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Modelling and flow conditioning to manage discolouration in trunk mains

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Abstract

This paper presents predictive discolouration modelling and subsequent field trial results 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 is also 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 is also presented, a possible cause of contaminant ingress and asset failure.

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Keywords: Discolouration; flow conditioning; PODDS; maintenance; mobilisation; regeneration

1. 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 for fear of consequences. In particular activities that result in increased flows are avoided, demonstrating the inherent understanding that discolouration is often hydraulically driven (Husband and Boxall, 2011). When increased flow through a trunk main is necessary (such as due to

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increased demand or source water changes), or unacceptable discolouration risk is 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 and 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 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. Firstly, material responsible for causing discolouration is particulate in nature, typically around 10 μm (Gauthier et al., 2001, Seth et al., 2004), so unless systems exhibit very low flows for prolonged periods, gravitational sedimentation is not a dominant factor describing material behaviour (Boxall et al., 2001). Secondly that 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 achieved. Other sources of material, such as resulting from contaminant ingress or the presence of corroding iron pipes and fittings, 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 through consideration of a force balance at the boundary between cohesive material layers and the shear stress forces generated by the system hydraulics (Boxall et al., 2001). The model has been widely verified to successfully simulate discolouration responses in distribution networks (Boxall and 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 supply water source (Husband and Boxall, 2010).

This paper details how the PODDS model and concept was applied to manage a cast iron trunk main system in the UK. The work is described in five stages. The PODDS model was initially used to predict the *discolouration risk* should an extreme flow event occur, such as likely following a burst. *Flow conditioning* modelling was then undertaken to determine flow increase steps that would be sufficient to mobilise material layers. This would effectively clean the pipe, but in a managed fashion so that bulk water quality would remain to acceptable standards throughout the process. The water company could then use this information to justify regulatory maintenance plans. Of note is that no relevant turbidity data or model parameter values previously existed for 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* was then conducted on an upstream pipe section where the flow could be isolated from supply. This enabled *empirical calibration* of the PODDS model to this network and verification of the initial predictive and flow conditioning modelling. With intensive monitoring, this trial also collected valuable additional *operational* 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).

2. Site Details and Predictive PODDS Modelling

2.1 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. 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 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) to reduce the risk of discolouration in the mains. As part of this, solutions were considered that would reduce risk, minimise customer interruptions and be cost effective.

2.2 Modelling discolouration risk

A calibrated hydraulic model (built in 2010 and validated by the water company in 2011) was converted to an Epanet hydraulic simulation for PODDS modelling purposes. 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 essential for shear stress calculations that are used to determine the forces occurring and causing mobilisation of cohesive material. Figure 1 shows a week's measured flows from within the system from 2011 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. This data indicates that the hydraulic model is an acceptable representation of the system for peak daily flows.

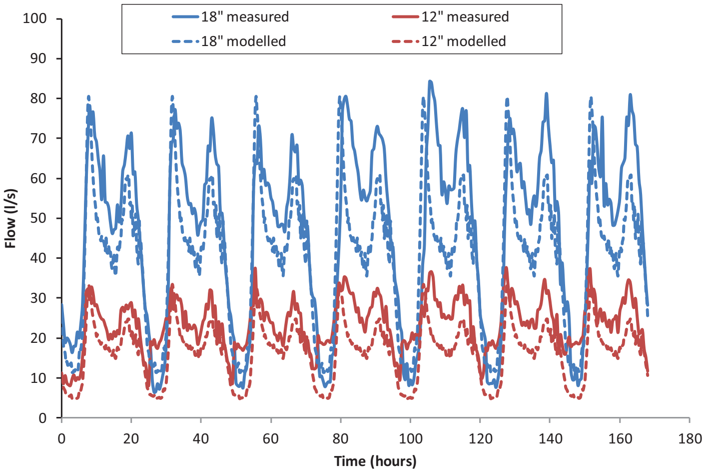
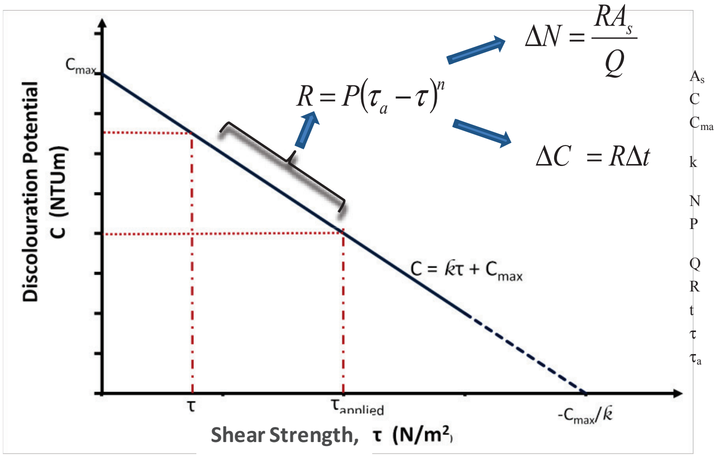


Figure 1. Measure and modelled flows, 18" and 12" trunk mains

For accurate discolouration modelling, calibrated PODDS parameters are required. Figure 2 pictorially 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 150mm) within distribution systems, and in a small number of trunk main systems (Boxall and Prince, 2006). This is typically achieved by elevating flows above the conditioned or peak daily maximum value, measuring the turbidity response and fitting the model to this 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 and Boxall, 2010). No previous calibration data however existed for CI trunk mains and no historic site specific turbidity data was 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, 3 parameters are required. For the results presented parameter k was constant, P had a hundred fold difference whilst n a threefold difference. All the model simulations assume that material layers are initially fully developed and in equilibrium with the normal daily peak shear stress.



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 2. The PODDS Model

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 is noted that time of burst and actual location may influence the turbidity response. These can be rapidly investigated using the model but are not considered here. Results shown are for a burst occurring at midnight and continuing for 24 hours. Model results using the two parameter sets are shown in Figure 3 and Figure 4. The simulations show propagation of the turbidity response from mid-distance down the 18" (green line), 12" (purple line) and at the terminal node (red line) where the pipes join.

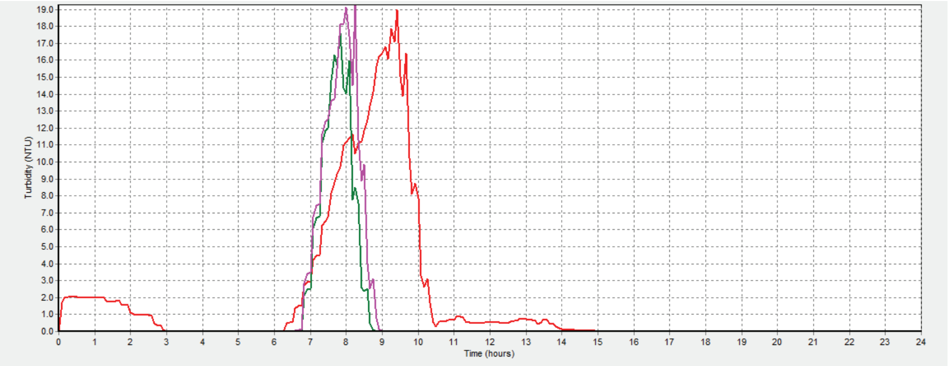


Figure 3. Burst scenario; PODDS parameters (1) with 55 l/s demand increase

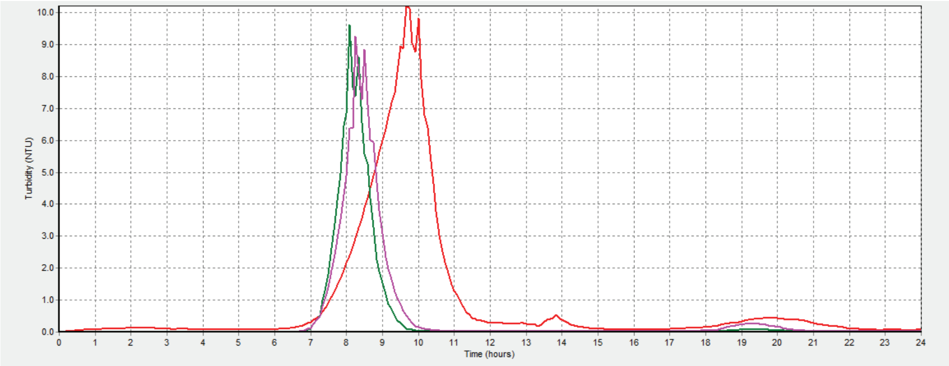


Figure 4. Burst scenario; PODDS parameters (2) with 55 l/s demand increase

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 generates the highest headloss, and therefore increase in material mobilising shear stress. Between the parameter sets there is a noticeable difference in the magnitude of turbidity predicted. Set (1) is the more sensitive, producing twice as much turbidity; 19 NTU as opposed to 10 NTU for parameter set (2). However the shape and duration of the turbidity responses is similar.

2.3 Modelling for flow conditioning

For PODDS style conditioning strategies that use controlled flow events to mobilise material, an operational limit of 1 NTU has typically been a target selected in the UK. 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. 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 late in 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."

3. 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 5 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.

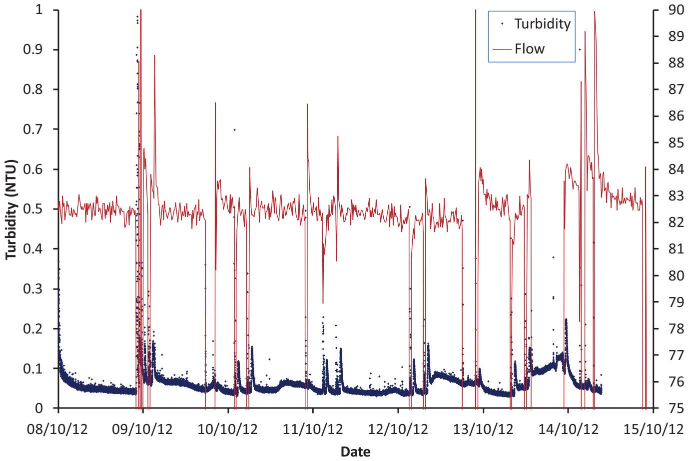


Figure 5. 21" CI trunk main pre-trial turbidity (blue dots)and flow (red line), October 2012

Following the pre-trial monitoring where the pump switching regime was observed, and with the knowledge that this main had experienced pump issues and mains leaks, the PODDS group decided to install additional pressure transient monitoring during the actual 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 5 it can be seen that the normal daily typical peak flow was approximately 85 l/s. 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 last about 20 minutes. 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. This would then be repeated a number of times to confirm the main was conditioned to this new, higher flow.

Figure 6 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 transient produced is highlighted in Figure 6 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, turbidity readings are invalid. The effect of transients on possible discolouration disturbance cannot therefore be analysed.

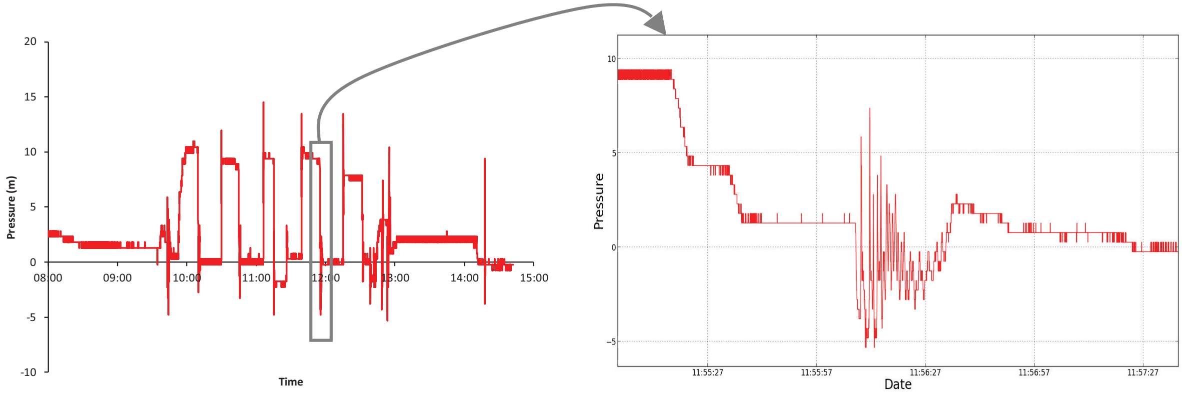


Figure 6. Flow trial pressure record and highlighted section showing pressure transient when pump switched off

Turbidity data recorded at the end of the pumped main during the trial, together with the flow record is shown in Figure 7. 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 was obtained. The highlighted section in Figure 7 identifies the periods of the turbidity record that are valid and of particular use for PODDS calibration. From this it can be observed that the first phase of flow increases resulted in nearly all material being mobilised (6 NTU) as no further significant mobilisation occurred during the repeated phases of the trial. This lack of material mobilisation following the first step demonstrates the trial was successful in its primary objective of removing material (in-situ cleaning) and conditioning the main to cope with a demand of 160 l/s should this be required.

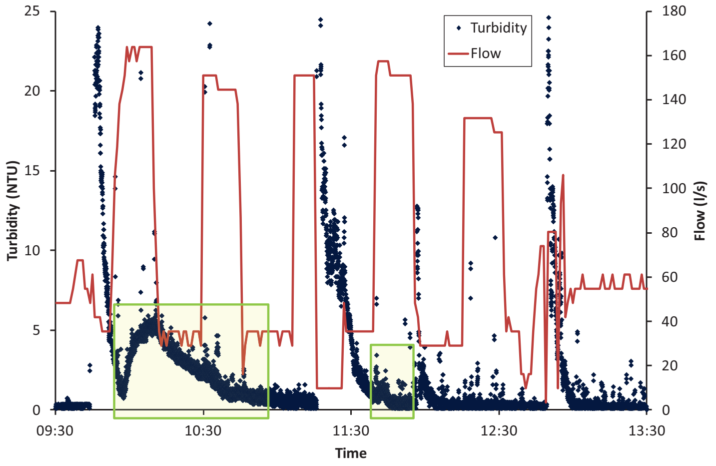


Figure 7. Turbidity response attributable to material mobilisation from 21" CI pumping main

Following the trial, turbidity data was again collected from the 21" CI pumping main supplying the reservoir and reservoir outlet. Although pre and post data is not directly comparable because flow rates/flow changes/duration are different they are shown plotted together in Figure 8. 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.

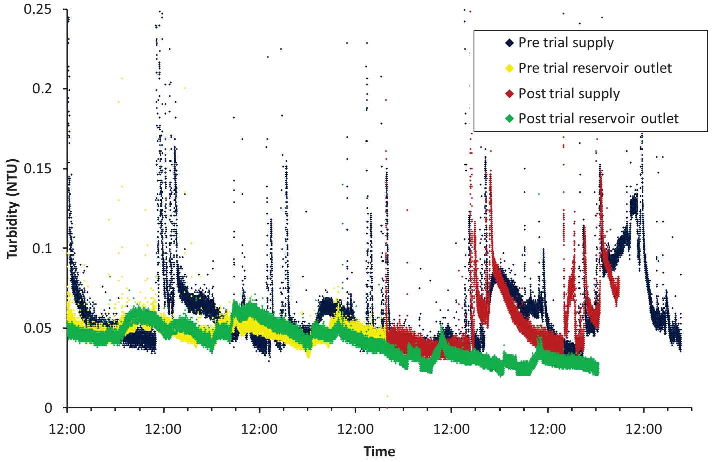


Figure 8. Pre and post turbidity monitoring of 21" CI pumping main and reservoir outlet

4. PODDS Model Calibration

Figure 9 shows 3 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 Figure 3 and Figure 4. 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 trails 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 an approximate guideline it can be 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.

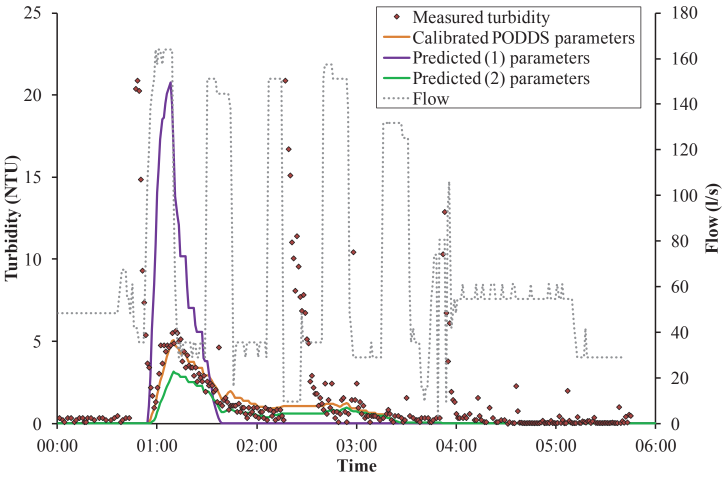


Figure 9. PODDS model turbidity simulations for modified parameter sets

5. Conclusions

Flow trials were undertaken on a 21" CI pumped main that has successfully been shown to remove accumulated material and condition the main 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. It is recommended that further trials be conducted in the near future to assess the rate of asset deterioration as material layers regenerate. This will allow effective and justifiable long term maintenance plans, in addition to the validated flow conditioning strategies, to be implemented safeguarding the water quality and mitigating for discolouration risk.

Summary:

- The trial successfully achieved planned objectives by removing discolouration material and 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.
- PODDS theory and modelling, including parameter transfer, validated for CI trunk mains and confidence shown that it can be used as a practical and effective management tool.

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