturbed (higher shear strength)  
364 material, and these will also have impacted flow conditioning trials 3 and 4 by shortening the period  
365 over which material could accumulate. Similar amounts of material were released from the two  
366 planned trials from the control main (TM-3) with a 12-month interval. Similar to TM-2, a burst in May  
367 2016 released high amounts of material with potential impact on the trial 2 response. However, due  
368 to the long interval period between the bursts in May and trial 2 in TM-3, it is difficult to quantify the  
369 impact.

370

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

379 To further assess how bulk water turbidity varied during transit and to quantify the impact of hydraulic  
380 events on turbidity responses, turbidity data of treated water and the three trunk mains is shown in  
381 box-whisker plots, Figure 8. Box-whisker plots were processed in monthly periods and show the  
382 median, 25<sup>th</sup>, 75<sup>th</sup> and 99<sup>th</sup> percentile range of turbidity data excluding flow conditioning trials and burst  
383 events. Monthly periods were chosen as providing sufficient data in each period but still allowing  
384 identification of possible seasonal trends and the impacts of bursts and flow conditioning. Figure 8(a)  
385 shows the treated water turbidity median lies between 0.07 and 0.15 NTU with no abrupt variations,  
386 suggesting consistent supply of low turbid water. TM-1, subjected to normal flow conditioning, shows  
387 that additional particles were generated compared to treated water responses as shown in Figure  
388 8(b). The initial turbidity response of TM-1 (October) was relatively higher than the WTW. From Figure  
389 8(b), median turbidity response was improved post flow conditioning trials that started in November

390 and after that median turbidity was closer to the WTW baseline. This suggests that flow conditioning  
391 is influencing material loading and hence turbidity behaviour. The only exception was observed in the  
392 final October, where relatively higher turbidity responses were measured than in the other months.  
393 This could be related to the change from summer to autumn cyclic seasonal loading, although TM-2  
394 data did not show similar behaviour. However, following trial 5 in TM-1 (implemented at the end of  
395 October), notable improvement in turbidity was observed from October (median=0.27 NTU) to  
396 November (median=0.075 NTU) and December (median=0.10 NTU).

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

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

416

417 **Customer contacts**

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

431

432 **DMA flushing results**

433 Figure 11 shows initial and repeat flushing turbidity data along with the stepwise demand increase in  
434 flow used to produce target shear stress values exceeding a design  $1.2 \text{ N/m}^2$ . This value was selected  
435 based on recommendations from UK trials by Husband & Boxall (2010) to remove material layers for  
436 smooth walled pipes and diameter less than 150 mm / 6". The patterns shown are consistent with  
437 those observed from all flushing trials and show that for each increase in flow (and therefore shear  
438 stress), additional material is released from the pipe walls. Pipes had been selected based on  
439 company records indicating long term undisturbed conditions. As a result, material accumulated on  
440 pipe walls pre-trial were assumed to have achieved an equilibrium state representing an effective  
441 maximum discolouration risk for each specific section. Figure 11 supports this as each pre-flush

442 produced a greater turbidity response than the post-flush 12 months later. This indicates that material  
443 layers had not fully regenerated during the 12 months between flushing exercises. By integrating the  
444 turbidity responses during the trial period as shown in Figure 11, a volumetric turbidity was calculated  
445 for pre and post flushing. Assuming a linear accumulation rate, a predicted return period to achieve  
446 the initial or maximum discolouration risk could then be determined.

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

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

## 467 **Discussion**

### 468 **Trunk main turbidity time-series data and diurnal profile**

469 Long term (>12 months) trunk main turbidity monitoring showed that transmitted water quality  
470 deteriorated in the control main (TM-3), Figure 9, with elevated downstream turbidity concentrations.  
471 The measured higher turbidity could be due to varying interactions, e.g. iron corrosion as the test  
472 mains were unlined CI (Carriere et al., 2005; Sarin et al., 2002, 2003), chemical reactions (Kirmeyer,  
473 2000; Sly et al., 1990) and biological growth (LeChevallier et al., 1987; Gauthier et al., 2001; Meckes,  
474 2001). This study was not however designed to investigate independent factors that contribute to  
475 degradation, rather to focus on the combined effects and flow conditioning impacts. Daily patterns in  
476 turbidity at the downstream end of each trunk main were not observed in the water treatment outlet  
477 data, indicating in-pipe processes. Lower turbidity was observed during night time low flows  
478 suggesting accumulation during this period, with subsequent mobilisation as flows increase, primarily  
479 during the morning peak. This field evidence suggests that a continuous daily material mobilisation-  
480 accumulation process cycle exists in the trunk mains. Similar turbidity correlations to diurnal flow  
481 patterns have also been observed by Cook, (2007) and Machell and Boxall, (2014) in local distribution  
482 systems. Mounce et al. (2015) used semblance techniques to correlate long-term continuous  
483 measured flow and turbidity data and suggested that as the correlation gets stronger there is a greater  
484 risk of discolouration due to increasing accumulations of pipe wall bound materials. The diurnal  
485 turbidity behaviour observed here was most apparent in TM-3 (control) main (Figure 7) compared to  
486 the other two flow conditioned mains, suggesting greater material accumulation / mobilising behaviour  
487 and therefore higher discolouration risk from this non-flow managed pipe.

488

### 489 **Material mobilisation and accumulation processes**

490 The trunk main flow conditioning trials (Figure 5) and DMA flushing data (Figure 11) showed that  
491 during each mobilisation phase there was a release of material for each increase in shear stress,  
492 evidencing that the material at the pipe wall was bound with a range of shear strengths. This confirms

493 what has been observed previously mainly for small diameter pipes (Boxall et al., 2003b; Cook and  
494 Boxall, 2011; Husband and Boxall, 2011, 2016). Both the trunk mains and small diameter pipes were  
495 also observed to exhibit ongoing material accumulation (Figure 6 and Table 4), supporting previous  
496 work and demonstrating periodic maintenance is essential to manage discolouration risk (Boxall et al.  
497 2003b, Cook and Boxall 2011). Of particular note is the novel finding that the accumulation within  
498 trunk mains occurs simultaneously across the shear strength range as evidenced by turbidity  
499 responses whenever an above normal flow event occurred, irrespective of magnitude. Previously  
500 work had observed this behaviour for small diameter pipes, both at controlled laboratory (Sharpe et  
501 al., 2017) and operationally (Husband and Boxall, 2011; Husband et al., 2010). This improved  
502 understanding of accumulation processes in trunk mains is critical to understand how discolouration  
503 risk develops and therefore for designing management strategies with appropriate maintenance  
504 periods and applied shear stress interventions to avert risk-promoting accumulations of discolouration  
505 causing material.

#### 506 **Impacts of shear stress on continuous turbidity profiles**

507 The experimental design used here stipulated that the three trunk mains had similar physical,  
508 chemical and biological attributes, including the same source water and similar hydraulic behaviour.  
509 This was to ensure that differences observed in the turbidity responses of the trunk mains was  
510 dominated by the imposed interventions. Long-term turbidity assessment (Figure 9) shows that  
511 background, or chronic turbidity loading, was improved by imposing periodic flow conditioning  
512 interventions compared to no interventions (TM1 and TM2 turbidities less than TM3). Although  
513 appearing to contradict initial findings of Gaffney and Boulton (2012), when the same data set was  
514 analysed by Mounce et al. (2015) it also showed a corresponding turbidity improvement after flushing.  
515 A concept to explain the improvement in chronic loading is shown in Figure 12. During normal  
516 operation, without any hydraulic disturbances, cohesive layers are in an equilibrium state (Boxall et  
517 al., 2001) and a continuous daily material mobilisation-accumulation process cycle exists (Husband  
518 and Boxall, 2011). From TM3 in Figure 9 it is apparent that this equilibrium state results in a net  
519 increase in turbidity over the pipe length and this is captured by image 1 in Figure 12. In this state, in

520 these pipes material is being sequestered from the bulk water and from corrosion of the cast iron  
521 pipes resulting in net increase over the pipe length. Image 2 captures the effects of flow conditioning  
522 with removal of wall bound material resulting in a short term increase in downstream turbidity. Image  
523 3 captures the post flow conditioning state where accumulation processes are again occurring as well  
524 as mobilisation, but because the layers are net accumulating, the net effect in this case is no or little  
525 change in turbidity over the pipe length. It is worth noting that if these were not cast iron pipes with  
526 corrosion of the pipe wall as a material source, this concept suggests that there might be negligible  
527 or very little net effect on turbidity under equilibrium conditions and reduced turbidity following flow  
528 conditioning.

### 529 **Normal and passive flow conditioning**

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

543

544 **Effects of acute and chronic material loading on downstream networks**

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

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

569

## 570 **Conclusions**

571

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

580 Specific findings indicate:

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

589

## 590 **Acknowledgements:**

591 The authors would like to thank Scottish Water for their active and ongoing engagement and  
592 support for the fieldwork reported here, of particular note are the contributions of Graeme Moore,  
593 David Main, Nick Drake, Kes Juskowiak and Kevin Mckenzie. The work is sponsored by Scottish  
594 Water and Pennine Water Group, EPSRC platform grant EP/1029346/1

595

596 **References:**

- 597 AWWA (2014). M28 Rehabilitation of Water Mains (American Water Works Association).
- 598 Blokker, E.J.M., and Schaap, P.G. (2015). Particle Accumulation Rate of Drinking Water Distribution  
599 Systems Determined by Incoming Turbidity. In *Computing and Control for the Water Industry*,  
600 (United Kingdom: Procedia Engineering), pp. 290–298.
- 601 Blokker, E.J.M., Schaap, P.G., and Vreeburg, J. (2011). Comparing the fouling rate of a drinking  
602 water distribution system in two different configurations. In *CCWI 2011 Urban Water Management:  
603 Challenges and Opportunities*, D. Savic, Z. Kapelan, and D. Butler, eds. (Exeter: Centre for Water  
604 Systems, University of Exeter,), pp. 583–588.
- 605 Boxall, J., and Saul, A. (2005). Modelling Discoloration in Potable Water Distribution Systems.  
606 *Journal of Environmental Engineering* 131, 716–725.
- 607 Boxall, J., Skipworth, P.J., and Saul, A. (2001). A novel approach to modelling sediment movement  
608 in distribution mains based on particle characteristics. In *Water Software Systems: V. 1: Theory and  
609 Applications (Water Engineering & Management)*, (Hertfordshire, UK: Research Studies Press), pp.  
610 263–273.
- 611 Boxall, J., Skipworth, P.J., and Saul, A.J. (2003a). Aggressive flushing for discoloration event  
612 mitigation in water distribution networks. *Water Science & Technology: Water Supply* 3, 179–186.
- 613 Boxall, J., Saul, A., Gunstead, J.D., and Dewis, N. (2003b). Regeneration of Discoloration in  
614 Distribution Systems. In *World Water & Environmental Resources Congress 2003*, (Philadelphia,  
615 Pennsylvania, United States: American Society of Civil Engineers (ASCE)), pp. 1–9.
- 616 Cook, D. (2007). Field Investigation of Discoloration Material Accumulation Rates in Live Drinking  
617 Water Distribution Systems. Doctoral Dissertation. University of Sheffield.
- 618 Cook, D., and Boxall, J. (2011). Discoloration Material Accumulation in Water Distribution Systems.  
619 *Journal of Pipeline Systems Engineering and Practice* 2, 113–122.

620 Cook, D.M., Husband, P.S., and Boxall, J.B. (2015). Operational management of trunk main  
621 discolouration risk. *Urban Water Journal* 0, 1–14.

622 Carriere, A., Gauthier, V., Desjardins, R., and Barbeau, B. (2005). Evaluation of loose deposits in  
623 distribution systems through unidirectional flushing. *Journal (American Water Works Association)*  
624 97, 82–92.

625 Frey, M., and Sullivan, L. (2005). *Practical Application of Online Monitoring* | IWA Publishing.

626 Gaffney, J.W., and Boulton, S. (2012). Need for and Use of High-Resolution Turbidity Monitoring in  
627 Managing Discoloration in Distribution. *Journal of Environmental Engineering* 138, 637–644.

628 Gauthier, V., Barbeau, B., Millette, R., Block, J., and Prvost, M. (2001). Suspended particles in the  
629 drinking water of two distribution systems. *Water Science & Technology: Water Supply* 1, 237–245.

630 Husband, P.S., and Boxall, J.B. (2011). Asset deterioration and discolouration in water distribution  
631 systems. *Water Research* 45, 113–124.

632 Husband, S., and Boxall, J. (2010). Field Studies of Discoloration in Water Distribution Systems:  
633 Model Verification and Practical Implications. *Journal of Environmental Engineering* 136, 86–94.

634 Husband, S., and Boxall, J. (2015). Predictive water quality modelling and resilience flow  
635 conditioning to manage discolouration risk in operational trunk mains. *Journal of Water Supply:  
636 Research and Technology - Aqua* 64, 529–542.

637 Husband, S., and Boxall, J. (2016). Understanding and managing discolouration risk in trunk mains.  
638 *Water Research* 107, 127–140.

639 Husband, P.S., Boxall, J.B., and Saul, A.J. (2008). Laboratory studies investigating the processes  
640 leading to discolouration in water distribution networks. *Water Research* 42, 4309–4318.

641 Husband, P.S., Whitehead, J., and Boxall, J.B. (2010). The role of trunk mains in discolouration.  
642 *Proceedings of the ICE - Water Management* 163, 397–406.

643 Kara, S., Karadirek, I.E., Muhammetoglu, A., and Muhammetoglu, H. (2016). Real time monitoring  
644 and control in water distribution systems for improving operational efficiency. *Desalination and*  
645 *Water Treatment* 57, 11506–11519.

646 Kirmeyer, G.J. (2000). *Guidance Manual for Maintaining Distribution System Water Quality*  
647 (American Water Works Association).

648 LeChevallier, M.W., Babcock, T.M., and Lee, R.G. (1987). Examination and characterization of  
649 distribution system biofilms. *Appl Environ Microbiol* 53, 2714–2724.

650 Meckes, M. (2001). Biofilms in Drinking Water Distribution Systems. In *Controlling Disinfection By-*  
651 *Products and Microbial Contaminants in Drinking Water*, R. Clark, and B.K. Boutin, eds. (Ohio, USA:  
652 USEPA).

653 Machell, J., and Boxall, J. (2014). Modeling and Field Work to Investigate the Relationship between  
654 Age and Quality of Tap Water. *Journal of Water Resources Planning and Management* 140,  
655 04014020.

656 Mounce, S., Gaffney, J.W., Boulton, S., and Boxall, J.B. (2015). Automated Data-Driven Approaches  
657 to Evaluating and Interpreting Water Quality Time Series Data from Water Distribution Systems.  
658 *Journal of Water Resources Planning and Management* 141, 04015026 (1-11).

659 Pothof, I.W., and Blokker, M. (2012). Dynamic hydraulic models to study sedimentation in drinking  
660 water networks in detail. *Drinking Water Engineering Science* 5, 87–92.

661 Ryan, G., Mathes, P., Haylock, G., Jayaratne, A., Wu, J., Noui-Mehidi, N., Grainger, C., and  
662 Nguyen, B.V. (2008). *Particles in Water Distribution System: Characteristics of particulates Matter in*  
663 *Drinking Water Supplies* (Australia: CRC).

664 Sarin, P., Snoeyink, V.L., Bebee, J., Jim, K.K., Beckett, M.A., Kriven, W.M., and Clement, J.A.  
665 (2002). Iron release from corroded iron pipes in drinking water distribution systems: effect of  
666 dissolved oxygen. *Water Research* 38, 1259–1269.

667 Sarin, P., Clement, J.A., Snoeyink, V.L., and Kriven, W.M. (2003). Iron Release from corroded,  
668 unlined cast-iron pipe. *Journal (American Water Works Association)* 95, 85–96.

669 Sharpe, R.L., Biggs, C., Boxall, J. (2017). Hydraulic conditioning to manage potable water  
670 discolouration. *Proceedings of the Institution of Civil Engineers - Water Management* 0:0, 1-11.

671 Sly, L.I., Hodgkinson, M.C., and Arunpairojana, V. (1990). Deposition of manganese in a drinking  
672 water distribution system. *Appl Environ Microbiol* 56, 628–639.

673 Storey, M.V., van der Gaag, B., and Burns, B.P. (2011). Advances in on-line drinking water quality  
674 monitoring and early warning systems. *Water Research* 45, 741–747.

675 Starczewska, D., Gaffney, J.W., Boulton, S., Mounce, S., and Boxall, J. (2017). Water network  
676 characterisation based on mass balance with regards to discolouration risk using high frequency  
677 turbidity monitoring. (Sheffield, UK: Figshare), pp. 1–7.

678 Sunny, I., Husband, S., and Boxall, J. (2018). Seasonal Temperature and Turbidity Behaviour in  
679 Trunk Mains. Vol 1, WDSA / CCWI Joint Conference 2018.

680 Swamee, P.K., and Jain, A.K. (1976). Explicit Equations for Pipe-Flow Problems. *Journal of the*  
681 *Hydraulics Division* 102, 657–664.

682 Van Den Boomen, M., van Mazijk, A., and S. Beuken, R. (2004). First evaluation of new design  
683 concepts for self-cleaning distribution networks. IWA Publishing.

684 van den Hoven, T., van der Kooij, D., and Brink, H. (1994). Methods to analyse and to cure water  
685 quality problems in distribution systems. *Water Supply IWSA (Zurich)* 12, 151–159.

686 Vreeburg, I.J.H.G., and Boxall, D.J.B. (2007). Discolouration in potable water distribution systems: A  
687 review. *Water Research* 41, 519 – 529.

688 Vreeburg, J.H.G., Schippers, D., Verberk, J.Q.J.C., and van Dijk, J.C. (2008). Impact of particles on  
689 sediment accumulation in a drinking water distribution system. *Water Research* 42, 4233–4242.

690 Vreeburg, J.H.G., Blokker, E.J.M., Horst, P., and van Dijk, J.C. (2009). Velocity-based self-cleaning  
691 residential drinking water distribution systems. *Water Science & Technology: Water Supply* 9, 635.

692 USEPA (2010). Water Quality Event Detection Systems for Drinking Water Contamination Warning  
693 576 Systems: Development, Testing and Application of CANARY (Washington, DC).