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Understanding and managing discolouration risk in trunk mains

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A R T I C L E I N F O

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A B S T R A C T

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.

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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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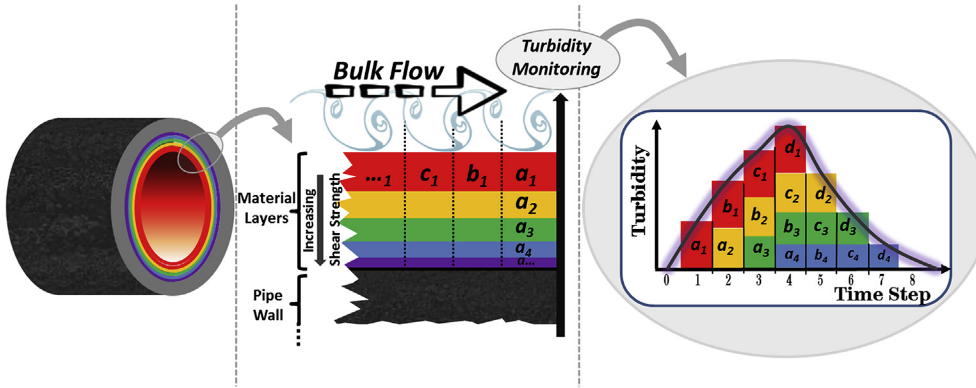

Fig. 1. Turbidity response due to increased hydraulic load in a pipe described by the PODDS model: Material layers in defined cohesive shear strength layers accumulate on boundary surfaces, weakest on top. At t = 0, following a step increase in shear stress (τ_{in}) above a hydraulically established conditioned value, material Layer 1 is mobilised into bulk flow at rate (R) determined by excess shear, where $R = P(\tau_{in}\text{-}\tau_{t=0})^n$ 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

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