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Understanding and managing discolouration risk in trunk mains

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ABSTRACT

There is currently no accepted concept or approach for understanding and controlling discolouration risk associated with trunk mains. This paper assesses the applicability of cohesive layer theories to manage discolouration and a steady state empirical modelling tool that describes the process of particulate material accumulation. Results are presented from independent field experiments across the UK and internationally that evidence hydraulically induced mobilisation, or effectively cleaning, once imposed system shear stress exceeds normal conditions. Model calibration to measured data validates the cohesive layer concept with transferability in empirically derived parameters demonstrating a viable operational planning tool. The experiments highlight the accumulation of material layers as a continuous and ubiquitous process, such that fully clean pipes can never exist and helping explain how discolouration risk changes over time. A major practical implication of the novel understanding demonstrated in this paper is that discolouration risk in trunk mains can be simply managed by pro-active strategies that regularly vary the hydraulic conditions. This avoids the need for disruptive and expensive out of service invasive interventions yet offers operators a cost-effective long-term strategy to safeguard water quality.

1. Introduction

Water companies need pro-active maintenance strategies if ageing and deteriorating networks are to remain fit for purpose and adapt to changing demands and pressures. In particular knowledge and tools are required to understand and manage the risks associated with trunk mains. However, the perceived risks (high consequence) associated with trunk mains have constrained such development. In 2001 a novel approach to understanding the phenomenon of discolouration in water distribution systems was published (Boxall et al., 2001). It was postulated that discolouration, the major cause of customer dissatisfaction regarding water quality, is due to particulate erosion from pipe walls and not gravitational sediment uplift and that material layers are negligibly thin compared to pipe roughness (Prince et al., 2003; Husband and Boxall, 2010; Cook and Boxall, 2011) Although a constant low-level background flux of particulate material exists in the bulk water (Seth et al., 2004; Verberk et al., 2006; Vreeburg et al., 2008), it was proposed that elevated concentrations visible to consumers is primarily caused by increases in applied hydraulic force; the shear stress on boundary surfaces. When the shear stress, determined from headloss, exceeds the cohesive shear strength of material layers that accumulate on pipe surfaces, material is mobilised (Van Thienen et al., 2011; Hossain et al., 2011). With this understanding the discolouration response was encapsulated as a force balance between the cohesive retaining forces and the mobilising shear stress. The Prediction of Discolouration in Distribution Systems model, or PODDS as it has become known, was coded as a user function into the freeware hydraulic modelling software EPANET 2.00.07bTB2 (Rossman, 2000). Empirical model calibration was achieved by monitoring flow and then elevating this above a conditioned state (that typically equates to the peak daily maximum flow) and measuring the turbidity response. To model mobilisation 3 parameters are required; k (gradient describing relationship between discolouration potential and applied shear stress), P (an erosion coefficient) and n (model exponential). Turbidity observed at monitoring points in response to elevated shear stress exceeding system conditioned values demonstrate a consistent pattern and the PODDS model can be used to explain this as shown in the simplified representation in Fig. 1. Since first publication extensive field and laboratory experiments have validated and verified the concept in distribution pipes with diameters less than 150 mm (Boxall and Saul, 2005; Husband et al., 2008; Husband and Boxall, 2010). Preliminary studies also suggested

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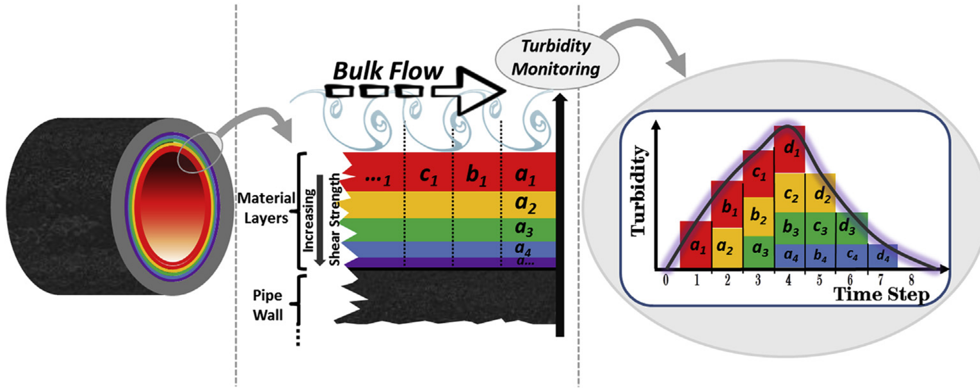

Fig. 1. Turbidity response due to increased hydraulic load in a pipe described by the PODDS model: Material layers in defined cohesive shear strength layers accumulate on boundary surfaces, weakest on top. At t = 0, following a step increase in shear stress (τ_{in}) above a hydraulically established conditioned value, material Layer 1 is mobilised into bulk flow at rate (R) determined by excess shear, where $R = P(\tau_{in}-\tau_{t=0})^n$ with P and n PODDS model parameters (a third parameter (k) is used to describe the relationship between layer strength and discolouration potential). At t = 1, flow propagation transports mobilised material [a_1] past the monitoring point. Layer 2 with higher shear strength is exposed and mobilised, but less material enters the bulk flow as excess shear stress ($\tau_{in}-\tau_{t=1}$) has decreased. At t = 2 turbidity observed is the sum of [a_2+b_1] and Layer 3 is mobilised. This process continues until material remaining has shear strength equal or greater than applied shear stress such that no further material is mobilised and all material has propagated past the monitoring point.

the same processes governing discolouration may occur in the larger trunk mains with diameters greater than 150 mm, and are applicable internationally (Boxall and Prince, 2006; Seth et al., 2009; Cook et al., 2015).

According to the PODDS theory as demonstrated in smaller diameter distribution pipes, flows above peak daily demands can lead to mobilisation of material from the pipe walls. If this holds valid in trunk mains, then with suitable control and monitoring, flow increases during standard operation may be used to incrementally remove accumulated material layers and hence reduce discolouration risk pro-actively. With appropriate flow control the concentration (or turbidity) of entrained material may be kept within regulatory levels, passing through the network and safely exiting the distribution system via demand points. With material layers of defined shear stress eroded, the main could be said to be ‘conditioned’ to these new higher flow values, that is increased resilience and no discolouration risk if flows kept within this threshold. These incremental increases may be repeated to confirm the new conditioned status or periodically to retain the protection against unplanned demand increases (such as bursts). By adopting a multi-step increasing strategy, trunk mains may be conditioned to achieve significantly higher flows during regular operation. With companies investing in control rooms and improved telemetry, these conditioning strategies can be monitored centrally and adopted into standard business practices. Confidence to promote strategies such as this however depends on validation of the cohesive layer concept describing the discolouration process within trunk mains.

This paper aims to confirm if the cohesive layer concept, as encoded in the PODDS model, is valid in trunk mains. If shown to be applicable, network controllers can design and justify appropriate viable and cost effective flow management strategies to mitigate discolouration risk and improve service.

2. Background

Analysis of over 160,000 customer contacts regarding discolouration over a 7 year period from a water company in the UK identified more than 40% as clustered, with clusters defined in the study as at least 5 contacts from a water supply zone within a rolling 24 h period (Husband et al., 2010a). Although several factors could explain this, it was proposed a likely proportion originated upstream of the distribution network, and hence could be directly associated with the supplying trunk main. Following robust cleaning of a 1.8 m diameter trunk main supplying 1.75 million customers, a 30% drop in clustered contacts with an associated 62% reduction in overall numbers was recorded (Husband et al., 2010a). In 2014 the UK regulatory authority for water quality reported 57 significant discolouration events with 2.9 million people estimated to have been effected (DWI, 2014). Of those nearly half were caused by water companies own planned operations with the majority in trunk mains. To prevent discolouration incidents and the number of customers effected, it is therefore expedient to understand the processes so appropriate operational strategies and preventative trunk main maintenance can be undertaken.

Although the origins of water supply systems are firmly rooted in protecting public health through ensuring water quality, management of distribution systems has often focused more on quantitative measures. Satisfying customer expectations however now increasingly requires detailed qualitative aspects and this is complicated by the non-inert behaviour of ageing and deteriorating distribution systems. Around the globe distribution systems are infinitely varied, complex physical, chemical and biological systems with large surface areas that interact with the transported water. While hydraulic changes account for most discolouration incidents, changes in water bio-chemistry, such as switching water source, dosing regimens, temperature or stagnation events may also contribute. Although these changes may cause precipitation of visible compounds in the bulk water, the typically low concentrations are unlikely to become evident to consumers. Where cohesive layers exist, these changes may affect the material adherence to the pipe surfaces. With a sufficient bio-chemical change, material layers may be weakened and mobilised from the pipe wall into the bulk flow in concentrations where it can be transported and observed by consumers. Trying to model these changes however is likely to be system, temporally and substance specific and therefore of limited application due to the unique structure and dynamic composition of individual networks. Conversely hydraulic control is globally applicable and is the remit of all water suppliers. It is therefore this hydraulic aspect that is the focus of this work with objectives to increase understanding and provide a platform on which operational strategies to manage discolouration can be developed.

Prior to the advent of the PODDS concept, discolouration was generally considered a gravitationally dominated process caused by the uplift of sediments from the pipe invert (Miller, 1994; Williams, 2000). This sedimentary approach was easily understandable, both for risk assessment via simple modelling exercises incorporating velocity thresholds, and network cleaning by flushing to achieve velocities above thresholds. As a consequence experiments to determine flow velocities required to induce saltation were conducted and used to derive network flushing guidelines (UKWIR, 2001; Slaats et al., 2002). These approaches are effective at controlling discolouration in smaller diameter pipes, but are generally conservative and not practicable for large diameter pipes. This is because sedimentary approaches are conceptually inappropriate. Analysis of discolouration material has shown it to be particulate in nature with characteristic particle size of around 10 μm with the consequence that self-weight forces would be insufficient to cause settling to the pipe invert in systems operating at design capacities (Mccoy and Olson, 1986; Boxall et al., 2003; Verberk et al., 2006). Furthermore, pipe cut-out and cleaning operations have repeatedly shown material accumulation around the entire pipe circumference, as shown in Fig. 2, and no invert sediments. Consequently the use of words such as ‘deposit’ and ‘sediments’ which inherently infer gravity dominated processes are misleading and should be avoided when describing discolouration, unless self-weight processes are explicitly shown to be occurring and dominating.

To understand the value of the PODDS concept, its limitations should be considered. For example the PODDS theory excludes classical self-weight/velocity driven sediment transport. Experiments in distribution pipes have highlighted some (but not all) balance (or tidal) points in looped networks and system dead-ends to generate significantly more material than generally observed elsewhere in the network (Mounce et al., 2014). In these circumstances where flow velocities can approach zero, the turbidity observed following mobilisation events suggests enhanced material accumulation, which could result from sediment deposition. A flow experiment in a 700 mm trunk main demonstrated gravitational sedimentation following pro-longed operation at a low, but fully turbulent velocity of 0.03 ms^{-1}, Re = 18,000 (Husband et al., 2010b). When flow was increased later after a period operating at 0.36 ms^{-1}, no further evidence of gravitational settling was observed. This indicates threshold conditions at which sedimentation may occur. It should be recognised that such sedimentation occurs in the longitudinal direction, creating ‘hot spots’ along the length of a pipe consistent with localised depressions or network features. It has long been believed there is also an upper hydraulic threshold that restricts or prevents material accumulation, thereby

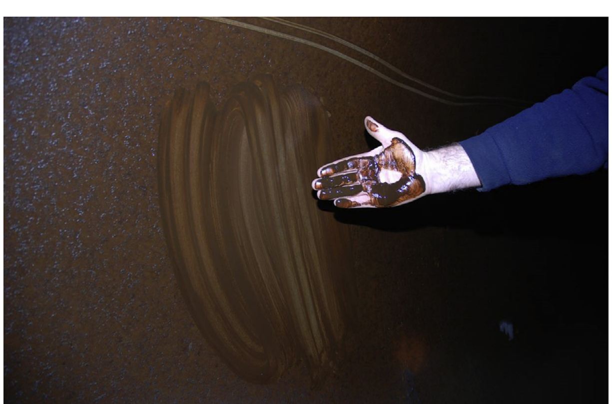

Fig. 2. Photograph from inside trunk main showing material adhesion across all boundary surfaces.

effectively producing self-cleaning pipes. This has been demonstrated in smaller distribution pipes and is now applied in the Netherlands (Van Den Boomen et al., 2004), with 0.4 ms^{-1} used as a self-cleaning network design velocity. No evidence has been published for self-cleaning velocities in larger diameter mains. Other transport processes associated with flow velocity or profiles have been postulated that affect forces on pipe walls and hence possible material mobilisation or accumulation rates (Van Thienen et al., 2011). For example, if material layers are shown to govern discolouration, is mobilisation (overcoming material cohesive shear strength) a vector property of flow, or can flow reversals be planned based on the historic conditioned shear stress irrespective of flow direction. Furthermore the PODDS model simulates the turbidity response based on steady state changes in network flow so the influence of dynamic responses, such as pressure transients, is not considered. Although some researchers have attempted to investigate the impact of transients on water quality and provide an indication that it may have an impact (Aisopou et al., 2014), differentiating the discolouration response due to dynamic fluctuations from the steady state increase in flow requires further research. A modelling study (Naser et al., 2006) suggested that while small magnitude and duration additional forces are generated due to the dynamic conditions, considering both 1D and 2D smooth wall approaches, the resulting simulated turbidity response is not improved over the steady state model. This is consistent with the observation that the PODDS model has been calibrated to simulate measured data from all sites using steady state simplifications. This suggests that for network management and understanding discolouration behaviour, consideration of steady state changes is sufficient. Trials in networks with measured regular transients due to on/off pumping regimes have shown pipes conditioned to the steady state and not dynamic peak flows (Husband and Boxall, 2015). Large atypical system events such as valve failures however may create changes in water quality where accumulated material not familiar with dynamic shockwaves may be affected. More research is needed to understand the potential impact but this is not the remit of this work where managed and monitored hydraulic changes are applied. It should also be noted that the PODDS concept does not consider what the discolouration material is, or the source of the retaining forces. These questions, although not directly addressed, are discussed in this paper.

As discolouration is not an everyday occurrence, network operators inherently appreciate a regular daily peak hydraulic demand is not an issue. This indicates that pipes, or more specifically the material generating on pipe surfaces, is effectively conditioned by the hydraulics. In network operation terms and therefore in setting discolouration modelling boundary conditions, it is assumed that no discolouration risk exists for flows up to and including this conditioned value. Experiments have shown pipes with low roughness values and diameters of 150 mm or less, a threshold flushing velocity above which no significant further material is mobilised. In the UK a velocity of 0.6 ms^{-1}, derived from a mobilising shear stress of 1.2 Nm^{-2}, has been recorded (Husband and Boxall, 2010). In the Netherlands a 1.5 ms^{-1} flushing velocity has been adopted incorporating a significant safety factor following field observations that have shown this to achieve effective pipe cleaning (Van Den Boomen et al., 2004). It is important to note that although little further material may be mobilised, the pipes cannot be considered fully clean as some material resistant to the hydraulic shear stress remains (Abe et al., 2012; Douterelo et al., 2013). The research by Husband et al in 2010 also noted that no threshold mobilising shear stress was observed in rough walled or cast iron pipes. That is for non-smooth pipe surfaces (typically a result of corrosion tubercles), material mobilisation was observed at every step increase in hydraulic shear stress irrespective of the absolute value once the conditioned value was exceeded.

Microbial interactions are increasingly being recognised as important within the distribution system environment (Douterelo et al., 2014; Fish et al., 2015). Aspects of this work have shown that biofilms exist throughout networks and they exhibit shear stress related development and mobilisation properties (Rittmann, 1982; Choi and Morgenroth, 2003; Abe et al., 2012). The microbial significance has been highlighted by experiments in a full sized temperature controlled pipe loop facility that demonstrates hydraulic regime impacting bacterial community and structure (Douterelo et al., 2013). If biofilms are integral components of water distribution systems, this could support the PODDS shear stress concept by providing both a mechanism for continual layer accumulation and bonding sites facilitating inorganic material attachment and retention.

3. Fieldwork

To explore if trunk mains accumulate material layers with a cohesive shear stress relationship, experiments from six selected trunk mains investigating turbidity response to managed increases in flow are reported. Four are from within the UK and two from sites in Europe. The sites range from 2.7 km to 10 km in length, with diameters from 360 mm to 1400 mm and include polyethylene (PE), cast iron (CI) and asbestos cement (AC) pipe materials. A summary of the 6 experimental sites including daily peak shear stress and induced peak shear stress is shown in Table 1:

The first five experimental sites reported include PODDS discolouration modelling of the observed response. Simplified Epanet hydraulic models focussing on only monitored trunk main sections were built for each site based on company supplied asset data. This included pipe length, pipe diameter and roughness. For PODDS modelling absolute pressures (and therefore elevations) are not critical as the turbidity response is based on shear stress calculated from headloss that in turn is dictated by pipe roughness. Although not discussed in this paper, changes such as these can be beneficial for hydraulic roughness calibration by monitoring pressure across a range of hydraulic conditions (Boxall et al., 2004). The last site reports on repeated operations to address the operational question of maintenance intervals as material layers accumulate. This is of direct relevance to network managers as this information is required to set justifiable maintenance strategies and inform future operating costs if the discolouration processes proposed here are validated by this study.

Undertaking flow experiments in operationally active trunk mains poses a number of management and logistical issues. The primary management concern is the knowledge that if not undertaken correctly there is the risk of creating a discolouration incident that could potentially impact millions of customers (Husband et al., 2010a). To mitigate for this the first four experiments reported underwent predictive modelling as part of the planning process. The objective of this modelling was to identify a flow increase that would only mobilise material from the pipe walls generating a low peak downstream turbidity, typically of 1 NTU. This conservative limit was set with regard to the 4 NTU regulatory limit at customers' taps in the UK. 1 NTU provides for a measurable response above typical background turbidity of less than 0.2 NTU, hence evidencing material being removed from the network and a cleaning benefit but providing a high factor of safety with respect to the regulatory limit or risk of customer contacts. It has been shown (primarily for smaller diameter pipes) that for similar properties and construction materials PODDS model parameters are transferable (Husband and Boxall, 2010). Turbidity predictions were therefore calculated based on parameters transferred from a PODDS calibrated experiment on a 13.3 km long 700 mm (27″) diameter lined steel trunk main that for many years had only received low sweetening flows (Husband et al., 2010b). It was therefore expected that fully developed material layers, and hence maximum discolouration risk, had been estimated. PODDS model parameter values were $k = -3$ NTUm^{3}N^{-1}s^{-1} and $n = 1$. Due to confidentiality agreements the erosion coefficient P, cannot be disclosed.

An essential part of simulating discolouration risk is an understanding of the current conditioned strength of the material layers. This is the value that is in equilibrium with recent maximum (peak) flows, the hydraulically induced shear stress up to which no material is mobilised. For PODDS modelling this value is a defined boundary condition. To evaluate this it is vital that current and recent historical flows are known. Ideally the peak flow has remained consistent over a period of time such that material layers with shear strengths in excess of this conditioned flow have been able to fully develop. If elevated flows have been experienced in the recent past, there is uncertainty over how much material with shear strengths in excess of the conditioning flows will have generated on the pipe walls during the intervening period.

An imperative when selecting sites is a functioning (and accurate) flow meter, so that flows and hence shear stress can be known and monitored. If a flow meter is present, then the next logistical issue is the ability to accurate control flow rates. Where trunk mains link assets such as treatment works and reservoirs, a steady state flow pattern may typically exist controlled by a pump or valve operational schedule. If sufficiently sensitive and centralised control exists, for example a variable speed pump or actuated valve, flow changes may be conducted remotely as a simple operation

Table 1
Summary of trunk main trial sites.

Site	Location	Pipe length km	Pipe diameter mm	Pipe material	Roughness k_s mm	Daily peak shear stress *(velocity, m/s)* Nm^{-2}	Experiment peak shear stress *(velocity, m/s)* Nm^{-2}
1	UK	8.4	800	PE	0.15	0.64 (0.6)	0.88 (0.72)
2	UK	8.4	457	CI	4	0.71 (0.4)	1.22 (0.52)
3	UK	3	360	CI	4	0.43 (0.2)	2.67 (0.5)
4	Portugal	2.7	1400	AC	1	1.03 (0.66)	6.83 (1.73)
5	Netherlands	10	400	AC	0.5	0.04 (0.2)	0.13 (0.35)
6	UK	4	400	AC	2.9	0.15 (0.18)	3.60 (0.92)

with the potential for future autonomous maintenance. In many trunk mains however flow is partially (or fully) customer demand driven. This makes controlling flows and ensuring they exceed the daily variable peak values more complex. The first two sites reported in this paper are directly customer demand driven and highlight different techniques to achieve effective flow increases. Site 1 rezones customer demands whilst Site 2 used a hydrant standpipe fitted with flow monitoring. Temporarily deployed turbidity monitoring was used for most of the experiments reported here. Fixed turbidity monitors as part of general network water quality monitoring can also be used. When appropriately deployed turbidity monitors can also allow long term maintenance strategies to be assessed and hence to estimate future network impact from changes such as capital investment to treatment works. UK experiments on operational systems utilised ATI 15/76 turbidity monitors *(http://www.analyticaltechnology.com)* modified for field use. The hydrant standpipe used was fitted with a battery powered ABB Electromagnetic AquaMaster flow meter *(http://www.langhamcontrols.com)* and flows logged at 15 s intervals whilst up to 1 s logging was feasible with the turbidity monitors.

4. Results

4.1. Site 1: 8.4 km of 800 mm PE

This 8.4 km 800 mm PE main is gravity fed from a surface and ground water blended water reservoir and serves an urban area in the North West of England with no take-offs along the monitored section. Customer demands create a typical diurnal pattern with the peak morning flow of 300 ls^{-1}, marginally greater than the afternoon peak as shown in Fig. 3. An 18″ CI trunk main runs parallel to this main (study Site 2) with has a typical peak flow of 60 ls^{-1}. To obtain a flow increase in the 800 mm above the daily peak it was planned to open a cross connection between the 800 mm and 18″ mains at the monitoring node whilst effectively shutting the 18″ just prior to this link (except for retaining a low level flow to avoid stagnation). This would result in both demands being transmitted via the 800 mm main, so approaching an effective peak of 360 ls^{-1}. Predictive PODDS modelling using previous calibrated parameters from a 700 mm main with fully developed and undisturbed material layers at the peak predicted combined flows indicated a worst case peak turbidity response of 3 NTU. However it was known that this main had experienced significantly higher flows within the previous year to satisfy demands when an international golf event was staged nearby. Unfortunately the flow meter on this 800 mm had only recently been refurbished as part of the requests for this research so the historic flow record was not

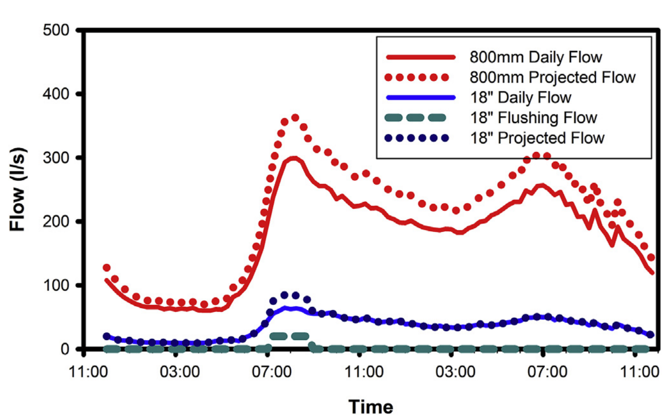

Fig. 3. Site 1 and 2 daily and experiment flow patterns.

available. However with an understanding of the recent flow activity, it was proposed that fully developed material layers would not have had time to develop as existed in the model parameter donor main. Based on this a second risk scenario was run with the erosion coefficient (P) adjusted downwards based on previous experience. This predicted a turbidity response of less than 0.3 NTU. A screenshot of the simple Epanet model and both discolouration predictions are shown in Fig. 4. With the understanding that the likely response would follow the latter prediction, and that on-site real time turbidity monitoring would be present together with a response team should observed turbidity be greater than anticipated, the experiment obtained consent to continue.

The experiment progressed with flow reaching 360 ls^{-1} and measured peak turbidity of 0.35 NTU, consistent with low risk PODDS modelling expectations shown in Fig. 4. PODDS model calibration using the measured flow as an input is shown in Fig. 5. Model parameters calibrated from this data remained as originally transferred with the exception of the reduced *P* parameter. Note the measured turbidity shows banding as a result of 12-bit logging resolution with a 0–40 NTU scale selected over a 4–20 mA signal (a 0–4 NTU range is available which increases resolution, but should the turbidity have exceeded this then the values would have flatlined at 4 NTU). It can be observed that the modelled response is not a perfect match to the measured data. With the variability in factors likely to affect material layer development and erosion along this 8.4 km trunk main and the low level turbidity response, it should be considered unreasonable to expect this. The ability to track the turbidity rise and decay, and of operational significance identifying peak turbidity however indicates the PODDS model is potentially capable of describing the discolouration response to hydraulic changes in this polyethylene trunk main.

4.2. Site 2: 8.4 km of 18″ cast iron

This 18″ (460 mm) cast iron (CI) main is the parallel 8.4 km pipe section to the main studied in Site 1. With daily peak flows over 60 ls^{-1} (Fig. 3), it was planned that sufficient additional flow could be imposed by attaching a flushing standpipe at the terminal node. A 20 ls^{-1} increase over the peak demand period was identified by predictive modelling as likely to produce a 1 NTU response. Parameters used were as in the previous study site and again with a reduced P value as this trunk main was also likely to have been impacted by flow increases due to the international sporting event. The experiment was undertaken with a peak flow in the main of 85 l/s^{-1} obtained due to the addition 20 ls^{-1} flushing discharge. A peak turbidity of 1.3 NTU was observed. A calibrated PODDS model turbidity simulation using the measured flow profile as an input is shown in Fig. 6. PODDS parameters remained as those transferred except for a modified erosion coefficient even though this main diameter is significantly less than Site 1 (800 mm) or the parameter donor site (700 mm). As for the previous site, the correlation of modelled to measured turbidity in Fig. 6 demonstrates the ability of the PODDS model to describe the discolouration behaviour of this cast iron trunk main due to hydraulic changes.

Perhaps surprising is that Site 2 produced a 1.2 NTU response (above a background 0.1 NTU) for a 20 ls^{-1} increase, whereas Site 1 had only a 0.25 NTU response for a 60 ls^{-1} flow increase. This is perhaps even more surprising when considering velocity changes, as this was equal in the two pipes. It is useful however to consider the PODDS force balance to help explain this difference in turbidity. Material mobilisation, as set out in the PODDS concept, is driven by the change in force acting on the boundary surface, the excess shear stress (τ_{excess}). The higher pipe roughness in the CI pipe results in significantly greater headloss and consequently excess shear stress when the flow is increased. The flow, velocity and shear stress

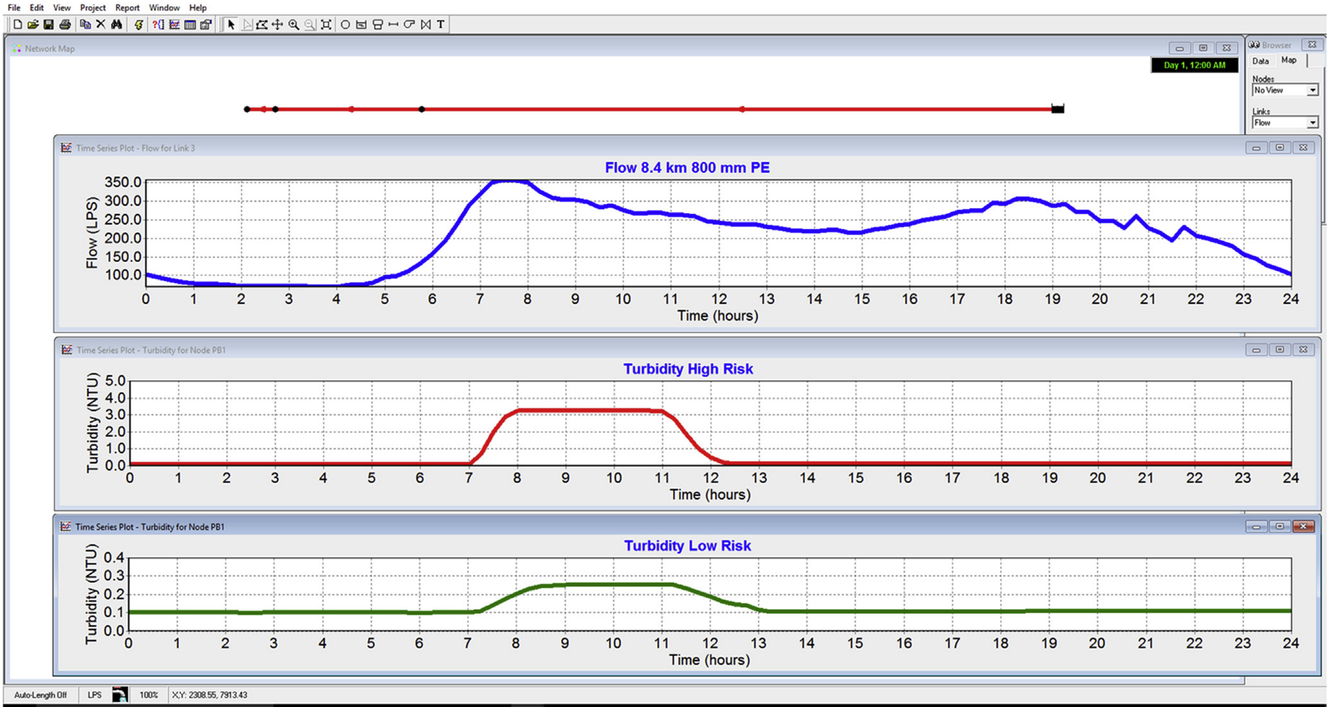

Fig. 4. Site 1 PODDS Epanet 24 h predictive modelling screenshot. A two-fold difference in the erosion coefficient produced the high risk (middle plot, $NTU_{max} \approx 3$) and low risk (bottom plot, $NTU_{max} \approx 0.26$) turbidity responses. Flow is shown in the top plot ($Q_{max} = 360\ ls^{-1}$).

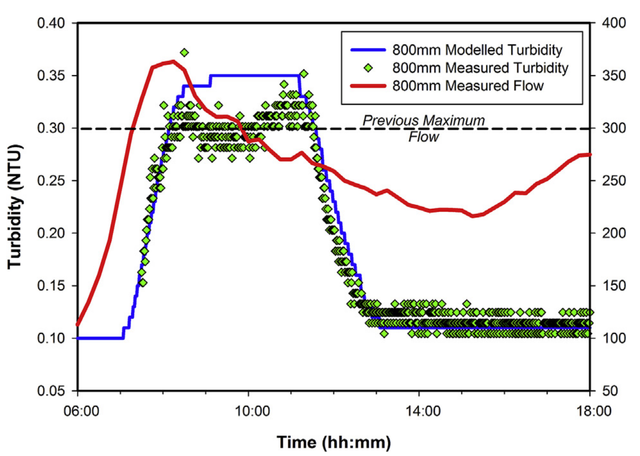

Fig. 5. Site 1 applied flow with measured and modelled turbidity.

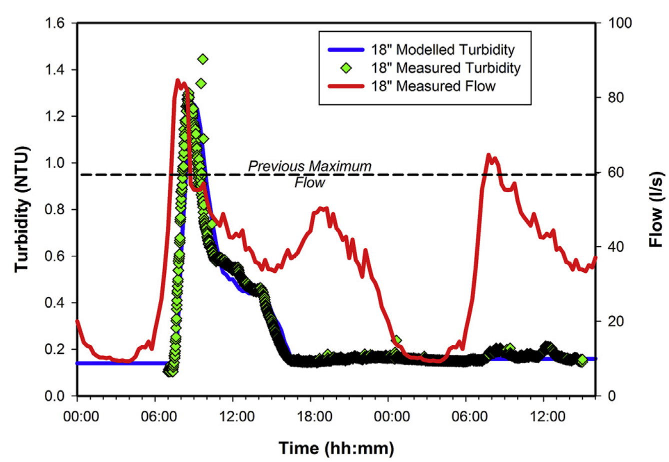

Fig. 6. Site 2 experiment flow profile with measured and PODDS modelled turbidity.

changes from both PE and CI trunk mains are shown in Table 2. From the two-fold increase in shear stress in the CI main a higher turbidity response would be expected. However this does not explain the five-fold increase in turbidity observed. It is known that both mains experienced increased flows in the preceding year due to an international sporting event occurring and as a consequence both mains have since undergone the same period of material accumulation. Previous research in smaller distribution pipes proposed accumulation is governed by bulk water quality, with the rate in CI distribution pipes noticeably greater than observed in non-CI pipes (Husband and Boxall, 2011). This has been attributed to corrosion processes acting as a second key source of material. The results from these two sites, with identical source water yet increased material available to be mobilised from the CI main, suggests the findings from smaller diameter pipes are equally applicable in trunk mains. In addition this highlights the risk from CI mains of not only increased discolouration risk themselves, but also degrading water quality through elevated iron concentrations negatively impacting downstream pipes. As a further consideration rough pipes have a greater effective internal surface area for material accumulation and subsequent mobilisation. While the PODDS model accounts for changes in pipe surface area to volume due to different pipe diameters, it does not account for increased surface area due to increased roughness. Such effects could be particularly significant in the extreme roughness case of large corrosion tubercles.

4.3. Site 3: 3 km 15″ cast iron

Site 3 is a 3 km 15″ (380 mm) CI main that forms part of the

Table 2
Site 1 and 2 changes in flow, velocity, shear stress and turbidity response.

Site	Q_{excess} (ls^{-1}) ($Q_{exp}-Q_{max\ daily}$)	u_{excess} (ms^{-1}) ($u_{exp}-u_{max\ daily}$)	τ_{excess} (Nm^{-2}) ($\tau_{exp}-\tau_{max\ daily}$)	$NTU_{response}$ ($NTU_{max}-0.1\ _{NTU\ background}$)
1. 800 mm PE $k_s = 0.15$ mm	60 (360–300)	0.12 (0.72–0.60)	0.24 (0.88–0.64)	0.25
2. 18″ CI $k_s = 4$ mm	20 (85–65)	0.12 (0.52–0.40)	0.51 (1.22–0.71)	1.2

supply infrastructure for a major city in the North of England. A flow meter and bypass valve at the downstream monitoring location allowed valve adjustments to be controlled such that flows into a receiving reservoir could be manipulated, effectively creating a flushing point. With a relatively flat daily flow profile, as shown in Fig. 7 inset A with $Q_{max} = 0.63$ Mld^{-1} and $Q_{min} = 0.4$ Mld^{-1} (1 $Mld^{-1} \equiv 11.57$ ls^{-1}), the additional demand was planned to be added after the morning peak had passed. This was important as it ensured the additional demand required in this main would not create issues upstream by causing flows to exceed their daily maximum. This is important to constrain the turbidity response to the monitored section only, but as a result requires a greater additional demand than for example aligning peak demands as in Site 2. An intermediary monitoring point 400 m along the main allowed collection of additional turbidity data. Pressure monitoring during the experiment combined with the flow changes facilitated rigorous pipe roughness and diameter calibration on behalf of the company to assess the state of this old CI main. This also allowed best estimation of resulting shear stress for hydraulic and discolouration modelling. Predictive pre-experiment modelling indicated that 1 Mld^{-1} flow increases could safely be accommodated with the turbidity response targeted at a conservative 1 NTU, whilst on-site turbidity monitoring as part of the risk assessment would allow for an immediate response if required. For operational resilience reasons the water company involved wished the main to be able to safely convey a target flow of 5 Mld^{-1}. It was therefore decided to increase flow in sequential 1 Mld^{-1} steps, taking full advantage of the accurate control possible at this site. A stepped flow profile has the additional scientific benefit that the shear stress/turbidity relationship could be investigated. Following 4 weeks of steady behaviour, the flow experiment was undertaken. The flow record pre and during the experiment are shown in Fig. 7, with inset B showing the experiment flow as recorded with 15 min polling.

The turbidity response to the flow increases is shown in Fig. 8. It

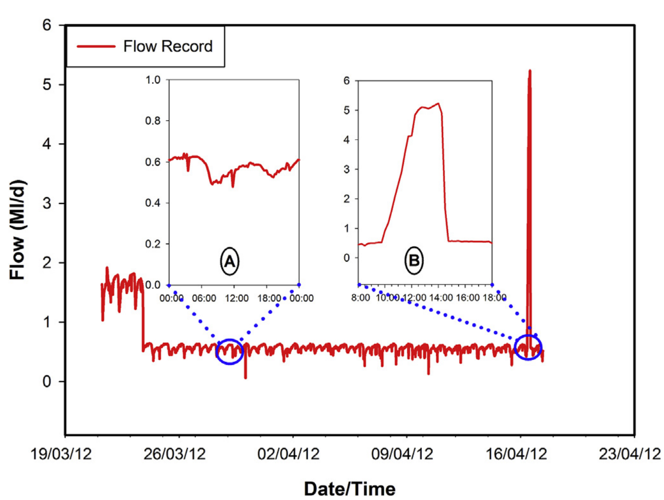

Fig. 7. Site 3 historic and experiment flow profile. Inset A shows 24 h daily profile, inset B experiment flow profile, 16/04/2012. [1 Mld-1≡11.57 ls^{-1}].

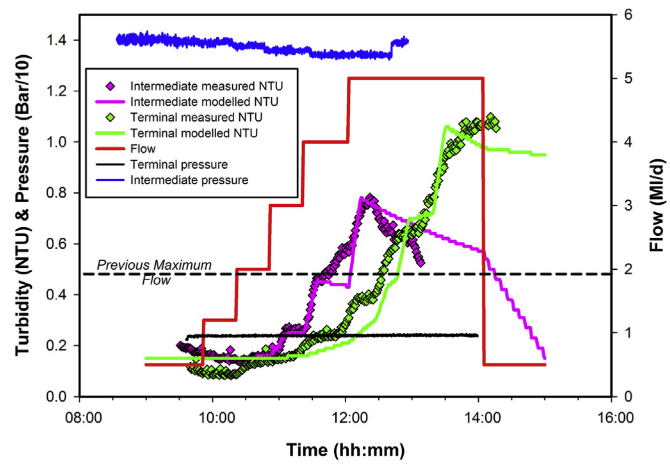

Fig. 8. Site 3 Experiment flow profile with measured turbidity and pressure and PODDS modelled turbidity. Elevation at measuring point 121.4 m, intermediate monitoring elevation 202.5 m [1 $Mld^{-1} \equiv 11.57$ ls^{-1}].

is noticeable that the first two flow increments result in almost negligible turbidity whereas the third (and subsequent steps) after passing 2 Mld^{-1} each have a marked response. This suggests that the main is conditioned to a flow around 2 Mld^{-1}. Evidence to support this can be found in the flow record of this main as flows approaching 2 Mld^{-1} had been experienced just 4 weeks previously, Fig. 7.

The turbidity response following each step helps demonstrate discolouration in this trunk main is a result of cohesive layers with a shear strength profile, not a sedimentation issue with mobilisation occurring above a given threshold. The propagation and increase of the turbidity trace between the monitoring points indicates that material remains entrained once mobilised and that material mobilisation occurs along the entire pipe length. As the main had elevation changes exceeding 80 m and local low points, the uniform mobilisation observed is further evidence that gravitational sedimentation is not a discolouration factor in this main. Corroboration of this result is shown in the PODDS model calibration for both monitoring points from a single two pipe model simulation as shown in Fig. 8. With a consistent set of parameters for both pipe sections this simulation reinforces the idea that material release, and therefore by inference accumulation, was uniform over the pipe length. Although retaining previously reported parameters produces an acceptable simulation, for optimum visual calibration the gradient term k was reduced from −3 to −1 $NTUm^3N^{-1}s^{-1}$.

By conducting an experiment with step changes in flow it is possible to directly investigate the shear stress and turbidity relationship. Data from the experiment is collated in Table 3 and the change in turbidity (effective result of each step increase) is plotted against change in flow (directly proportional to velocity) and change in shear stress, Fig. 9. Simple linear trendline analysis returns a goodness of fit (R^2) value of nearly 1 for a shear stress relationship, whilst a flow (or velocity) relationship of less than 0.6. This basic statistical analysis indicates the PODDS modelling concept that discolouration, or more appositely mobilisation of

Table 3
Site 3 Change in turbidity vs. changes in flow and shear stress.

Q Mld^{-1}	U ms^{-1}	dQ Mld^{-1}	T Nm^{-2}	Dτ Nm^{-2}	NTU	dNTU
0.5	0.05		0.027		0.09	
1.2	0.12	0.7	0.155	0.128	0.09	0
2	0.2	0.8	0.429	0.274	0.13	0.04
3	0.3	1	0.963	0.534	0.24	0.11
4	0.4	1	1.710	0.747	0.4	0.16
5	0.5	1	2.670	0.960	0.65	0.25

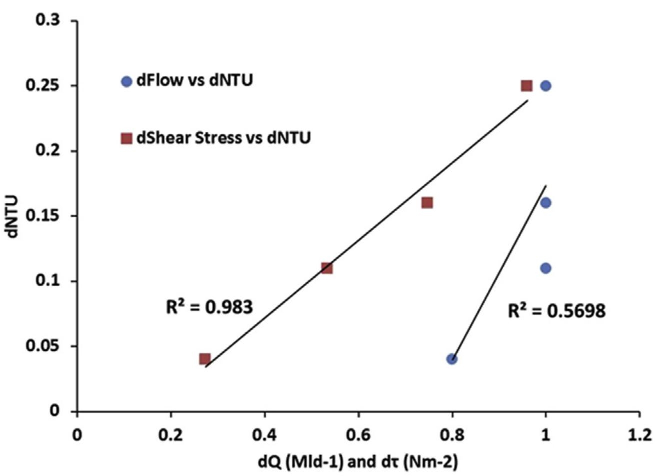

Fig. 9. Site 3 Change in turbidity vs. changes in flow and shear stress. (Note in this main; du $(ms^{-1}) = dQ\ (Mld^{-1})/10$).

discolouration material, follows a shear stress relationship. This result has significant operational implications in that turbidity responses may not be consistent within trunk main sections undergoing equal changes in flow or velocity. Of concern is that sections with higher conditioning flows have greater changes in shear stress for equivalent flow changes. Therefore it is more likely upstream sections with greater consequences will be impacted. To manage or predict discolouration risk, it is therefore important to understand the changes in shear stress.

4.4. Site 4: 2.7 km 1400 mm asbestos cement Portuguese main

A water company in Northern Portugal wished to increase the resilience (ability to transport higher volumes of water) of a trunk main without removing it from service or creating water quality issues. The 2.7 km long, 1400 mm diameter, asbestos cement (AC) main had an average flow of 1000 ls^{-1}. Following discussion and PODDS predictive modelling, using a simple 2-pipe Epanet model based on supplied network information, a field experiment was planned with a 15 min flow increase aimed at limiting the turbidity response to around 1 NTU. It had been ascertained that flow could be controlled up to an identified 2600 ls^{-1}. In addition to achieving the company aims, this experiment would facilitate testing the PODDS concept and model calibration in a system remote from UK operational policies. The experiment was successfully conducted and a 1.2 NTU peak turbidity response was observed. The measured flow and turbidity were input to the simple Epanet model. This allowed for turbidity measurements from an intermediate node to be assessed together with data collected at the terminal node. For the modelled pipe sections PODDS parameters from previously reported studies were used in the prediction targeting 1 NTU. These were then retained for calibration to measured data with only modification of the erosion coefficient P required. The Epanet simulation is shown in Fig. 10.

The simulation results at the terminal node returned high calibre visual calibration supporting model application in this non-UK system. This is not however repeated from the intermediate node at 1200 m. The initial modelled response tracks the turbidity rise but then deviates significantly from the measured data. Upon investigation it was found "a problem on the readings at 1200 m, the electric generator stopped (run out of fuel) at t = 90 min and the NTU concentration raised again as you can see on the graphic, as there was the change to the portable turbidimeter and of course after this time the values are not trustable. This therefore appears to show the model provides good calibration at both locations." (C. Sá, personal communication).

In addition to validating the PODDS methodology, this example highlights how easily turbidity responses can be misleading, especially when networks are undergoing significant flow changes that can effect equipment sample flow rates/pressures. This sensitivity of turbidimeters may still be a potential issue, but when maintained appropriately the network management benefits outweigh the care required for data collection and interpretation.

4.5. Site 5: 10 km 400 mm AC Dutch main

As part of collaborative international research and to test the suitability of the PODDS approach in non-chlorinated systems, the turbidity response to a planned step flow increase from 80 ls^{-1} to 160 ls^{-1} on a 10 km AC 400 mm diameter Dutch main was investigated. Using the model parameters from Site 3 and 4 ($k = -1$, $n = 1$) and importing the measured flow profile, a resulting PODDS Epanet turbidity simulation was undertaken and is shown in Fig. 11. As for the Portuguese experiment (Site 4), this demonstrates the PODDS model is not constrained to material mobilisation behaviour in the UK. In addition it indicates cohesive layer concepts and shear stress driven mobilisation processes are valid in systems without residual disinfectant. Furthermore the rapid increase in flow could be considered a dynamic change yet the turbidity response is consistent with behaviour simulated by the steady state PODDS model. This suggests that when considering the discolouration response, analysing the steady state component is sufficient. Asset records indicated the trunk main had circa 1.5 years of fouling time since an earlier flushing operation. To achieve the calibrated fit as shown in Fig. 11, as with the other sites discussed in this paper, the erosion coefficient P was the sole parameter modified. For this site, the calibrated P term was five times greater than that calibrated in the Portuguese main. This difference may be a factor of the period between mobilisation events and/or how the conditioning flows affected the accumulation processes. It may also be suggested that the higher coefficient observed at this site, representing a higher turbidity response for equivalent changes in shear stress, could be associated with the absence of residual disinfectant. The absence of disinfectant would suggest the increased discolouration potential could be a result of more rapid and/or weaker biofilm growth. The microbiological significance and role of *biofilms in drinking water systems* is currently a key area of research (Fish et al., 2016) and are discussed later in this paper. In the meantime experiments such as these are helping investigate the internationally observed behaviour of discolouration material whilst highlighting the operational value from application of the PODDS concept.

4.6. Site 6: 4 km 400 mm AC & DI

As part of a longer term strategy, a water company in the south of England planned to maintain resilience in a 4 km trunk main fed from a surface water source. The initial 3 km was 400 mm asbestos

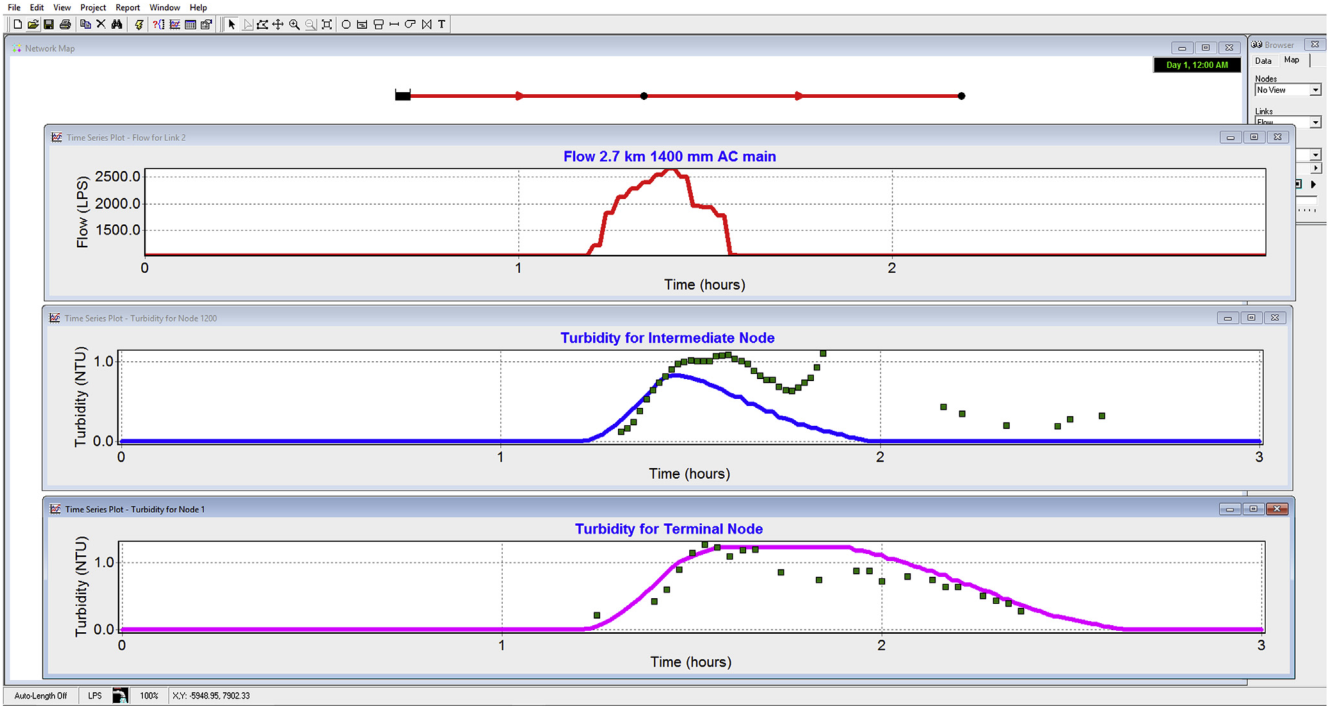

Fig. 10. Site 4 PODDS Epanet 3 h simulation screenshot showing measured flow and measured/modelled turbidity from 2 locations from 2.7 km 1400 mm diameter AC main.

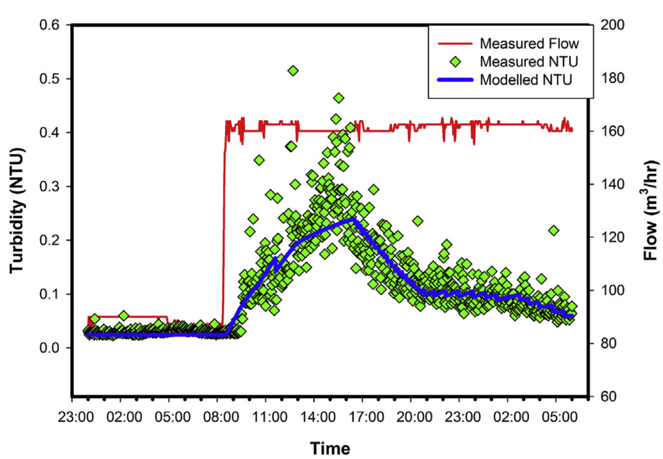

Fig. 11. Site 5 measured flow and turbidity and PODDS modelled simulation.

cement (AC) with the last 1 km 363 mm lined ductile iron (DI), based on company asset records. The main linked two reservoirs with 40 m difference in elevation. The main had a history of associated discolouration issues. Based on close relationships, experience and trust and the high costs of alternatives, it was decided to explore regular pro-active conditioning as an innovative low-cost and logistically practical approach for the first time. Specifically it was proposed that layer accumulation and therefore discolouration risk could be managed by regularly achieving the maximum required operational, or event, flow. Adopting this new strategy for long-term maintenance was also driven by the knowledge that increased flows in this main could be called upon without notice. With automatic valve control available off-site (via a control-room), a simple conditioning strategy merely required a control room operator to adjust settings as part of a regular schedule. Flow increases using on-site pumps would take the flow from 2 Mld^{-1} to 10 Mld^{-1}. Turbidity monitoring was coordinated for three (non-consecutive) weekly visits. The flow profile over the period incorporating five flow increases, but with only three monitored for turbidity, is shown in Fig. 12. A decrease in the background flow as well as pump start and stop cycles of different durations is also evident. The three measured turbidity responses, synchronised for plotting purposes with an 11 o'clock start, are shown in Fig. 13.

A number of factors are apparent from the turbidity results in Fig. 13. The turbidity response remains elevated for 100 min, consistent with expected turnover times for this trunk main. The uniform response indicates material accumulation along the entire length and with no distinction between the two pipe surfaces (AC and lined DI). This ubiquitous layer development suggests the material responsible originates from outside this trunk main and pipe material (with the exception of corroding mains) is not a dominating factor in accumulation processes. A second observable factor is that accumulation follows a consistent, repeatable pattern with time. Discolouration risk is therefore not a random process. In this system only a week's material accumulation time results in a 1 NTU response. The causes of this rapid deterioration are uncertain,

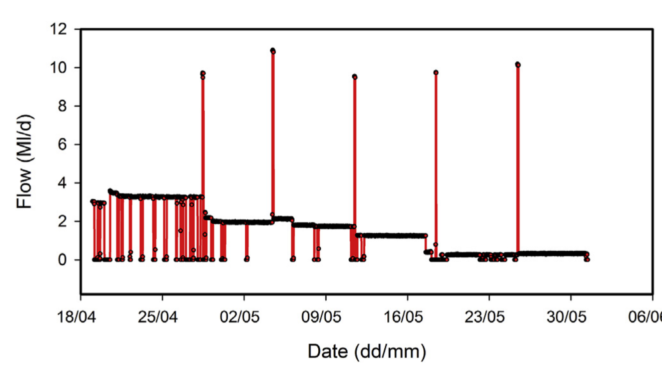

Fig. 12. Site 6 flow record indicating weekly flow conditioning experiments.

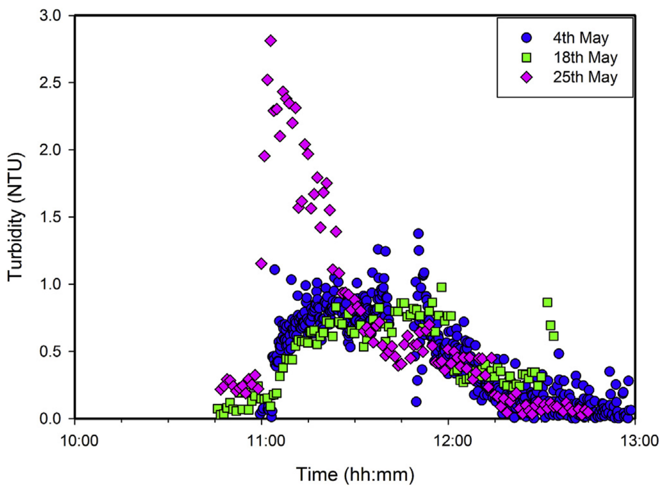

Fig. 13. Site 6 weekly flow conditioning turbidity responses.

but the even response over the full pipe length indicates that it is not dominated by corrosion effects in the downstream DI pipe section. As a result it is more likely associated with properties of the bulk water in this system.

This experiment demonstrates a limitation in the current PODDS model. The PODDS model is able to accurately simulate turbidity response (material mobilisation) due to individual increases in shear stress. However to simulate a series of material mobilisation events requires a temporal accumulation functionality. When PODDS was originally conceived there was no information or knowledge of accumulation processes but the future need was perceived. As a result during initial coding it was decided to implement accumulation as simply the reverse of mobilisation, that is material accumulation described as sequentially from strong shear strength layers to weak. However this behaviour has not been observed with material in smaller diameter pipes and laboratory based pipe facilities have shown material to accumulate simultaneously with a range of strength characteristics (Douterelo et al., 2013; Husband et al., 2008). As a result attempting to utilise the existing PODDS accumulation functionality to model this time series data of repeated mobilisation events is unsuccessful. The individual events can be effectively modelled, but require significant modification of the *P* term. Research developing the PODDS model to incorporate both the continual erosion and accumulation of discolouration material across a range of different strength bands simultaneously is however being investigated (Furnass et al., 2014).

The three sets of turbidity results in Fig. 13 show there was a higher initial turbidity response from the last flow increase, reaching 2.5 NTU on the 25th May. As the turbidity decay matches the other two traces it may be suggested that this is a result of an operational factor or contamination of the sample cell used to measure turbidity. Many operational factors could influence the turbidity results, such as a back-up pump may have been used, variation in valve operation (closure rate) or other system changes that may have increased shear stress due to dynamic acceleration or even transient effects (Collins et al., 2012; Pothof and Blokker, 2012).

Following these successful experiments the company has now implemented regular flow increases as an ongoing activity with a view to automating. Improvements in discolouration response have been noted.

There is a body of engineering experience that suggests the reversal of flow in a pipe has an increased risk of discolouration. However when cases of this are explored there are often many contributing factors, such as change in bulk water quality that may impact existing layers, a net increase in flow as well as change in direction etc. An opportunity was perceived to investigate the effect of flow reversal on this main, independently of any other factors. Two reverse flow trials were therefore undertaken. One after the maintenance conditioning reported above and a second seven months later. The regular operational flow conditioning that had been implemented following the primary experiment reported above had not been conducted for a month prior to the second reverse flow experiment. Flow reversal was achieved using fixed speed pumps at the downstream reservoir to pump water to the higher reservoir, achieving 13 $\mathrm{Mld^{-1}}$. The turbidity results at the second reservoir inlet are shown in Fig. 14. When weekly conditioning had been occurring prior to the first reverse flow experiment a gradual increase in turbidity, reaching 1.8 NTU, was observed prior to a very obvious turbidity spike starting at 11:05. Excluding the spike, this turbidity is in line with that observed from flows in the forward direction that attained a peak turbidity of 1 NTU (Fig. 13). The higher value during the reverse experiment is expected due to the additional 3 $\mathrm{Mld^{-1}}$ produced by the pumps (13 $\mathrm{Mld^{-1}}$ compared to the 10 $\mathrm{Mld^{-1}}$). When weekly conditioning had not been occurring, prior to the second reverse flow experiment, the turbidity response was greater, attaining nearly 4 NTU before an even more evident turbidity spike. These results suggest that accumulation of material is a continuous process and that for this low roughness main, flow direction has little impact on material mobilisation, i.e. mobilisation is a scalar property of the change in shear stress. The similar mobilisation patterns for both forward and reverse flow increases also indicate that accumulation is consistent along the length of the main.

The PODDS concept defines that due to the particulate nature of discolouration, material once mobilised will remain entrained in the flow. This was observed by the experiment in Site 3 showing propagation of the turbidity response evident in Fig. 8. Using this knowledge together with the PODDS Epanet model (that uses a Lagrangian transport algorithm), the transport time and duration of the turbidity trace in Fig. 14 was analysed focussing on the obvious turbidity spike. Modelling results suggested 100 m of poor main (high discolouration potential) adjacent to the pumping point could reproduce this effect. On-site investigations by the water company following these experiments identified that during the reverse pumping a section of approximately 100 m unlined ductile iron bypass pipe was called into service linking the pumps to the trunk main. This highlights the analytical value from measuring network turbidity with results that can be used to identify and assess high risk pipe sections.

5. Discussion

5.1. Discolouration experiments

This paper reports on six experiments in operational trunk mains investigating the discolouration (turbidity) response to

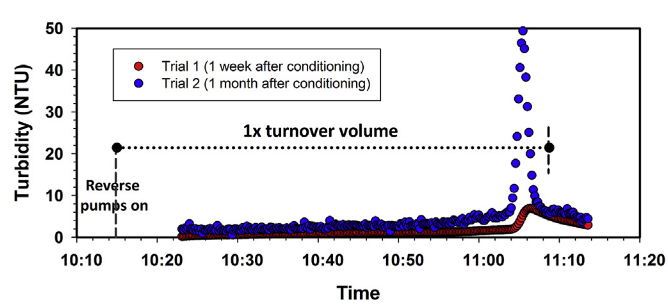

Fig. 14. Site 6 reverse flow trials.

hydraulic changes. At all sites a turbidity response was only achieved once the regular (daily) peak conditioning flows were exceeded, evidencing the ubiquitous presence of hydraulically conditioned material layers. The PODDS model was able to accurately simulate the turbidity response at all sites, confirming the applicability of the cohesive layer concept in trunk mains.

The sites selected highlight different features of the PODDS concept and management considerations. Site 1 demonstrates the concept facilitates viable and effective trunk main asset management, both for planning flow increases and monitoring evidencing of a cleaning effect. There is therefore a clear practical impact with value in safeguarding water quality and justifying financial decisions regarding short term operation and longer term maintenance. Site 2 demonstrates the importance of appreciating system configuration and in particular the deleterious effect of unlined cast iron. Corroding mains are a source of material contributing to the low level background concentrations of material within the bulk water. This additional material loading increases layer accumulation rates within that main and also negatively impacts the downstream network. In turn this highlights water treatment and the final water quality as a key factor in driving discolouration issues. Yet even with water treated to the highest standards currently obtainable, particulate material layer accumulation will occur, although at a reduced rate. This has been shown by a trial in the Netherlands where material accumulation was measured for particle-free supplied water (Vreeburg et al., 2008). Therefore investment and operations to supply (and maintain) the best quality water can be viewed as minimising the rate of layer accumulation and effective asset deterioration, but not eliminating it. This reduction in the rate of discolouration risk return can extend maintenance intervals so reducing costs. However it may also be considered that with an understanding of the accumulation processes demonstrated here, proposed capital spend at treatment works may be better invested in ongoing operational pipe maintenance. Perhaps the simplest and most cost-effective way to achieve long term management of discolouration risk is by applying PODDS style flow conditioning, especially when centralised monitoring and control protocols are in place as at site 6. The second site with the presence of exposed CI mains indicates that even the best quality treated water and the necessary processes (or proposed) required to achieve this, may be negated by the presence of additional material sources such as corroding pipes/fittings. It has been clearly shown that with due care and attention material mobilisation from trunk mains can be controlled to be within regulatory limits, and hence pass safely through the downstream system. However, it is uncertain if these elevated fluxes of material would adversely affect downstream infrastructure. It is feasible that the short duration of this acute loading is negligible in comparison to the chronic, long term loading of normal bulk water quality. No adverse downstream effects have been observed for any of the sites reported here, however evidence is required to understand and quantify the possibility. Future long term studies and cost-benefit analysis investigating water treatment versus trunk main investment and maintenance is required to investigate this capital and operational balance and help optimise source to tap water quality.

By utilising accurate control to apply a multi-stepped flow increase, Site 3 highlights a shear stress, not a flow/velocity, material mobilisation relationship. In addition the careful use of flow increments demonstrates how material layers are conditioned by the prevailing hydraulics and therefore the importance of access to the flow records for discolouration control. Site 4 shows the international value of the cohesive layer concept and the PODDS approach, and the care required when analysing turbidity data. This experiment was also planned using predictive simulations and later calibrated solely through email contact. This indicates the ability that this concept can be quickly and efficiently utilised by water suppliers worldwide. Site 5 starts to question the factors contributing to material layer accumulation. This includes determining the current state of material layers and how this may involve a number of unknown factors and site specific characteristics. In addition to time varying water quality composition for example as a result of seasonal factors, it is important to appreciate the accumulation and the intervening hydraulic history. The hydraulic history is important as it has been shown to influence bacterial community structure and composition in an experimental drinking water distribution system and this is associated with discolouration risk (Douterelo et al., 2013). However the impact of conditioning hydraulics on biofilm conformation and therefore discolouration remains unquantified.

The experiment at Site 6 demonstrates that accumulation of material layers in trunk mains is a constant and repeatable process, as previously identified in smaller distribution pipes (Husband and Boxall, 2011). Managing this repetitive layer accumulation process can therefore be used to reduce discolouration water quality failures, with benefits such as a reduction in customer complaints (Husband et al., 2010a). This site shows how PODDS strategies can be used proactively to plan and manage operational interventions to achieve this, providing longer term discolouration risk management in trunk mains. Further data from this site evidences the mobilisation of material was independent of flow direction, being merely a function of change in shear stress, or that material layer shear strength in non-corroding pipes is a scalar property. This is important for network operators as flow reversals may be considered feasible without additional work if the planned shear stress in the reverse direction does not exceed normal operation. The final data from site 6 demonstrated how the PODDS tool can be used for network analysis by investigating the turbidity response, such that higher discolouration risk pipe sections may be identified and located.

5.2. Modelling

The turbidity response was successfully simulated for each site using the PODDS model with simplified network representation, supporting the application of the PODDS concept of cohesive material layers for trunk mains. The consistency, and hence transferability, in calibrated PODDS model parameters provides confirmation of the empirical approach adopted. By reporting results from multiple sites, combined with earlier published data from individual trunk mains, this paper validates the PODDS approach as applicable to larger diameter mains in drinking water systems. With this confirmation and previous verification in the smaller distribution pipes, it is now possible to apply the proposed processes of layer accumulation/mobilisation as occurring on all pipe surfaces in water distribution systems. Operational value is confirmed with the PODDS concept incorporated into the risk assessment plans for these experiments, whilst model predictions facilitated company approval of these activities within sensitive operational networks directly supplying large numbers of customers. The results demonstrate that managed changes in shear stress can be undertaken with predictable and controlled turbidity response. By collecting, sharing and analysing the turbidity response data, the water companies involved have developed confidence that managing flows can be utilised as a network maintenance tool and have evidence to demonstrate that beneficial cleaning effects can be achieved.

Of course not all the PODDS turbidity simulations exactly replicate the measured response. It would be unrealistic to expect this given the chemical, physical and biological complexities of distribution systems. In cases where unexpected turbidity results occur, this can highlight network features or irregularities not considered, such as sections of corroding iron main identified at Site 6. With the infinite range of interactions that occur in distribution systems, the inherent assumptions in hydraulic models (including the equation used to determine shear stress; $\tau = \rho gRS_o$, where *shear stress = fluid density x gravitation force x hydraulic radius x headloss*), inaccuracies measuring flow, interpreting historic flow regime on material layer development (compounded by the typical 15 min logging response in the UK so actual peak values may be missed), temperature effects etc., it is almost inconceivable that any single discolouration model can characterise all networks. Yet the PODDS model achieves this whilst remaining sufficiently simple for daily operational use and not purely a research tool. If viewed on the micro-scale, the homogenous cohesive material layer behaviour described by the PODDS approach is not an accurate representation. Images from microscopy work on pipe surfaces clearly show heterogeneous biofilm development as evident in Fig. 15. However on the macro-scale, as in water distribution systems and portrayed in Fig. 1, the averaging of the response from the large pipe-wall contact area permits the PODDS model to yield useful results.

Of significant interest to water providers is information regarding the rate at which material layers accumulate. This is significant when quantifying discolouration risk and therefore maintenance scheduling and costs. The experiments reported in this paper demonstrate that managed flow conditioning can be considered both as a short term tactical solution to increasing flow demands or operational resilience and as a long term sustainable option to reduce asset deterioration. However as highlighted by site 6, the validated PODDS model is limited to simulation of turbidity response (mobilisation) due to a single set of flow increases only. Longer term time series scenarios of varying flows cannot be effectively simulated. This is due to the limitation of the original PODDS EPAnet coding that assumed accumulation as the reverse of the mobilisation process. The results from Site 3 however demonstrate that layer accumulation is simultaneously across all shear strengths. Updated models to incorporate simultaneous layer development across multiple strength bands being developed should facilitate long term discolouration modelling (Furnass et al., 2014).

5.3. Discolouration material

By implication the empirical PODDS model makes no references to the composition or bonding forces of the material that accumulates on pipes walls. However this study and preceding data all indicate this is a feature common to networks worldwide. Increasingly microbiological factors appear to be this unifying factor in layer development and hence discolouration risk. Biofilms have long been known to exist and grow throughout distribution systems, even in the presence of disinfectant residuals (Block et al., 1995). Research under idealised conditions has indicated shear forces influence biofilm attachment strength, with erosion associated to increasing system shear stress (Choi and Morgenroth, 2003; Abe et al., 2012). Biofilm erosion has also been observed to result in particulate release (Telgmann et al., 2004). In addition stratification in the cohesion of biofilms, or the formation of layers with the weakest layers on top, has been measured (Derlon et al., 2008). All these behaviours are consistent with the PODDS assumptions. Another approach implicating the microbial significance has been the trend observed in the UK between temperature and discolouration incidents, where higher summer temperatures result in more discolouration incidents (Cook et al., 2015). It could be proposed that this is partly a result of increased microbial activity as water temperature is elevated. It is interesting to note that the presence of biofilms may be essential, but perhaps it is the entrapment of inorganic material that drives the aesthetic discolouration potential. Images of developing biofilms grown in a full scale pilot plant with specialised pipe coupons that fit flush to pipe walls thereby retaining realistic shear conditions (Dienes et al., 2010) show this inorganic incorporation, Fig. 15. The image indicates the biofilm and entrapped inorganic particles to be around 10 µm or less, consistent with the understanding underpinning the PODDS concept (particle size too small for self-weight, hence sedimentation, to dominate behaviour). The processes governing this inorganic entrapment could be pivotal in understanding discolouration risk and highlights research to be done. With the rapid increase in knowledge and understanding of the importance of biofilms in water distribution systems and associated operational implications, it is important to continue and expand the current activity in water distribution system microbial research. It is also important that research should consider the impact of treatment and disinfection regimes for bulk water effects on network biofilm development, as well as network management practices.

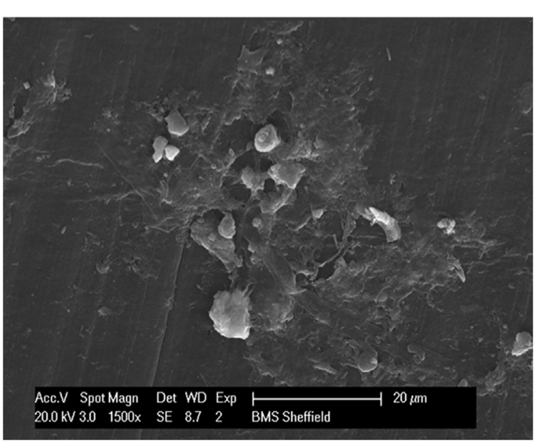

Fig. 15. Developing biofilm growing on 79 mm HPPE pipe in full scale temperature controlled laboratory pipe loop showing inorganic incorporation (Image courtesy of BMS Imaging Facility, University of Sheffield, UK).

5.4. Operational implications

The range of study sites reported here demonstrates the different strategies available to network operators to control flow and therefore manage network resilience or discolouration risk. The strategies include rezoning of demands (Site 1), addition of a flushing discharge point (Site 2), increasing reservoir inflows (Site 3) and varying pumping configuration (Site 6). Data from sites outside the UK (Site 4 and Site 5) highlight discolouration is an international issue with the PODDS concept remaining equally valid.

For network operators the PODDS concept of ubiquitous and continual accumulation of material layers, combined with the understanding that mobilisation is driven by exposure to excess shear stress, highlights three important operational considerations. Firstly there is realistically no such thing as a clean pipe. That is as soon as a pipe is in service, material layers, most likely following primary biofilm colonisation, will start to accumulate. It is therefore important for operators to consider what flow the main may be required to transmit (and when) to ensure appropriate maintenance plans are in place to proactively condition the material layers such that when events do occur there is minimal excess shear stress. Likely scenarios to be considered could include seasonal demand variations, increased resilience requirements or potential asset failure such as bursts. Secondly, with layers starting to develop as soon as any surface is exposed, *any* mains cleaning strategy is only a temporary measure. This raises questions about the long term sustainability of invasive cleaning strategies that are typically disruptive, labour/equipment intensive and expensive. These considerations lead to the third point that the potential discolouration risk is linked to how long the material layers have had to develop (layer condition) and the magnitude of the excess shear stress applied. These considerations impact short term tactical planning and long term strategic network maintenance and therefore have direct implications on any financial scheduling.

Once a pipe section is identified as posing a high discolouration risk, maintenance options available to network managers include rehabilitation (replacement, relining) or cleaning. Replacement or relining are typically capital intensive. In addition undertakings of this nature will require re-routing of water whilst the identified mains are out of service. This may be logistically problematic as with trunks mains shown to ubiquitously exhibit cohesive layer properties, re-routing demands is likely to create additional discolouration risks in the associated infrastructure. In addition knowledge that following replacement or relining, discolouration risk will return as layers accumulate highlights that even these highly capital intensive options are not a 'fit and forget' long term solution. Operational reasons, such as poor asset condition (leakage/burst risk) or exposed cast iron (negative impact on water quality and therefore detrimental to all downstream pipes) should therefore be considered as primary drivers for such interventions.

Invasive mains cleaning (such as jetting, scouring, pigging or ice-pigging in the UK) are considered a solution to discolouration risk in trunk mains. Like main rehabilitation, these typically involve re-routing supplies with associated additional risks and so typically involve significant costs and risks in associated pipes. Following the work in this paper highlighting continual layer accumulation, companies are realising these invasive strategies are unlikely to be sustainable. Another option is flushing, whereby system shear stress is elevated in a managed fashion by discharging a flow to waste, mobilising and removing accumulated material. Alternatively flow conditioning can be achieved without discharging water as system shear stress is increased through managed steps and allowing low level material concentrations to pass safely through the network. With tools and knowledge presented here these concentrations can be managed below regulatory or customer impacting levels. Where practical these can be simple, low cost and rapid solutions. In many trunk mains flushing is not typically feasible due to operational or disposal issues regarding the volumes of water involved. Where it has been applied to trunk mains, results demonstrate it as an effective cleaning strategy (Husband et al., 2010b). Of interest is that experiments results from distribution pipes also suggest that flushing is as effective as rehabilitation for controlling discolouration risk in networks where no other system changes occur (Husband and Boxall, 2008). This should not be considered surprising as asset deterioration due to material layer accumulation is associated to water quality and the hydraulic regime and these are not affected by standard maintenance strategies.

6. Conclusions

This paper presents results from a series of international experiments conducted on operational trunk main systems that validate the application of cohesive layer concepts to understand and hence manage the primary discolouration processes occurring within trunk mains. The applicability of the concept is confirmed through evidence of discolouration material mobilisation from pipe walls of trunk mains due to increasing hydraulic shear stress, with mobilisation a scalar property of the system shear stress for smooth walled pipes. In particular the evidence presented highlights that mobilisation only occurs once a conditioned state is exceeded, typically defined by daily peak operating hydraulic conditions. The cohesive layer concept is the basis of the PODDS model as encoded into freeware software EPANET. This was successfully calibrated to provide accurate simulation of the measured data, further validating the cohesive layer concept as applicable to trunk mains. International transferability of the PODDS model is demonstrated, indicating consistent behaviour and ubiquitous processes. It is suggested that this consistency and the strength behaviour and accumulation of cohesive layers may be governed by the universal presence of biofilms.

The results demonstrate how managed increases in flow can be utilised to effectively and efficiently reduce the discolouration risk posed by trunk mains without the need for expensive and disruptive invasive interventions. The operational implications of this improved understanding and the ability and tools to simulate turbidity response in trunk mains thereby facilitate viable and cost effective management strategies that can be used to safeguard and improve water quality.

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