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Short-term forecasting of turbidity in trunk main networks

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ABSTRACT

Water discolouration is an increasingly important and expensive issue due to rising customer expectations, tighter regulatory demands and ageing Water Distribution Systems (WDSs) in the UK and abroad. This paper presents a new turbidity forecasting methodology capable of aiding operational staff and enabling proactive management strategies. The turbidity forecasting methodology developed here is completely data-driven and does not require hydraulic or water quality network model that is expensive to build and maintain. The methodology is tested and verified on a real trunk main network with observed turbidity measurement data. Results obtained show that the methodology can detect if discolouration material is mobilised, estimate if sufficient turbidity will be generated to exceed a preselected threshold and approximate how long the material will take to reach the downstream meter. Classification based forecasts of turbidity can be reliably made up to 5 h ahead although at the expense of increased false alarm rates. The methodology presented here could be used as an early warning system that can enable a multitude of cost beneficial proactive management strategies to be implemented as an alternative to expensive trunk mains cleaning programs.

1. Introduction

With the advancements in science and technology, so too have customer expectations risen of the service they receive from their water provider. This has been most recently reflected through regulatory bodies placing heavier incentives, penalties and fines for water quality related issues (OFWAT, 2009). The UK regulatory body OFWAT introduced penalties for water companies that exceed an acceptable number of customer contacts for discolouration back in 2009, yet in 2013 alone over 2 million UK customers were still estimated to have been affected by water discolouration issues (DWI, 2014).

Although improvements have been made to reduce discolouration, it is almost completely dealt with in a reactive way by water companies (Blokker, 2010; Cook et al., 2015). This is done in the form of cleaning parts of the network once a sufficient number of discolouration contacts are reported in that area. With ever increasing regulatory pressures and tighter standards, it is evident that reducing discolouration is a key challenge facing the water industry today and new management methods need to be considered.

Discolouration formation is complex and not completely understood with bulk water quality, temperature, network layout, pipe material and age all believed to be factors (Abe et al., 2012; Husband and Boxall, 2011; Van Thienen et al., 2011; Vreeburg et al., 2008). Discolouration has been seen to vary even between different parts of the same water distribution network and yet is still similarly experienced throughout the world regardless of the wildly differing factors between their Water Distribution Systems (WDS) (Armand et al., 2015; Blokker and Schaap, 2015; Husband et al., 2008; Vreeburg and Boxall, 2007). Discolouration mobilisation is believed to be primarily caused by sufficiently large hydraulic changes in the WDS resulting in the detaching and transportation of the accumulated discolouration material through the network and producing discoloured water at the consumer's tap (Boxall et al., 2003; Prince et al., 2001; Vreeburg et al., 2005).

Trunk mains have been categorised as especially high discolouration risks as their size allows for them to act as a form of a reservoir for discolouration material build up (Cook and Boxall, 2011). Trunk mains can play two roles in the discolouration process, a passive role of slowly sending material downstream to build up in other distribution pipes or an active role of a widespread high consequence discolouration event if the discolouration material is rapidly mobilised.

Cleaning a trunk main can result in the improvement of bulk water quality leaving the trunk main which has been shown to

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reduce the likelihood and magnitude of downstream discolouration events (Blokker and Schaap, 2015). This in turn also reduces the frequency of maintenance and cleaning required in downstream distribution pipes. This is further evidenced by a study in the UK showing that between 30% and 50% of discolouration events seen in the reported District Metered Areas (DMAs) could be linked to imported discolouration material from upstream trunk mains (Cook et al., 2015). The study also found that depending on the DMA, between 0% and 51% of discolouration contacts could be linked to upstream trunk mains. While the mean was only 9%, this shows that some WDS are significantly more susceptible to discolouration events from trunk mains than others.

The benefits of cleaning trunk mains are easy to observe in extreme examples such as where a trunk main supplying 1.75 million customers saw an associated 62% reduction in overall customer contacts after being cleaned (Husband et al., 2010a). However the significant consequences and logistical complexities associated with trunk mains mean that regular cleaning programs are expensive and difficult to implement. This has resulted in very infrequent trunk main cleaning programs usually carried out reactively in situations where the benefits are evident (Husband et al., 2010b; Vreeburg and Boxall, 2007).

According to our best knowledge, the only turbidity prediction model validated on trunk mains in the field is the Prediction of Discolouration in Distribution Systems (PODDS) model (Husband and Boxall, 2016). This model was developed for the cleaning of single pipe stretches with minimal invasive action required. However, due to unknown pipe conditions and discolouration material build up rates, this model requires hydraulic model with onsite model calibration before each use making it unsuitable in the context of continuous (rather than individual event based) turbidity prediction. The Variable Condition Discolouration Model (VCDM) builds upon the PODDS model and is capable of emulating material erosion and regeneration in pipes over time (Furnass et al., 2014). However, the VCDM is currently unverified as it requires repeated site specific turbidity events for model parameter calibration and a calibrated hydraulic model to track the turbidity response. This twin modelling constraint also increases the complexity and therefore potential for error when applied to operational applications.

The requirement of a well calibrated and accurate hydraulic model has been noted as a major limiting factor in many existing water quality models (Machell et al., 2009, 2014; Skipworth et al., 2002; Vreeburg, 2007). This is similarly a common theme found when developing a burst detection model, water demand model or anomaly detection model that must build upon a well calibrated and accurate hydraulic model (Arad et al., 2013; Blokker et al., 2009; Machell et al., 2010; Tao et al., 2014). Whether this has prevented the use of the model in certain areas (Tao et al., 2014) or resulted in a clear decrease in model accuracy away from the calibrated area (Leeder et al., 2012), the dependency of a satisfactorily calibrated hydraulic model limits the application of these model types. These issues stem from the expense of developing and regularly updating hydraulic models and the fact that they are usually calibrated from “24 h” data reflecting an average day in the water distribution system (WDS). This creates an additional problem for accurately forecasting discolouration as discolouration events are thought to be primarily a function of irregular hydraulic disturbances that mobilises the accumulated material and are not therefore part of the “average day”.

To be free from the issues associated with using hydraulic models and to ensure application to almost any WDS that has suitable meters installed, a data driven methodology for short-term forecasting of turbidity was explored and validated on a real trunk main network. While prior work showed that a data driven methodology for forecasting turbidity was possible, the Artificial Neural Network (ANN) based model only forecasted 15 min ahead and with limited accuracy (Meyers et al., 2016). The methodology presented in this paper greatly expands on this by comparing multiple machine learning methods with an improved set of model inputs and forecasting over multiple significantly longer forecast horizons. Additionally, a completely alternative modelling approach is also presented that simplifies the machine learning objective by only predicting if turbidity will exceed a prespecified threshold at a specific time horizon in the future.

2. Site details and data

Flow and turbidity measurements were taken from a section of a trunk main network in the UK over 11 months, starting from 01 September 2013 to 01 August 2014. Hydraulic data was captured from one import flow meter and six export flow meters from the network section while turbidity data was captured from one turbidity meter.

As shown in Fig. 1, in addition to a flow meter placed immediately downstream of the upstream service reservoir, which is the sole inlet for the trunk main network, a flow meter was placed at each water exporting branch. The turbidity meter was placed just before the flow meter at the inlet to a downstream service reservoir so that all turbidity measurements have an associated exact measurement of the flow rate going through the turbidity meter. Between the upstream water inlet and downstream turbidity meter there is 10.5 km of ductile iron trunk main piping.

The flow and turbidity data was recorded at 15 min intervals with flow being logged as the sum of water through the meter during that interval and turbidity being logged as the current turbidity passing through the meter on the 15 min interval mark. Flow was measured in cubic meters per 15 min (m^3/15min) and

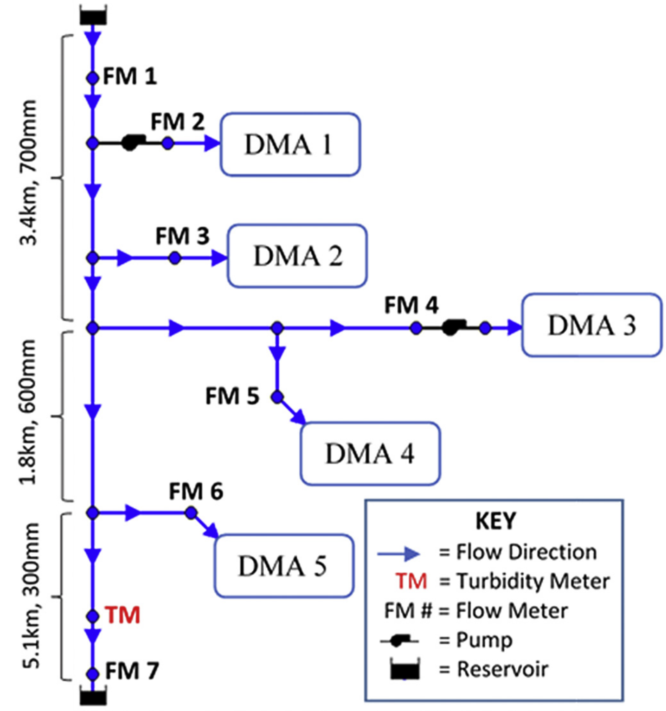

Fig. 1. Trunk main network schematic showing the placement of flow and turbidity meters. Lengths and diameters are shown next to the trunk mains connecting the upstream service reservoir to the downstream turbidity meter.