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Predictive water quality modelling and resilience flow conditioning to manage discolouration risk in operational trunk mains

[Short title: Predicting discolouration and resilience conditioning in operational trunk mains]

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ABSTRACT

This paper presents predictive discolouration modelling and subsequent field trial validation for a cast iron trunk main network. This enabled a UK water company to propose an *'operational flow conditioning'* maintenance plan that reduces discolouration risk, improves network resilience and asset condition and yet does not require the trunk main to be decommissioned for invasive cleaning. This represents substantial time and cost benefits. Pre- and post-trial turbidity monitoring data are presented which identified a daily flux of material, a factor in the regeneration of material layers that have been shown to cause discolouration when mobilised. Additional data detecting the occurrence of pressure transients are also presented, a possible cause of contaminant ingress and asset failure. After six months a second flow trail was conducted and modelled, confirming the regeneration of particulate discolouration material across the range of mobilising forces applied during the trial. It also indicated full layer development, or maximum discolouration risk, may occur in just over two years for this cast iron main. This highlights the need for appropriate maintenance strategies, such as periodic flow conditioning identified here, to mitigate discolouration risk and help safeguard water quality.

Key words | discolouration, flow conditioning, maintenance, mobilisation, PODDS regeneration

INTRODUCTION

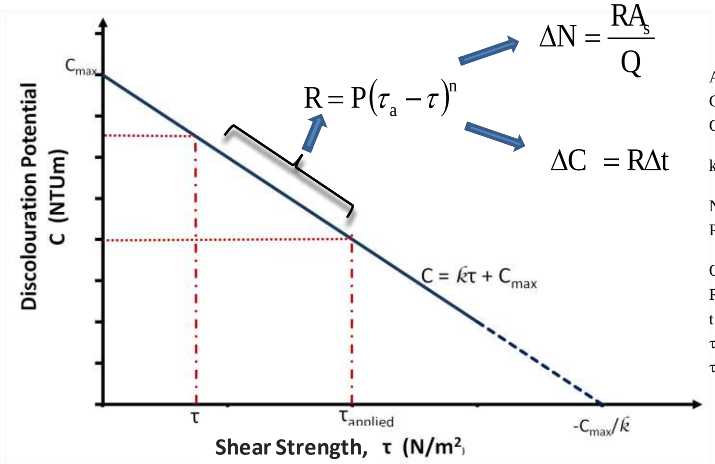
Due to a legacy of discolouration incidents following operational activities associated with trunk mains, increasing regulatory attention and the potential high consequences (large populations exposed), UK water companies have tended to shun trunk main operations in live networks for fear of consequences. In particular, activities that result in increased flows are avoided, demonstrating the inherent understanding that discolouration is primarily hydraulically driven (Husband & Boxall 2011). When increased flow through a trunk main is necessary such as due to increased demand or source water changes, or unacceptable discolouration risk is otherwise identified, trunk mains have typically been taken out of service to undergo invasive cleaning. Although this may achieve good results in terms of risk reduction, the process is disruptive, requires specialist teams and tools, discolouration risk may be increased elsewhere as network settings are altered to re-allocate demand, and ultimately the cost is usually high.

Critically, with discolouration material now known to continuously and ubiquitously regenerate throughout networks, any cleaning is seen to be of finite benefit (Vreeburg et al. 2008; Husband & Boxall 2011). This leads to questions about the longer-term cost-effectiveness and sustainability of one off invasive cleaning strategies. As an alternative the PODDS conditioning strategy facilitates in-service cleaning by pro-actively managing incremental increases in flow. With no specialist tools required and the ability to be integrated as part of a standard and regular maintenance procedure involving no service disruption, discolouration material can be removed and the trunk main conditioned to accept higher flows at little cost.

The PODDS approach to managing discolouration risk is founded on a number of well-documented observations. First, material responsible for causing discolouration is particulate in nature, typically around 10 μm (Gauthier et al. 2001; Seth et al. 2004; Verberk et al. 2006), so unless systems exhibit very low flows for prolonged periods, gravitational sedimentation is not a dominant factor describing material behaviour (Boxall et al. 2001). Second, this particulate material is ubiquitously present at low background concentrations in treated water and as it passes through the network it accumulates as cohesive layers on all boundary surfaces (van Thienen et al. 2011). Water quality, or the concentration of material such as iron and manganese, appears to directly influence the rate at which these material layers develop

(Husband et al. 2008). Improvements in treatment processes are therefore capable of reducing the development rate and so potential discolouration risk, but even ultra-filtered water has been shown not to eliminate layer development (Vreeburg et al. 2008). At some point a trade-off between capital spend on improved treatment and maintenance of distribution systems needs to be considered. Other sources of material, such as resulting from contaminant ingress (LeChevalier et al. 2003) or the presence of corroding iron pipes and fittings (Nawrocki et al. 2010), can also exacerbate the rate of layer development.

The PODDS model describes the rapid mobilisation of material accumulated at the pipe wall into the bulk fluid. It achieves this through a force balance at the boundary between cohesive material layers and the shear stress forces generated by the system hydraulics (Boxall et al. 2001). This relationship between the system forces and the discolouration potential is shown represented in Figure 1. The model has been widely verified to successfully simulate discolouration responses in distribution networks (Boxall & Saul 2005). For optimal simulation, site-specific calibration of empirical model parameters is desirable. However, transfer of parameters has been successfully demonstrated in systems of similar pipe properties and water source (Husband & Boxall 2010).



A_s	m^2	Pipe surface area
C	NTUm	Turbidity (discolouration) potential
C_{max}	NTUm	Maximum turbidity (discolouration) potential
k	$NTUm^3N^{-1}$	Relationship between yield strength and cohesive layers
N	NTU	Turbidity
P	$NTUm^3N^{-1}s^{-1}$	Coefficient of eroding force
Q	m^3s^{-1}	Discharge
R	$NTUms^{-1}$	Rate of supply
t	s	Time
τ	Nm^{-2}	Current or initial layer yield strength
τ_a	Nm^{-2}	Applied shear stress

Figure 1 | The PODDS model.

This paper details how the PODDS model and concept was applied to manage a cast iron trunk main system in the UK. Field data are shown to support the foundations of the PODDS concept of particulate cohesive layers accumulating continuously and their rapid mobilisation by increased hydraulic conditions leading to discolouration. The work is described in six stages (6). The primary stages were first reported at the CCWI 2013 conference (Husband et al. 2014) with further detailed repeat trials and water quality modelling highlighting asset deterioration and network behaviour reported here. In stage 1 the PODDS model was used to predict the discolouration risk (1) should an extreme flow event occur, such as likely following a burst. Flow conditioning (2) modelling was then undertaken to determine flow increase steps that would be sufficient to mobilise material layers but in a managed fashion so that bulk water quality would remain at acceptable standards throughout the process. If applied this could effectively ‘clean’ the pipe such that the obtained flows could provide network resilience with no discolouration risk for a defined period. If the rate at which the material layers regenerate is known, the length of this resilience period can be determined. The water company could then use this information to justify regulatory maintenance intervals. Of note for this work is that no relevant turbidity data or model parameter values were available for cast iron (CI) trunk mains. Model simulations were therefore based on existing parameter sets transferred from lined steel trunk mains. Prior to any maintenance work being undertaken, a controlled flow trial (3) was conducted on an upstream pipe section where the flow could be isolated from supply. This enabled empirical calibration (4) of the PODDS model to this cast iron network and verification of the initial predictive and flow conditioning modelling. With intensive monitoring, this trial also collected valuable additional operational (5) data. This included the detection of pressure transients, highlighting a possibility of contaminant ingress and increased risk of asset failure (LeChevalier et al. 2003; Collins et al. 2012). After six months a second flow trial was conducted to investigate material layer regeneration (6) and the rate at which it occurs within this system. This knowledge could then be used to manage both short-term operations where flow increases may be required, such as demand changes or resilience planning, and safeguard long-term water quality. Additional monitoring of particle sizes during the mobilisation phase was conducted to provide supporting information.

SITE DETAILS AND PREDICTIVE PODDS MODELLING

Site details

The trunk main network investigated is centrally located in the UK and comprises just over 5 km of two parallel mains, gravity fed from a reservoir (Figure 2). One is 18″ (460 mm), the other 12″ (305 mm) in diameter; both are recorded as cast iron (CI). A pumping station supplies the reservoir via a 590 m length of 21″ (530 mm) diameter CI main. The borehole supplied raw water output is 60 l/s with a further 20 l/s available from an additional borehole. A manganese removal plant at the site is capable of treating 80 l/s. The variable speed high lift pumps normally pump treated water at the rate of 80 l/s to the reservoir, in order to maintain equilibrium within the suction tank.

The water company has an undertaking in place with the Drinking Water Inspectorate (DWI – a regulatory body that provides independent scrutiny of water company activities for supplying safe drinking water to consumers in England and Wales (DWI 2000)) to reduce the known risk of discolouration in the mains. As part of this, solutions were considered that would reduce risk, minimise customer interruptions and be cost-effective.

Modelling discolouration risk

A calibrated hydraulic model (built in 2010 and validated by the water company in 2011) was converted to an Epanet format for PODDS modelling purposes (Figure 3). Darcy-Weisbach pipe roughnesses values were predominately 15 mm in the 21″ and 18″ and 10 mm in the 12″ Accuracy of roughness values are important for shear stress calculations that are used in the force balance between the cohesive properties of the material layers and the imposed hydraulics that can lead to material mobilisation.

An essential part of assessing potential discolouration risk is an appreciation of the current conditioned state. Figure 4 shows a week's measured flows from within the system from 2011 for the 18″ and 12″ pipes against the hydraulic model simulation. For PODDS style analysis peak daily flows are important as these set the pipe conditioned status, effectively the flow at (or below) which no material is mobilised. These data indicate that the hydraulic model is an acceptable representation of the system for peak daily flows.

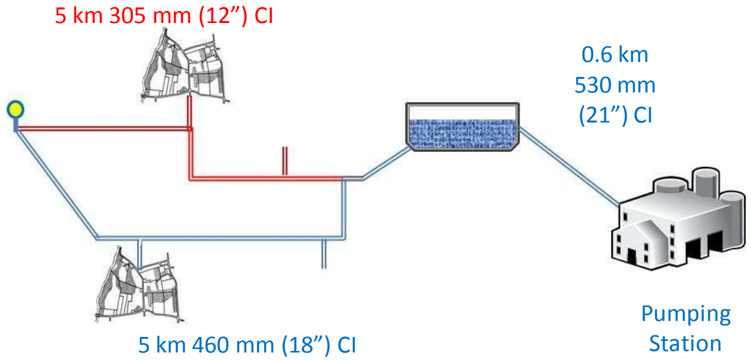


Figure 2 | Network schematic.

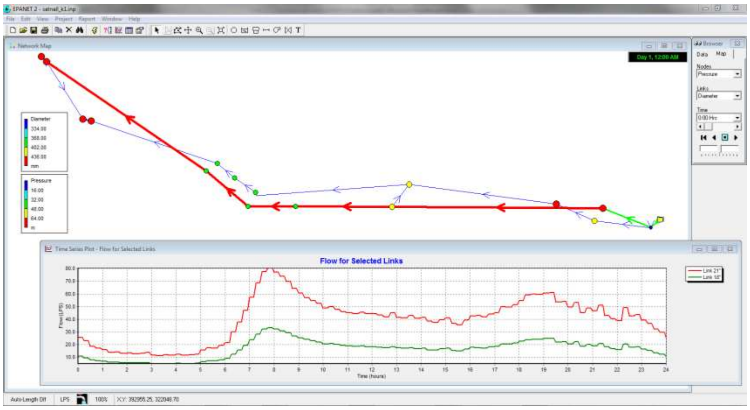


Figure 3 | Epanet hydraulic model with 24 hour flow profiles in 21″ (higher flow) and 18″ mains.

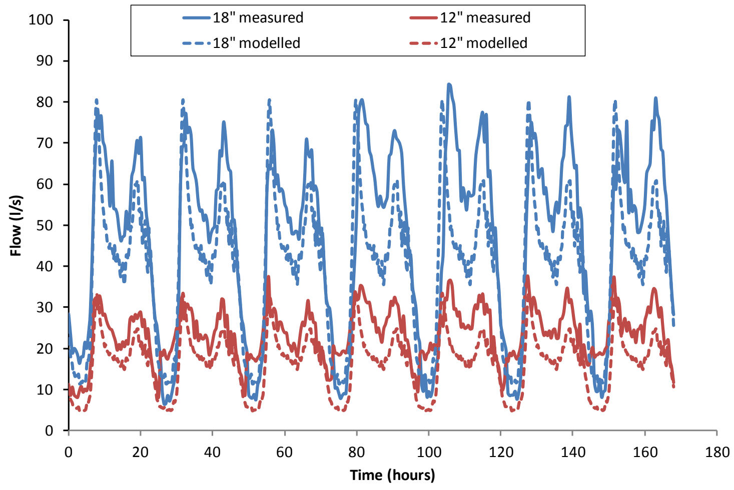


Figure 4 | Measure and modelled flows, 18″ (higher flow) and 12″ trunk mains.

For accurate discolouration modelling, calibrated PODDS parameters are required. Figure 1 represents the PODDS model that is coded into Epanet 2.00.07bTB2 (2001). Empirical calibration has been achieved extensively for small diameter pipes (≤6″ or 150 mm) within distribution systems (Boxall & Saul 2005; Husband & Boxall 2010), and in a small number of trunk main systems (Boxall & Prince 2006; Husband et al. 2010). This is typically achieved by elevating flows above the conditioned or peak daily maximum value, measuring the turbidity response and fitting the model to these data. It has also been demonstrated (again primarily for smaller diameter pipes) that for pipes of similar properties and construction material (bulk water/pipe boundary surface) these parameters are transferable (Husband & Boxall 2010). No previous calibration data however existed for CI trunk mains and no historic site-specific turbidity data were available. Turbidity predictions were therefore calculated based on professional judgement of transferred parameters from previous non-CI sites. Due to confidentiality agreements actual parameter values cannot be published. For the report two parameter sets were used. The first (1) was derived from trials on a 700 mm lined steel main. The second (2) was based on a cement-lined ductile iron main (440 mm), that due to the iron flocculation process used at the treatment works, was considered to be lined by iron particulates so possibly emulating CI pipe behaviour. To model mobilisation, three parameters are required.

For the results presented, parameter k (gradient describing relationship between discolouration potential and shear stress) was constant, P (erosion coefficient) had a hundred-fold difference while n (exponential) a three-fold difference. All the model simulations assume that material layers are initially fully developed and in equilibrium with the normal daily peak shear stress.

With PODDS parameters selected and initial layer strength conditions set, a discolouration response can be simulated by adding additional demand to the model. Hydraulic analysis by the company indicated that in response to a burst at the lowest elevation, a potential 55 l/s flow increase above demand might be observed in this system. This value was applied as an additional demand at the terminal node to investigate the response. It should be noted that time of burst and actual location may influence the turbidity response. This can be rapidly investigated using the model, but is not considered here. Results shown are for a burst occurring at midnight and continuing for 24 hours in addition to the typical daily demand. Model results using the two parameter sets are shown in Figures 5 and 6. The simulations show propagation of the turbidity response from mid-distance down the 18″ and 12″ (equivalent responses attaining maximum turbidity at around 8:00 am, correlating with daily peak customer demand) and at the terminal node (maximum turbidity around 9:30 am) where the pipes re-join. The results indicate that in the event of a 55 l/s burst, a customer impacting discolouration incident would occur. This supports the identified discolouration risk posed by these pipes. It should be noted that these simulations are worst case scenario as it is assumed material layers are fully developed and in equilibrium with the peak daily hydraulic forces. The results also indicate that the primary source of material mobilised is in the first section of the main prior to any system take-offs. This is as expected because daily flows here are greatest, so the additional demand (equal across all pipes) generates the greatest increase in headloss, and therefore increase in material mobilising shear stress. Between the parameter sets there is a difference in the magnitude of turbidity predicted. Set (1) is the more sensitive, producing twice as much turbidity at 19 NTU peak, as opposed to 10 NTU peak for parameter set (2). However the shape, timings and duration of the turbidity responses is similar indicating that both sets are independently viable as a management tool, although the combination of the two provides a potential range. With the simplicity of the hydraulic model required, simulations require only a fraction of a second run-time, so multiple predictions are straightforward to achieve.

Modelling for flow conditioning

An operational limit of 1 NTU has typically been a target selected in the UK for planning PODDS style conditioning strategies that use controlled flow events to mobilise material. This is consistent with regulations for water leaving water treatment works and conservatively below the 4 NTU limit for distribution networks. Modelling was therefore undertaken to identify the hydraulic increases that could be made but limit turbidity response below 1 NTU. Results of this modelling suggest that flow increases had to be less than 4 l/s using the more sensitive parameter set (1). Controlling flows at this level for a temporally varying demand pattern and main of this size are potentially unfeasible and high risk. This could rule out a PODDS strategy of incrementally raising flows to remove discolouration material. Results from parameter set (2) however require a 16 l/s increase to achieve 1 NTU, suggesting a PODDS flow conditioning approach is feasible.

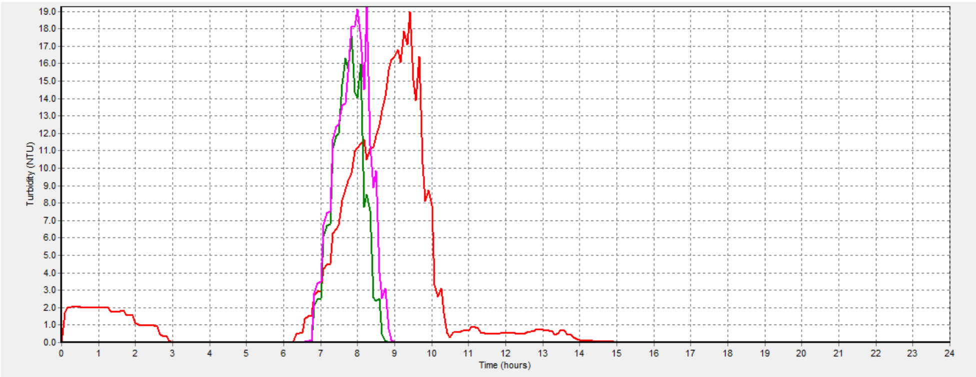


Figure 5 | Burst scenario; PODDS parameters (1) with 55 l/s demand increase.

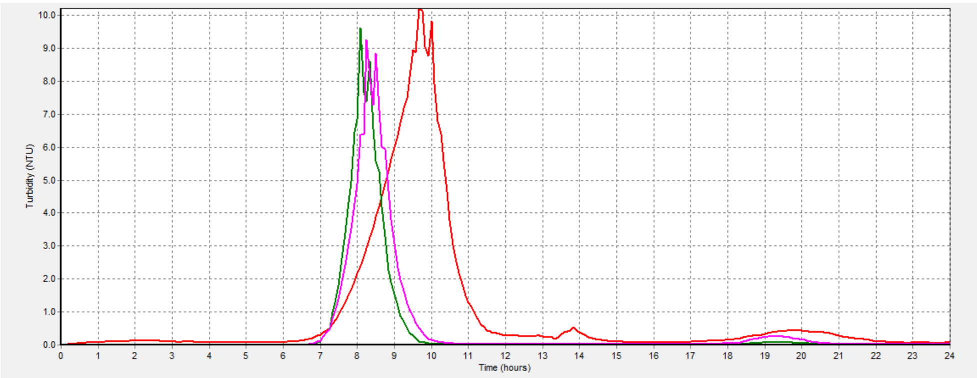


Figure 6 | Burst scenario; PODDS parameters (2) with 55 l/s demand increase.

Given the degree of uncertainty in these predictions, it was concluded that field measurements were required to determine the most appropriate parameter set that may be used to describe the mobilisation characteristics for this CI trunk main system. The 21″ pumped trunk main upstream of the reservoir was selected for these flow trials. This was due to the relatively short pipe length, hence rapid turnover, the flow control available and critically the ability to isolate the volume of water transmitted within a reservoir chamber prior to discharge, rather than it entering supply. Original trial dates were postponed when issues were encountered with the pumps and leaks in the main. The trial went ahead in late 2012. Below is a description of the proposed work from the water company Mains Cleaning Risk & Contingency Assessment:

> As part of an undertaking given to the DWI, it is proposed to clean the 21″ diameter cast iron pumping main in order to remove an accumulation of discolouration material (iron and manganese deposits)... using PODDS (Prediction of Discolouration in Distribution Systems) methodology which has been developed by Sheffield University and UK water companies.
>
> The methodology involves increasing the velocity of water in a pipeline in order to apply increased shear force on the pipe wall to dislodge accumulations of particulate material from the internal walls of the pipe, and remove the discolouration material using the flow through the pipe, without the need to use swabs or to cut into the existing pipeline. The pipe is then classified as being conditioned and therefore safe to operate up to that flow rate for a period of time. To keep the main conditioned it is necessary to repeat the process on a regular basis, the frequency of which is determined by the return period of the accumulation of discolouration material. In order to achieve the required turnover at the increased flow rate, the PODDS cleaning process is expected to take approximately 6 hours to complete for this scheme with a further 2 hours for the associated valving operations.

The waste water (high iron and manganese) will be deposited into the previously isolated [reservoir] Compartment. Although none of the waste water is expected to enter Distribution system, it should be noted that [this zone] ranks as being the worst in respect of discolouration issues. Turbidity readings shall be monitored at various locations before, during and after the cleaning process.

FIELD TRIALS

Prior to the planned flow trial, turbidity recordings were made at the reservoir inlet (high point of the pumping main) and reservoir outlet, using ATi 15/76 turbidity monitors modified for field work use and extensively trialled by the PODDS team. Figure 7 shows the flow logged at 15 minute intervals and the pumping main turbidity logged at 20 seconds. Spikes in flow and turbidity can be observed that correlate with pump switching regimes. During periods of no flow in the main (and hence no flow through the turbidity monitors) these spikes are associated with the probe and the stagnant sample within it and are not characteristic of the main. When the pumps are re-started it can be seen that material mobilisation patterns exist, demonstrating a low-level flux of material through this main. On the weekend of the 13th and 14th October, the turbidity response is greater than previously observed, up to 0.2 NTU. This correlates with marginally higher flows. Although this level of turbidity is not an issue, it does highlight the discolouration sensitivity associated with the hydraulic conditions within this main.

Following the pre-trial monitoring where the pump switching regime was observed as influencing measured turbidity, and combined with the knowledge that this main had previously experienced pump issues and mains leaks, the PODDS group decided to install additional pressure transient monitoring during the flow trial. For this a 100 Hz logger developed at the University of Sheffield for transient evaluation was sited with the turbidity monitor at the end of the pumping main. With flow logging at 15 minute intervals insufficient to capture the necessary information during the trial, the pressure record would also act as an indicator of when the pumping output, and hence flows, were changed.

From Figure 7 it can be seen that the typical daily flow just exceeded 80 l/s, excluding the spikes observed during pump start-up. With the pump at maximum output, a flow of 160 l/s was anticipated. Due to suction tank size and in-flow rates, it was calculated that for flow at 160 l/s, trial duration would be a maximum of 20 minutes before the suction tank would run dry.With the objective to condition the main to as high a shear force as possible, the trial was planned to run at the maximum pump rate permissible. Due to the short operational temporal it was planned to repeat this higher flow (shear stress) a number of times to confirm the main was capable of operating at this level with no discolouration risk, i.e., conditioned to this new, higher flow.

Figure 8 shows the measured pressure during the trial and the five repeated flow increases achieved. From the plot it can also be observed that for each time the pump is turned on/off a transient is produced. This has potential implications both on asset condition and hence service life (cause of leaks/burst?) and negative transients (in this case repeatedly down to −5 m) that may cause contaminant ingress. An example of the transients produced is highlighted in Figure 8 that shows the effect on pressure of reducing the pumped flow from 150 l/s to zero in three steps over a minute. It can be noted that it is the final shut down that appears to create the transient of ±5 m. Although negative transients were observed, it should be remembered that this system was not operated in a typical manner for this trial and the trunk main was isolated from supply. An indication of the impact of this transient behaviour on asset performance was observed during the trial when the pump tripped out during the third flow step (11:15). In addition to the negative pressures with associated risk of contaminant ingress, the pipe and surrounding ground was visibly observed to vibrate. However, with no flow through the turbidity probe flow cells during this negative pressure period and air being drawn in, turbidity readings are invalid. The effect of transients on possible discolouration disturbance cannot therefore be analysed.

Turbidity data recorded at the end of the pumped main during the trial, together with the flow record are shown in Figure 9. On initial inspection this appears to be dominated by three spikes at 9:43, 11:13 and 12:49. These all however correlate with when the pump was switched off and represent air/water mixture being drawn backwards through the turbidity probe due to the negative pressures. The turbidity values are considered invalid for these periods. Following this air/water mixture entering, the turbidity probe required a number of minutes before the response settled and valid data were obtained. The highlighted section in Figure 9 identifies the periods of the turbidity record that are valid and of particular use for PODDS calibration.

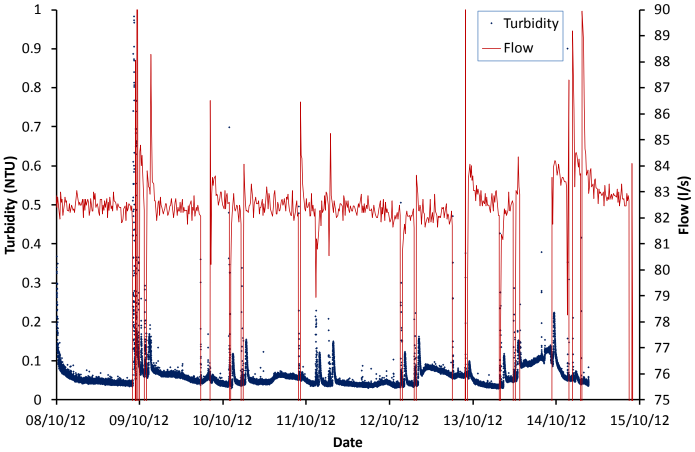


Figure 7 | 21″ CI trunk main pre-trial turbidity and flow, October 2012.

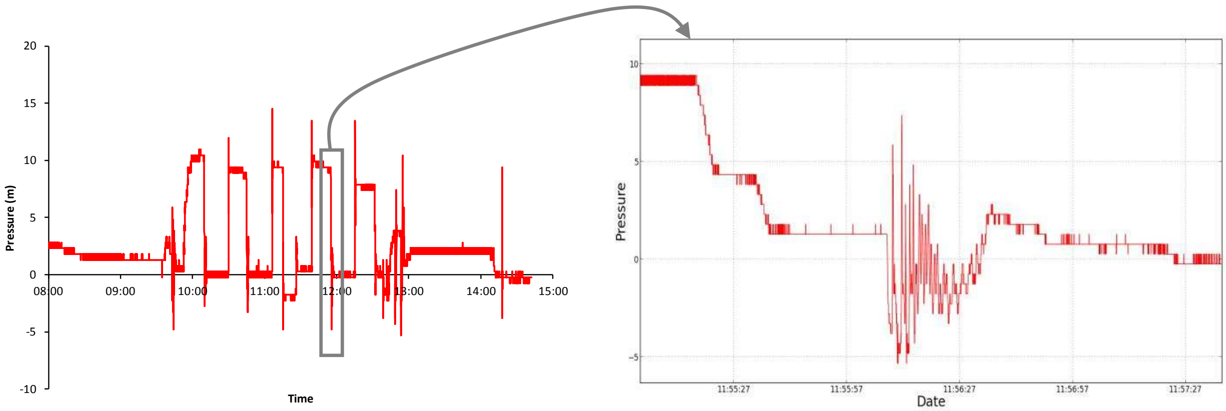


Figure 8 | Flow trial pressure record and highlighted section showing pressure transient when pump switched off.

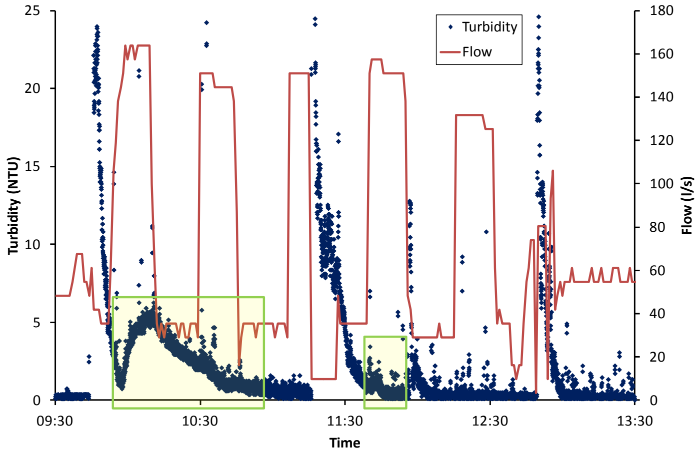


Figure 9 | Turbidity response attributable to material mobilisation from 21″ CI pumping main.

From Figure 9 it can be observed that no further significant turbidity was observed during the repeated phases of the trial. Therefore the first flow increase step effectively removed all material up to this shear stress value and attained 6 NTU in the process. This lack of material mobilisation following the first step demonstrates the trial was successful in its primary objectives of removing material (in situ cleaning) and conditioning the main to cope with a demand of 160 l/s should this be required.

Following the trial, turbidity data were again collected from the 21″ CI pumping main supplying the reservoir and reservoir outlet. Although pre- and post-data are not directly comparable because flow rates/flow changes/duration are different they are shown plotted together in Figure 10. It can be observed that the trial has little observable impact on the daily flux of material. From this it can be suggested that this movement of material is due to material originating upstream of this main so not affected by the cleaning, and/or due to processes including corrosion and precipitation that occur on a daily basis.

PODDS MODEL CALIBRATION

Figure 11 shows three sets of results from running PODDS model simulations for the flow events occurring during the field trial. Two simulations were made using the parameter sets from the predictive modelling, as shown in Figures 5 and 6. A calibrated simulation result is also shown. It is apparent that the calibrated simulation result falls between the two predicted sets, although there is only a marginal difference between the calibrated and parameter set (2). This result validates the applicability of the PODDS theory of discolouration in trunk mains and provides confidence in this modelling approach as an operational management tool.

The objective of the field trials had been to investigate if controlled in situ incremental flow increases could be used to condition and in the process clean, CI trunk mains as a maintenance option. This trial, in successfully completing its cleaning and conditioning objectives in line with the PODDS planned approach, has also allowed successful PODDS model calibration of hitherto untested CI trunk mains. The results indicate that these mains may be accurately modelled and, of operational significance, that the parameters required to achieve a match to measured turbidity are close to those of set (2). It can therefore be proposed that this system may successfully respond to PODDS style maintenance strategies. As a guideline it is proposed that a step increase of 1 Mld (11.6 l/s) above typical flows or conditioned state, is a realistic and practical value that should safeguard water quality within a 1 NTU target value (maintaining a safety of error margin below the modelled 16 l/s that produced a 1 NTU response) in these pipes.

SECOND TRIAL INVESTIGATING LAYER REGENERATION AND TESTING OPERATIONAL GUIDELINES

Building on the success of the initial trial demonstrating the potential of using flow increments as a short-term measure to provide mains resilience, and the subsequent PODDS model validation, a second trial was planned. In conjunction with the PODDS understanding that material layer development is a continuous and ubiquitous process, this trial was to investigate the rate of asset deterioration, or more specifically the rate at which material layers developed. The results from this would inform the interval between maintenance interventions and allow long-term maintenance costs to be determined and appropriate operational strategies to be put into place. In addition, future changes to upstream processes, such as to the manganese removal plant at this site, could be evaluated in terms of reduced asset deterioration rate with respect to water quality by further repeating such operations after implementing such changes.

The initial trial had indicated a 1 Ml/d (11.6 l/s) increase as a realistic and practical flow step. After six months a trial was therefore planned with incremental flow increases of this magnitude. In addition to turbidity monitoring at the reservoir inlet, an ATI C10/77 particle count sensor was connected to collect additional data. This would primarily examine for potential changes in mobilised material sizes during the trial and investigate the particulate claims inherent in the PODDS concept.

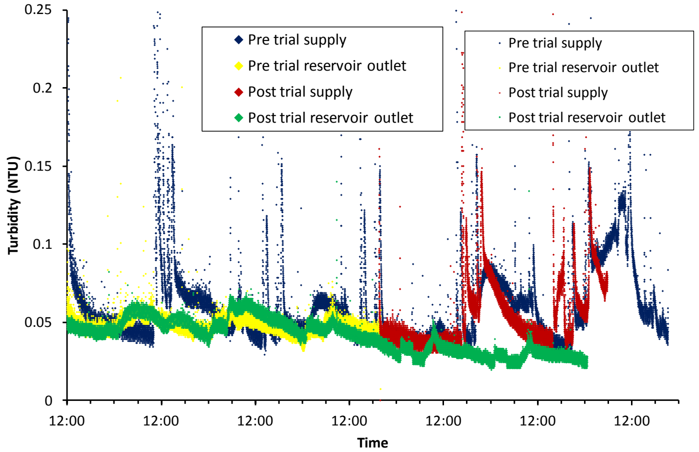


Figure 10 | Pre- and post-turbidity monitoring of 21″ CI pumping main and reservoir outlet.

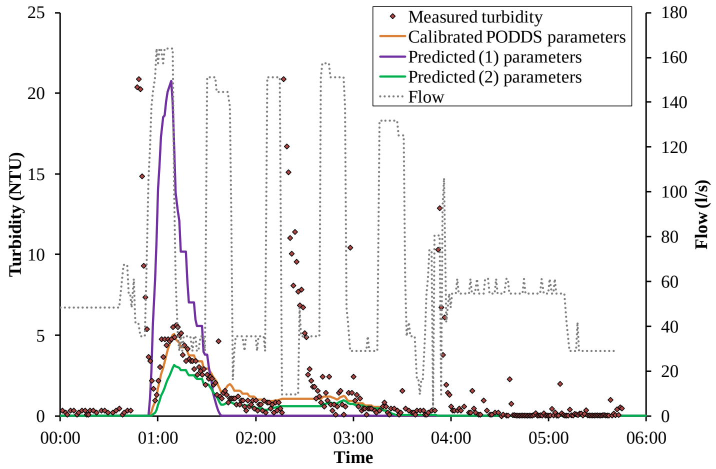


Figure 11 | PODDS model turbidity simulations for modified parameter sets.

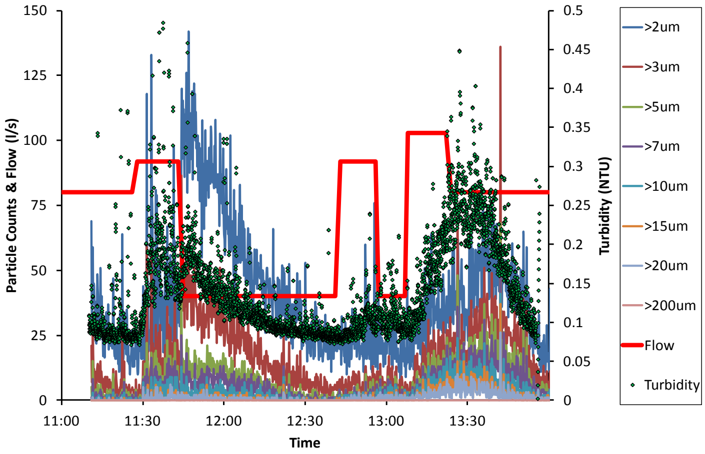


Figure 12 | Six month regeneration trial: flow, turbidity and particle count data.

From the lessons learned during the first trial, it was planned that between flow increases the pumping rate was to be reduced, not stopped. This would allow a continuous viable turbidity response by preventing air ingress to the probe cell due to negative pressures, yet facilitate sufficient filling of the pump suction tank between flow increments. As in the first trial, it was planned for the initial flow step to be repeated. This would confirm if the duration of the elevated flows were sufficient to fully condition the main. That is, no further material being eroded if flows are elevated to this level, or in operational terms, a safe working flow rate with no risk of discolouration. The trial flow rate (obtained by manual recording of pump house flow meter), turbidity and particle count data from this trial are shown in Figure 12.

From Figure 12 the three flow steps can be observed, the first two at 92 l/s (12 l/s above the typical 80 l/s) and the third/final step at 103 l/s. For each new flow increase there is a distinct turbidity response, peaking at nearly 0.3 NTU from the background level of 0.1 NTU. For the second flow step, a repeat of the first, there is only a small effectively negligible response (0.02 NTU). From this it can be stated, as previously recorded in the first trial for this 590 m main, a 15 minute flow increase is sufficient for conditioning purposes.

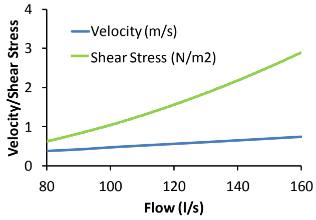
The PODDS model always predicts that for equal increases in shear stress, equal turbidity responses will be observed. Table 1 summarises the hydraulic data taken from the Epanet hydraulic model for this trial. From this it be seen that there was a slightly greater increase in excess shear stress due to the second flow increase, 0.215 N/m^2 compared to the first, 0.207

N/m^2. Visual inspection also shows a slightly greater turbidity response from the second shear stress increase, supporting the PODDS concept. Of further significance is that the results also indicate the regeneration of material responsible for discolouration occurs equally across the shear stress steps. Some degree of speculation may remain about effective shear stress increases above typical because although the pumping output settles at a relatively steady state (for this main 80 l/s), from Figure 7 on start-up there is typically a flow spike. It could be suggested that this pump-driven initial flow transient leads to some form of the weakest layer degradation (in PODDS analogy this would be the top, or least consolidated layer). This may in turn mean less material available for mobilisation, hence the lower observed turbidity in the first step, and may also cause the initially noisier turbidity response seen during the first flow increase (Figure 12).

The PODDS concept as applied to this trunk main is reinforced by turbidity modelling of this second trial. All previous PODDS model simulations had assumed fully developed material layers, or maximum potential discolouration risk. In the six month period between trials full layer development was not anticipated. However, for modelling to be viable, equal regeneration of material across all shear strengths would be required. This is demonstrated in Figure 13. To achieve this visually acceptable model fit to measured data, the PODDS model parameters remained the same as previously calibrated (Figure 11) with the exception of the eroding coefficient (P) being a tenth less. This highlights a shortcoming of the PODDS model as described here. Although shown capable of predicting turbidity response to changing hydraulics, it does not have the capacity to track regeneration occurring simultaneously with multiple layer strengths. A new version of the PODDS model, simulating both the continual erosion and regeneration of discolouration material has been coded to address this and is undergoing trials (Furnass et al. 2012). With the 'full risk' calibrated parameters, the peak predicted turbidity response is 1 NTU. If linear material regeneration is assumed (Husband et al. 2008; Husband & Boxall 2011), with a 0.2 NTU response after six months, full regeneration would be anticipated in just over two years. This appears to be a short period of time, but can be considered possible due to the likely addition of material from corrosion of the cast iron trunk main. Furthermore, this matches the findings from deterioration trials in cast iron distribution pipes (Husband & Boxall 2011). Of note to network operators is the plot of flow against velocity and shear stress in Table 1. This highlights that as flow (velocity) increases, so does the change in shear stress. That is, at higher velocities more material is likely to be mobilised for equal step increases in velocity.

Table 1 | Six month regeneration trial hydraulic values (including plots of flow vs. velocity/shear stress)

Flow (l/s)	**Velocity (m/s)**	**Headloss (m)**	**τ (N/m^2)**	**τ_{excess} (N/m^2)**
80	0.37	0.5006	0.644	–
92	0.42	0.6611	0.851	0.207
103	0.48	0.8277	1.066	0.215
160*	0.74	1.9905	2.88	-



*Flow achieved at first trial.

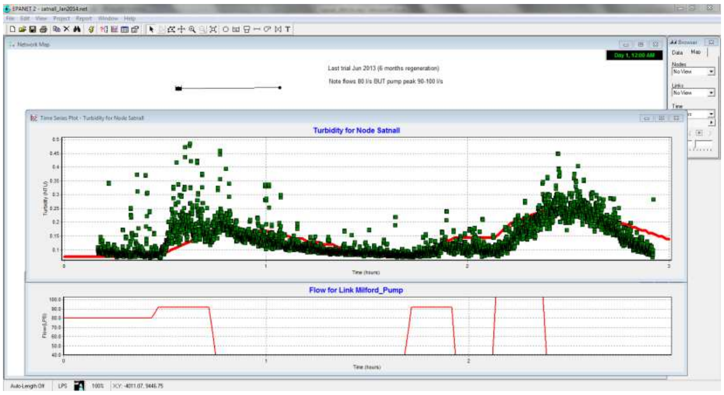


Figure 13 | Six month regeneration trial PODDS Epanet modelling results (upper plot shows turbidity with squares measured data and continuous line modelled result, the lower plot shows model flow demand).

In addition to the turbidity data, synchronised particle counting was undertaken. The trends observed in Figure 12 correlate with the turbidity data. With only 2.8% of the counts from particles >20 µm, this supports the particulate approach of the PODDS model, with particle behaviour not dominated by gravitational self-weight forces. With the majority of particles less than 20 µm, settling or sedimentation does not occur unless quiescent conditions exist for extended periods (Boxall et al. 2001; Vreeburg et al. 2008). This therefore indicates some form of force must be present to retain the particles that enter the boundary zone (van Thienen et al. 2011). This information helps demonstrates the PODDS concept is valid to larger diameter trunk mains, as well as the previously verified smaller diameter distribution pipes (Husband & Boxall 2010). A feature of the particle count data is that following the first flow step when the flow is decreased from 92 to 40 l/s, there is a jump in recorded numbers of particles <5 µm. Reasons for the anomaly have not been identified.

CONCLUSIONS

Flow trials were undertaken on a 21″ cast iron pumped trunk main that were successful in showing removal of accumulated material and resilience conditioning to receive operational flows of up to 160 l/s. By incorporating repeat flow increases, the conditioned status was confirmed. Intensive monitoring of the trial allowed accurate PODDS model calibration and this has indicated that PODDS style maintenance strategies may be applied to this network. Pre- and post-monitoring indicated a small daily flux of material along this main, with the cleaning having no observable effect on this. A further trial has shown material regeneration occurs across all shear strengths and for this main indicates maximum risk could return in as little as just over two years. The results from these trials validate the PODDS concept in cast iron trunk mains. As a consequence, it allows for effective and justifiable pro-active short- and long-term maintenance plans to be implemented, safeguarding water quality and mitigating for discolouration risk.

In summary:

- The trial achieved objectives by removing discolouration material and increasing resilience by conditioning the main to receive operational flows of 160 l/s.
- Pre- and post-monitoring showed a low level (0.05 NTU) daily flux of material that can be associated with asset deterioration as material layers responsible for discolouration develop.
- Material layer regeneration was shown to occur simultaneously across all shear strengths.

- Full layer regeneration (maximum discolouration risk) may take two years in this CI trunk main.
- PODDS concept and modelling, including parameter transfer, are validated for CI trunk mains and confidence shown that PODDS strategies can be a practical and effective network management tool.

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