Aggressive flushing for discolouration event mitigation in water distribution networks

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Abstract Discolouration is one of the biggest causes of customer complaint associated with potable water. The flushing of systems has been widely identified as an appropriate pro-active means of removing material from distribution networks and hence controlling discolouration. Such flushing involves creating aggressive hydraulic forces within the network such that the materials that contribute to discolouration are mobilised and removed. Understanding of the causes and mechanisms leading to discolouration are poor. Previous work has been presented on the characterisation of material and particles collected at hydrants during flushing trials in the UK. From this data it was hypothesised that the materials causing discolouration originated from cohesive layers on pipe walls, and that once disturbed the material is maintained as a permanent suspension even under the most quiescent of networks conditions. The work presented in this paper attempts to validate the hypothesis that the discolouration materials originate from cohesive layers, and investigate the nature and variability of such layers within live distribution systems.

The study involved the aggressive flushing of a long discrete length of cast iron pipe with known discolouration problems. The results showed a progressive generation of material over the length of the pipe, confirming that the material originated from a uniformly distributed cohesive source. This was followed by a sequence of flushing operations for the systematic cleaning of a complex network area, encompassing a mixture of pipe materials and ages. All measured turbidity traces showed exponential decay with time. Such exponential decay may be predicted by a model based on a change in layer strength with degree of erosion. Hydraulic forces appear to be a key factor governing the availability and mobilisation of material. Iron is the dominant material mobilised from all the pipes. There is no direct trend between the amount or the composition of the material mobilised from the different pipes.

Keywords Aggressive flushing; discolouration; potable water

Introduction
Discolouration is one of the biggest causes of customer complaint within the water supply industry, and is usually the result of fine suspended particles in the water rather than true dissolved colour. If a sample of discoloured water is left for a sufficiently long time it will normally clear and a slight deposit will form. WRc (1989a) and Gaulthier (1996a) recognised potential sources of materials leading to discoloured water in distribution systems as treatment works, storage reservoirs and in-system processes. Currently treatment works in England and Wales produce high quality water and hence discoloured water rarely originates directly from source treatment or holding reservoirs. Discolouration is believed to result primarily from in-system processes, with events triggered by changes in the hydraulic regime within the network. Such in system sources are supported by Gauthier et al. (1996b), where a net overall increase in material being transported through a distribution system was found.

OFWAT, the regulatory body in England and Wales, stated that mains rehabilitation was unlikely to be economically justifiable on the basis of a sole, aesthetic driver such as discolouration (OFWAT, 2000). Hence on the assumption that pipes cannot be rehabilitated on the basis of discolouration alone, other “cleaning” methods have to be adopted to prevent the occurrence of discolouration events. These are commonly swabbing, air scouring and
flushing (WRc, 1989b). Of these approaches, flushing is generally recognised as the simplest and most robust method. Flushing can be either aggressive or passive. Passive flushing is the bleeding of contaminated water from the system at a low flow rate such that hydraulic forces do not exceed peak daily operational conditions. By contrast aggressive flushing uses high flow rates such that hydraulic forces in excess of the daily maximum are generated and discolouration materials mobilised and removed. WRc (1998b) presented guidance on the required velocity that should be exceeded for effective mains flushing in pipes of different diameters. These velocities were derived from loose sediment transport theory. The removal of discolouration materials by aggressive mains flushing is not a common operational practice. There is considerable confusion over the forces that need to be generated and the methodologies to ensure the progressive removal and subsequent control of the route of dirty water. It is also unclear as to the areas where the materials causing discolouration are likely to be located and hence the areas that should be targeted by flushing operations. Aggressive flushing is sometimes seen as a “high risk” operation because the nature of the process involves the creation and transportation of discoloured water within live distribution systems. However, it is only a lack of knowledge and understanding which makes it a “high risk” operation.

**Discolouration materials**

To characterise the materials mobilised in flushing operations, in terms of size and chemical composition, several organisations within the UK have collected discrete samples from systems at the time of flushing. Results from such samples were presented by Boxall et al. (2001). From analysis of such data it can be shown that the materials obtained are readily mobilised into suspension and that the smallest hydraulic activity is sufficient to maintain the particles in suspension. From this it was hypothesised that the materials causing discolouration originate from pipe walls, where they exist as cohesive layers. A cohesive transport model was developed to describe discolouration based on these conclusions (Boxall et al. 2001). The model theory has been coded into EPANET as a water quality option. This paper describes results from fieldwork undertaken for preliminary model validation. The comparison of results is encouraging. It should be noted that these modelling ideas can be applied to any layers of cohesive material within distribution systems, for example clays deposits in Australian distribution systems (Prince et al., 2001).

Smith et al. (1997) examined the composition and characteristics of particles found within live distribution mains. A direct link between the operational hydraulics and the condition of the corrosion products observed within the main was suggested. This is again consistent with the idea of cohesive layers, and that the layers are conditioned by the imposed hydraulics as described by Boxall et al. (2001). Smith et al. (1997) further concluded that the materials appeared to be concentrated around pipe joints.

Gaultier et al. (1996a) presents findings from analysis of sediments in storage reservoirs and distribution pipes. Iron was the dominant material found in the pipe deposits, with levels significantly increased over those in the reservoir deposits. Gaultier found no relationship between pipe material and deposit composition.

**Monitoring**

Four Biwater SpectraCense colour and turbidity meters were used to monitor system response to flushing operations. To provide improved data rates the instruments were modified to run in a calibration mode, logging directly to PC. The instruments were found to be sensitive to air entrainment and a modification was made to the flow cells to facilitate checking for air and to facilitate purging. Fittings were developed to allow the instruments to be connected to conventional taps, or to the standpipe used during the flushing
operations. This was to ensure that measurements could be made at a number of points within the networks and directly at the output from the system (the hydrant). Field operational kit is shown in Figure 1. Once set up, flow was run continually through the instruments such that real-time readings were obtained. Calibrated turbidity readings were obtained at 11-second intervals.

Discrete sample collection was also undertaken with the intention of improving understanding of the processes, mechanisms and sources controlling discolouration, i.e. the generation of corrosion and other cohesive layers. These measurements were also made to assess the variation in the materials mobilised through the duration of the flushing operations. The samples were analysed for metals and physical parameters.

**Study areas**

**Single pipe**

The first study undertaken had a single pipe with known discolouration problems. This offered the opportunity to observe the propagation of turbidity in a “long” pipe length of a single material. The historical hydraulic regime had also been consistent in the period leading up to the test. The site had a 3” (75 mm) cast iron pipe of total reach length 1.6 km. The pipe supplied a small number of properties and has a modelled daily flow in the range 0.04 to 0.22 l/s. A flushing flow rate of 2.5 l/s was used in the tests.

**Looped network area**

A complex looped network in a heavily urbanised area was selected for the trials so that realistic conditions in a typical complicated network were examined. The network area was chosen for a number of reasons.

- It comprised a variety of pipe materials, ages and conditions, as shown in Table 1.
- The area was self-contained, with a single input and no exports. This had the advantage that it was possible to limit the risk associated with the impact of discoloured water at the time of the test.
- The area is mainly residential, hence minimising the impact on industrial users.
- An online monitoring system was already in place to provide high quality flow and pressure data at the entrance to the DMA (District Meter Area) of which the study area was a part.
- The DMA was believed to have a “well calibrated” hydraulic model.

In this complex network area a flushing sequence was devised with the aim of aggressively flushing all pipes within the identified area. The hydraulic forces generated within the network were not judged against any arbitrary velocity criteria (WRc, 1989b), but where instead programmed to maximise the excess shear stresses generated within each pipe, that is the shear stress above the daily maximum. The plan involved a sequence of

![Figure 1 Field operational turbidity measurement equipment](https://iwaponline.com/ws/article-pdf/3/1-2/179/477699/179.pdf)
Hydrant openings and valve movements to isolate flow paths, maximise the hydraulic forces generated, and control the route of the dirty water. The plan was iterated with input from field operatives and detailed interrogation of a GIS. Minimising and simplifying the number of operations was the primary driver. Flushing was undertaken at night to minimise customer impact. This had the advantage of maximising the available pressure but with the disadvantage that the base flow conditions were at a minimum. Table 1 gives details of the flushing operations and information relating to the pipes primarily affected by each flush.

**Results**

**Single pipe**

Figure 2 shows the measured turbidity responses from an aggressive flush of a 1.6 km length of 3” cast iron main. An inlet monitor was included to provide a measurement of the boundary conditions. However the instrument experienced air entrainment problems and the trace is therefore not valid. From the initial data recorded it is assumed that the inlet turbidity was negligible to that generated through the pipe itself. The remaining three traces show a progressive increase in turbidity level along the length of the pipe. All three traces exhibit an exponential decay in turbidity after an initial steep increase. Exponential decay is most logically described through consideration of variable strength characteristics of the layers contributing to turbidity, i.e. cohesive forces.

<table>
<thead>
<tr>
<th>Flush No.</th>
<th>Pipe material</th>
<th>Diameter (mm)</th>
<th>Pipe length (m)</th>
<th>Flushing rate (l/s)</th>
<th>Velocity (m/s)</th>
<th>Excess shear (N/m²)</th>
<th>Year laid</th>
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<tr>
<td>2</td>
<td>PVC</td>
<td>160</td>
<td>726</td>
<td>10</td>
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<td>1.2</td>
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</tr>
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<td>104</td>
<td>5</td>
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<td>2.7</td>
<td>1995</td>
</tr>
<tr>
<td>4</td>
<td>CI</td>
<td>90</td>
<td>117</td>
<td>2</td>
<td>0.35</td>
<td>0.6</td>
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<tr>
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<td>64</td>
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<td>1890</td>
</tr>
<tr>
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<td>30.0</td>
<td>1980</td>
</tr>
</tbody>
</table>

Figure 2 Turbidity response from single pipe flushing operation
Figure 3 shows results from analysis of discrete water samples collected at the hydrant, at ten minutes intervals through the single pipe flushing. Clearly there is a direct and strong relationship between turbidity, total iron and total manganese. The trend of the turbidity trace and values shown in Figure 3 cross correlate well with those of Figure 2. This shows that the measurements provided by the SpectraCense equipment were representative and accurate.

From Figure 3 it can be seen that the dominant material in the samples was iron. This suggests that the material was derived from corrosion of the cast iron main. Manganese is also present in significant quantities. A possible explanation of these high values is that the area is fed from a manganese rich source and that manganese “slimes” were formed on the pipe walls (Twort et al., 2000) and that this “slime” was mobilised by the aggressive flushing operation. In contrast Gaulthier et al. (1996a), only found trace elements of manganese and predominately iron. However Sly et al. (1990) specifically note the strong binding and co-deposition of iron and manganese in distribution systems. Differences in iron and manganese deposition are probably attributable to differences in source water and chlorination regimes. Analysis was undertaken for dissolved and total, iron and manganese. For both parameters the dissolved values were at the limit of detectability (0.01 and 0.001 mg/l respectively). This indicates that the material is in a particulate form. This suggests that the source was from the near proximity of the measurement as the material had insufficient time to form a solution.

**Looped network area**

Figure 4 shows two selected traces from the flushing tests completed on the complex network area. Flush 4 is the turbidity resulting from flushing a dead end cast iron main. Flush 11 is the result from flushing a more complex network area. The very high peak turbidity value of Flush 11 is the result of mobilising materials that had been trapped behind a previously permanently shut valve. All the measured traces exhibited a steep increase in turbidity (some deviation due to propagation effects and valve movements) followed by an exponential decay in turbidity.

Figure 5 shows results from the analysis of discrete samples collected at the time of the complex network area aggressive flushing exercise. The results are from samples taken immediately after the start of each flush event, and represent material mobilised from the pipe immediately downstream of each hydrant. The material of each pipe and the excess

![Figure 3](https://iwaponline.com/ws/article-pdf/3/1-2/179/477699/179.pdf)
shear stress generated during the flushing exercise and the peak daily shear stress for each pipe (calculated from a hydraulic model) is shown in Figure 5 (as detailed in Table 1). The average turbidity values (over duration >5 NTU) for each traces recorded at the hydrant are also given. The results in Figure 5 have been presented in order of increasing pipe diameter, there is no relationship between pipe diameter and the material mobilised. This highlights that the approach suggested by WRc (1989b) of applying force or velocity criteria on the basis of pipe diameter is not supported by the results of these experiments.

Figure 5 demonstrates a direct relationship between turbidity and iron concentration for the discrete samples. The samples were analysed for a range of metals and physical properties. Most showed no change for samples taken immediately before during or after each flush. Several of the flushes showed increases in zinc, lead and aluminium during flushing. However iron concentrations increased above background levels by one to three orders of magnitude at the beginning of each flush.

Experience, intuition and the results from the single pipe flushing lead to the hypothesis that iron is the dominant discolouration material, and that the corrosion of cast iron mains is the dominant source of material. If this were correct the cast iron pipes within the complex

Figure 4
Typical turbidity response obtained from Flush 4, “old” chocked Cl pipe, exponential decay in turbidity clearly shown and Flush 11, highlighting high peak turbidity resulting from opening a previously long term closed valve and exponential decay (inset)

Figure 5
Water quality results from complex network flushing sequence
network area would produce the most material and therefore highest turbidity. However, there is no clear relationship between pipe material and turbidity/iron shown in Figure 5 to support such a hypothesis.

Iron corrosion releases ferrous ions, (AWWA, 1996; Smith et al., 1999). These ferrous ions are released as a by-product due to the formation of corrosion layers. The material being mobilised from the plastic pipes may be the product of adhesion of ferrous ions resulting from such iron pickup. Alternatively it may be suggested that the iron originates from coagulants used at treatment works, (Twort et al., 2000). Historical statutory sampling results from the service reservoir supplying the study areas show very low iron concentrations (typical 7 µg/l). However the long-term effects of even this low exposure level is unknown. Further work is required to address this issue.

Examination of the discrete sample results the cast iron pipes shows that Flush 7 and 4 have the highest turbidity response, whereas Flushes 8 and 5 exhibit amongst the lowest turbidity values. The excess shear stress during Flush 7 was one of the highest, but Flush 4 was one of the lowest. Examining the ages of the pipes shows Flush 4 and 5 to be the oldest pipes in the area. However Flush 4 has a high turbidity response and Flush 5 a low one. Flushes 7 and 8 are also older cast iron pipes, 7 had a high turbidity response and 8 a low response. In summary Flushes 5 and 8 have low turbidity responses despite being cast iron and of comparative age and excess shear stress to Flushes 4 and 7 respectively, which have high turbidity responses. However if peak daily shear is examined it is soon evident that the pipes associated with Flush 5 and 7 have high daily shear stresses. Hence the cohesive layers in these pipes will be cleaned by the daily forces to a greater extent than in the other pipes. This explains the lower turbidity response of Flushes 5 and 8 as compared to Flushes 4 and 7.

Conclusions

• All the turbidity traces measured during flushing operations exhibited exponential decay. Exponential decay is explained through consideration of the cohesive-like nature of the fine sediments that are thought to exist in variable strength layers on the walls of pipes within the distribution system.
• The progressive accumulation in turbidity along the length of a pipe has been shown. It is postulated, therefore, that the source is uniformly distributed cohesive layers, rather than concentrated around joints or from gravity-biased sedimentation of non-cohesive material.
• Iron has been shown to be the dominant material mobilised during flushing, increasing above background by one to three orders magnitude at the start of each flushing event, irrespective of pipe material.
• The variation in iron concentration throughout the duration of the flushing operations was shown to be directly related to turbidity.
• All the material mobilised was fine particulate, average diameter ~10 µm.
• There was no apparent link between the pipe material, pipe age, or flushing hydraulics and the amount or characteristics of the material mobilised. However, the peak daily shear was related to the amount of material mobilised.

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References


