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Operational Management of Trunk Main Discolouration Risk.

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Despite significant on-going investment, water companies continue to receive an unacceptable number of discolouration related customer contacts. In this paper, data from intensive distribution system turbidity monitoring and cluster analysis of discolouration customer contacts indicate that a significant proportion of these contacts are due to material mobilising from the trunk main system, and operational flow increases are shown to have a higher discolouration risk than burst incidents. A trunk main discolouration incident highlighting this risk is discussed, demonstrating the need for pro-active trunk main risk assessments. To identify the source of the material event flow rates were modelled using the PODDS (Prediction Of Discolouration in Distribution Systems) discolouration model. Best practice pro-active management is demonstrated in a case study where the PODDS model is used to implement managed incremental flow changes on a main with known discolouration risk with no discolouration impact to customers and significant cost savings.

Keywords: Discolouration; PODDS; trunk mains; turbidity; Distribution Operation and Maintenance Strategies (DOMS).

Introduction

Discolouration is the largest cause of water quality related customer contacts in the UK water industry (Cook et al 2005). Discolouration as reported by customers is either caused by the presence of fine particles in the water, measured as turbidity, or by true colour (Gauthier et al. 1996; Marshall 2001; Polychronopolous et al. 2003; Ryan et al. 2003). However, flushing experiments carried out by Boxall et al. (2003), Polychronopolous et al. (2003), Prince et al. (2003) and Seth et al. (2003) found very little true colour, but significant turbidity. This indicates that particulate turbidity is typically the cause of discolouration as reported by customers, Vreeburg and Boxall (2007). Flushing trials also report iron and manganese as dominant within discoloured water samples with a strong correlation between their concentration and the turbidity of the water, Gauthier et al. (2001), Mc Coy and Olsen (1986) and Boxall et al. (2003).

Identifying the cause of discolouration customer contacts is important to water companies to enable prioritising of mains cleaning or other risk management operations. Traditionally water companies have directed cleaning activities to smaller diameter pipes at the District Meter Area Level (DMA). This is primarily cost driven as traditional trunk main cleaning methods are invasive, require detailed planning and are therefore complicated and expensive. Recent research however has suggested that trunk mains contribute significantly to discolouration processes. This is both as a reservoir of material that seeds downstream pipes, and if mobilised rapidly, may create a serious widespread discolouration event (Husband et al 2010).

This paper highlights the discolouration risk posed by trunk mains using both micro scale in-line turbidity monitoring for 5 DMAs and macro regional analysis of discolouration customer contacts for a large UK water company. Gathering accurate, reliable data using the former method is an intensive process, whereas the results from the latter method can be achieved using regulatory recorded data. Planning interventions based upon customer contacts however is a re-active approach and doesn't inform the water provider of discolouration potential until an incident occurs.

The need for a pro-active approach is demonstrated in a case study of a major trunk main discolouration event which occurred on a main with no previous discolouration history. In this paper the PODDS (Prediction of Discolouration in Distribution Systems) model, developed by the University of Sheffield, was used to model the discolouration event and hence determine the location where the mobilisation of discolouration material occurred. As a result of this modelling, a flow balancing operational maintenance schedule, is proposed.

Finally a second case study is presented to demonstrate how the PODDS concept and model was applied to manage a significant flow increase in a trunk main of known high discolouration risk. This strategy proved successful with no discolouration contacts and resulted in considerable cost and time savings over traditional invasive cleaning techniques.

Online Turbidity Monitoring

CT-Cense Colour and Turbidity monitors, Censar Technologies (2011), were deployed in 5 District Meter Areas (DMAs) (named A to E in this paper) for a period of up to 3 years. Three to four loggers, depending on DMA size, were installed in each DMA on the service pipe in Manifold Small Meter (MSM) chambers. Loggers were set to measure turbidity at 1 minute intervals and record the average of five readings. This data frequency necessitated a 3 weekly logger download.

Turbidity data was first corrected for gain and offset using calibration data and a secondary offset correction was applied to the data to align with the independent Hach handheld readings taken at logger installation and every download. Over the long deployment period, drift was seen in the recorded turbidities. This was attributed to material depositing on and fouling the optics. This drift effect and corresponding offset instability of up to 0.02 NTU per day caused problems comparing information between different loggers, and reduced confidence in absolute values.

As the CT-Cense loggers used here tended to drift over the long term and be relatively stable over a 24 hour time period, and cleaning the loggers on a daily basis was not practical due to distance travelled and interruptions to customers supply, the standard deviation in turbidity recorded per day was deemed a suitable method to compare turbidity values between loggers since the mean proportion of the equation would take into account the differing amounts of drift, and the RMS from this mean would account for the amplitude in the daily turbidity cycle and spikes from discolouration events Figure 1 shows an example of drifting logger data which has had the standard deviation method applied. It can be seen that drift has been eliminated from the data but the turbidity spikes present in the original data are still apparent in the standard deviation data set. As well as eliminating drift, this method is useful for summarising long term data into a more manageable format.

In conjunction with turbidity data, flow data from the inlet meter to each of the monitored DMAs was collected to indicate hydraulic conditions. Flow data was recorded as 15 minute values. Discolouration customer contacts were also collated for the monitoring DMAs.

Turbidity events were identified manually as abnormal ‘spikes’ in the data where turbidity was seen to rapidly rise above background levels. Recorded turbidity events during the long term monitoring phase of this project indicated that turbidity events can be attributed to a limited number of factors which were used for subsequent turbidity event classification for 5 DMAs shown in Table 1:

- **A Local Event-** A small localised increase in demand; not large enough to affect the inlet flow meter but caused a turbidity response at a single location. This could have been caused, for example, by a small high level consumer, a farm filling water tanks, hydrant use etc,.
- **DMA Demand Increase -** A large increase in demand; recorded by the inlet flow meter and affected a wide area of the DMA, which caused a turbidity response at several monitoring locations. This could have been attributed to a major hydraulic event such as a burst or re-zoning of a DMA.
- **Imported Material**- a turbidity response was recorded at multiple locations which could not be attributed to an increase in flow. A turbidity response was also seen at the inlet to the DMA (if equipment was installed and working),

verifying that this material was imported into the DMA from an event occurring elsewhere in the Water Supply System (WSS).

- **Unknown –** An turbidity event was recorded at one location, but due to logger malfunction no data was available at other locations and no increase in demand was seen at the DMA meter.

This type of discolouration classification is extremely useful to water practitioners as it enables a judgment to be made on the effectiveness of DMA level mains cleaning as opposed to cleaning the upstream trunk mains. For example in DMA C050, all the discolouration events are likely to have originated from within the DMA itself. DMA level cleaning would therefore be beneficial. However in DMA J722, almost 50% of the discolouration events appear to have originated upstream from the DMA inlet. Therefore if DMA level mains cleaning was applied the discolouration customer contacts may only at best be reduced by 50%.

Clustered Discolouration Customer Contact Analysis

Although turbidity monitoring at DMA level is effective for informing targeted cleaning operations, it is relatively labour intensive and time consuming. Therefore a method of analysing routinely collected regulatory data at the regional companywide level is considered. Water Supply Systems (WSS) are groups of DMAs which receive water from a common source through a common trunk main distribution system. Therefore analysing discolouration customer contacts and determining clusters that occur in multiple DMAs in the same WSS at the same time, as opposed to customer contacts occurring in a single DMA, could be a suitable and rapid method for classifying and differentiating Trunk Main or DMA level events (Husband et. al. 2010).

Discolouration customer contacts were analysed over a ten year period. The number of discolouration contacts occurring in a DMA on the same day were summed.

These summed contacts were then determined as an ‘event’ based upon the number of contacts and number of properties within the DMA in accordance with Table 2.

The discolouration contact ‘events’ were then classed as a trunk main discolouration ‘incident’ if more than one discolouration ‘event’ occurred in the same Water Supply System on the same day.

Analysis of the contact data shows that the percentage of overall discolouration customer contacts per month that are clustered ranges from 0 to 51%, Figure 2. The mean however is quite low at 9% with a standard deviation of 12. This high variance indicates that only a small proportion of water supply systems are highly susceptible to discolouration events resulting from the mobilisation of material from the trunk mains. However their overall contribution to the total number of customer contacts cannot be ignored.

The occurrence of trunk main discolouration incidents, identified by cluster analysis, against the overall discolouration customer contact rate (contacts/1000properties/year) over a ten year data period is shown in Figure 3. A noticeable fall in the discolouration customer contact rate is seen between 2005 and 2007 and between 2010 to the beginning of 2013. The former could be associated with the success of the blanket wide UK water industry Section 19 (S19) cleaning activities and the latter the Distribution Operation and Maintenance Strategies (DOMS) where there was limited but more targeted spend (DWI 2002). However both these periods correlate with fewer large trunk main discolouration contact events.

In Figure 3 it can also be seen that the overall discolouration contact rate increases following a large trunk main discolouration contact event and remains elevated throughout the one year rolling window of the discolouration contact rate.

Further investigation is required to determine whether the reduction in trunk main customer contacts is the result of fewer trunk main mobilisation events or better operational management when they occur. To investigate this further, the number of clustered discolouration customer contacts was compared to the occurrence of large diameter pipe failures.

Clustered contacts and large diameter bursts.

Pipe diameter was not available from mains repair records, hence the locations of bursts were plotted in GIS and each record was then snapped to the nearest pipe. Burst records that were allocated to pipes greater than or equal to 300mm in diameter were then considered to have occurred in trunk mains. This method of identification is somewhat crude as when several pipes are in close proximity the mains repair might not be allocated to the correct pipe. It is also not generally useful to classify a trunk main on size alone as >300mm diameter pipe may not necessarily be functioning as trunk main due to network evolution, but this was deemed the best method available. The trunk main bursts were then classified as 'discolouration contact causing' if clustered discolouration customer contacts occurred in the same water supply system ± seven days of the recorded mains repair. This time period was a somewhat arbitrary advice, selected to try to account for contacts generated by a burst which may have been running for several days before it was repaired and for contacts that may have occurred during the subsequent reinstatement of the main after repair.

A graph of the number of discolouration causing and non-discolouration causing bursts per month from 2008 until 2013 is shown in

Figure 4. It can be observed that there is a general downward trend in the total number of trunk main bursts. Table 3 shows that the total number of Trunk main bursts has fallen by over a half from 2008 - 2009 (293) to the 2012 - 2013 year (133). The

total number of clustered contacts associated by trunk main bursts per year is generally falling from 1190 in 2008-2009 to 340 in 2012-2013 . However barring an usually high figure in the 2009-2010 data it can be observed that there is an increasing number of discolouration customer contacts per burst event.

Perhaps surprisingly this data set highlights that few trunk main bursts result in discolouration customer contacts. For the 5 years shown, on average only 5% of trunk main bursts result in customer reported discolouration incidents. However magnitude of the burst in terms of hydraulic conditions is not recorded, therefore the mobilisation potential of the bursts is unknown. The lack of correlation between burst events and discolouration customer contacts was also present in previous work by Cook (2005). Here seasonal trends in burst and discolouration customer contact frequencies were analysed for a five year period for two water companies (Figure 5). Vertical dotted lines on the figure highlight the winter and summer periods. These have been inserted to loosely correlate with max/min air temperatures, since these do not fall in the same period each year. Cook 2005 noted that burst frequencies peaked in winter whereas discolouration frequencies peak in the summer months. In addition following a noticeable lack of bursts in one winter, elevated discolouration customer contact levels were seen the following summer.

This data suggested that bursts could have a cleaning effect on trunk mains, and that they do not necessarily cause discolouration customer contacts as the discolouration material exits the system at the burst location. Increased flow events in the trunk main system, such as increases in demand, or rezoning activities, are however likely to cause discolouration contacts as the discoloured water is retained in the distribution system, unlike bursts where the discolouration material is lost. This hypothesis is tested by a recent discolouration incident of significant magnitude that it required reporting to the

UK Drinking Water Inspectorate (DWI). This event occurred due to the failure of a flow control valve causing a 30Ml/d flow increase in a 36” trunk main.

Trunk Main Discolouration Event Case Study 1

In February 2013 an increase in flow occurred in trunk mains downstream of two Water Treatment Works (WTW) in the North of England. This was caused by the failure of a cross-connection Flow Control Valve (FCV), Figure 6. This resulted in flow increasing through-out the day from 30 to 62 Ml/d. The increased flow, and therefore boundary shear stress in the 36-inch main, resulted in mobilisation of accumulated discolouration material causing extensive discolouration of supplies to the North of a large city centre. A total of 760 discolouration contacts were received from customers over three days, across 34 DMAs and covering an area of approximately 60 square kilometres.

Increased flows were seen through the cross connection, WTW B outlet and the 36” trunk main but it was not clear which of these mains were responsible for causing the mobilisation event. The 33” main from WTW B was ruled out as this main had recently been swabbed and put back into service the day before. Travel times between the recharge and re-commission of this main and the first discolouration customer contacts were out by 24 hours. Prediction of Discolouration in Distribution Systems (PODDS) modelling software, developed by the University of Sheffield was utilised to identify the main likely to have caused the discolouration. This was done by matching the modelled turbidity response to the occurrence of discolouration customer contacts, taking into account travel times to the first contact.

PODDS Modelling

Extensive work by the University of Sheffield, (Boxall et al. 2001; Boxall et al. 2003; Boxall et al. 2004; Boxall et al. 2005; Boxall and Saul 2005) has looked into discolouration events and carried out extensive flushing experiments to characterise discolouration particles and mobilisation processes. This has led to the development and verification of a Prediction of Discolouration in Distribution Systems (PODDS) model (Boxall et al. 2001).

The PODDS model is based on the theory that material accumulates as cohesive layers with defined shear characteristics on pipe walls within a distribution system. These layers are subjected to a daily conditioning shear stress as a product of the network demand. Exceedances of the conditioned shear stress leads to material mobilisation and discolouration.

Discolouration occurs when the equilibrium between layer strength and mobilising forces is unbalanced and higher shear stresses are generated, such as increased demand, re-zoning or a burst. The layers exposed to higher shear stresses will be mobilise until new equilibrium conditions are reached or until the layer is exhausted (Boxall et al. 2001). Following a discolouration event, regeneration of discolouration material occurs at a rate governed by source water quality and pipe material until equilibrium is again reached between layer strength and erosion forces (Cook and Boxall 2011 and Husband and Boxall 2011)

The PODDS model is a valuable tool as it can predict the turbidity response to increased flows above conditioning forces in terms of peak turbidity and duration. When correctly calibrated it has been shown to accurately simulate a wide range of UK discolouration events (Husband and Boxall 2010).

Modelling the Discolouration Event.

The three mains in Figure 6 were individually modelled using the PODDS tool to determine the likely turbidity source for the event. Default pipe and mobilisation parameters were used in the model as no actual turbidity data was available for calibration. Historic flow records were used to determine the conditioning flow rates, and 15 minute flow meter data recorded at the FCV and WTW B outlet during the event were used to determine the mobilisation forces.

Modelling of the FCV and WTW B Outlet mains indicated a turbidity response of approximately 5 NTU during the event, Figure 7. This is insufficient magnitude to have caused the large number of discolouration customer contacts. In addition the turbidity responses predicted were at the same time as and 3 hours after the occurrence of the first customer contacts for WTW B outlet and the FCV respectively. Rather than the 4.5 hours in advance as required to be consistent with system travel time. Note that at the time of the incident there was an open bypass round the service reservoir depicted in Figure 6 therefore the effect of storage could be discounted.

Historically the 36” main had been run at higher flow rates (69ml/d) than during the incident without any turbidity problems. Over the last 9 months however this main had been operated at considerable lower flow rates. According to PODDS theory, during this period material accumulation would have been occurring resulting in weaker, but unknown strength layers. Therefore the turbidity response for this main was modelled assuming different conditioning flow rate/initial layer strengths (i.e. decreasing the flow this main could experience without material being mobilised). Figure 8 shows that if this main was conditioned to 60 Ml/d a turbidity response of 8 NTU occurs after the time of the first customer contacts. At a conditioning flow rate of 33 Ml/d the modelled turbidity response was occurring much earlier than the occurrence of the first customer contacts. A conditioning force of 41 Ml/d was required to produce a modelled turbidity response where 10 NTU (a likely level for customers to first become aware of discolouration) was achieved at the time of the first contact. Note that the location of the first customer contact was very close to the end of the 36” main and therefore no travel time had to be accounted for. The reduction in the conditioned value, effectively asset deterioration, of this main over only a short period of time (9 months in this example) is extremely important for water practitioners to understand operational capacity when managing bulk water transmission. This study shows significant asset deterioration in only 9 months. If the recent lower flow regimes are once again resumed in this pipeline, the conditioning layer strength would again decrease and after a similar period the 36” main would again pose a significant discolouration risk.

An important feature of this data and site is that historically flow was only changed very gradually. This is likely to have slowly removed discolouration material of levels that were undetectable by customers and hence conditioned the main to higher flows. The ability to manipulate flows and remove discolouration material gradually is an important consideration in managing transmission systems, especially when it is used as a mains cleaning technique. Potentially this is a simple and cost effective strategy, in that it removes the necessity for the main to be taken out of service. Planning stepped flow increases to maintain turbidity to below regulatory limits is where the PODDS model is a valuable tool. An example of this is when the PODDS model was used to facilitate increasing the flow from 20 to 60 l/s in an 18” unlined cast iron main.

Trunk Main Diversion Case Study 2.

A section of 21” trunk main on the outskirts of a large town in the North of England was required to be taken out of service to enable the laying of new pipe in a diversion. Ordinary procedures would be to install line stops at both ends of the intended diversion with temporary overland piping to maintain supply. However, in this particular situation the costs were particularly high, due to the size of the main and necessary route taken.

Therefore an alternative solution was investigated whereby the 21” trunk main was closed and the additional 38.4 l/s (identified as necessary to maintain supply), was rerouted through an 18” unlined cast iron trunk main, Figure 9. This flow increase posed significant discolouration risk on a main which had suffered a DWI reportable incident in the past. Hence the PODDS model was utilised to plan stepped flow increases yet maintain turbidity to below regulatory limits.

The valve closure (location3, Figure 9) was first modelled in Info Works to see if the full network would cope hydraulically to the closure and identify the mains of greatest discolouration risk. Modelling indicated that peak flow along the 18” is increased from 20.6 l/s to 58.7 l/s. This would pose significant discolouration risk. The PODDS model was then used to model the discolouration response along the pipes identified. Field flushing trials were used to accurately calibrate the PODDS model.

Field calibration and valve schedule

To calibrate the PODDS model, flushing field trials were performed by opening a hydrant at a DMA inlet immediately off the trunk main of interest with flow rate monitored at location 1, Figure 9. Flow increases of 6 and then 10 l/s were induced at peak daily demand on two occasions, whilst monitoring the turbidity response using Analytical Technologies NefNet Mini turbidity logger unit, connected to the flushing standpipe via a ¼” British Standard Pipe push fit fitting . The turbidity response was very small for both flushing operations, 0.3 NTU at 6 l/s and only 0.4 NTU at 10 l/s. Results of the 10 l/s additional flow field trial are shown in Figure 10. The field turbidity results were then used with the PODDS model and the empirical parameters adjusted until a good fit between field and actual results were achieved. An example of the resulting fit following empirical calibration between field and modelled turbidities for the 6 l/s field trial is shown in Figure 11. The PODDS parameters achieved by calibration are shown in Table 4. Grab samples were taken at regular intervals during the flushing and analysed for iron, manganese and aluminium. Iron was shown to be the dominant metal found in all samples. The relationship between iron concentrations and the recorded turbidity for this network is plotted in Figure 12, a strong linear relationship can be seen. The extrapolation of this correlation indicates that the regulatory limit for iron, 200 µg/l, will be exceeded at approximately 0.6 NTU.

With the PODDS parameters calibrated the predicted turbidity response from closure of the 21” main in a single operation is shown in Figure 13. It can be seen that the turbidity response reaches the regulatory limit of 4 NTU on the first morning peak in demand. Due to the variable daily demand, the discolouration response takes several days until all material is removed and the main is conditioned to the additional flow. According to this prediction and Figure 12, Iron would exceed regulatory limits by over seven times. Therefore it was recommended that a stepped valve closure be applied, whereby the turbidity response be targeted below regulatory limits. The PODDS modelling indicated that 7 valve steps, with 7 days between each operation, taking a total duration of 42 days, would be required to close the 21” trunk main. A schedule for closing the required valves is shown in Table 5.

Flushing stagnant leg

In order to close the 21” main, a boundary valve would have to be opened and a stagnant 333 meter length of 18” unlined cast iron main brought back into service. Conditioning was achieved by flushing a hydrant at location 2 (Figure 9) at 20 l/s until the turbidity fell to below 4 NTU. During flushing there was no risk of water entering supply, hence the turbidity response did not have to be controlled. Due to field issues with disposal of water, difficulty maintaining a consistent flow rate and time constraints of night activities, 3 nights were required to bring the turbidity to below regulatory limits. Maximum turbidities of 160 (night 1), 60 (night 2) and 20 NTU (night 3) occurred during flushing.

During night 1 of flushing the flow rate was increased to 15 l/s and maintained until a significant fall in turbidity was achieved, then flow was increased to 20 l/s. However due to the risk of flooding the flow rate was reduced to 10 l/s and flushed until the turbidity reached < 4 NTU, Figure 14.

During night 2 a sufficient length of hose was used to dispose of the water down the nearest culvert. Flow was gradually increased in steps until 20 l/s was achieved and turbidity rose peaked at 61 NTU, Figure 15. At approximately 2:10 am the flow had to be reduced to re attach the hose which had become detached. Unfortunately when the hydrant was re-opened, the flow was marginally higher (0.5 l/s) This caused an increase in turbidity as additional layers of discolouration material were mobilised. At 3:20 am the flow rate was reduced until the turbidity fell to below 4 NTU as the operation was exceeding its time window.

The third night of flushing achieved the objectives as turbidity fell to below regulatory limits after 3 hours of flushing, Figure 16, equating to 4 pipe turnovers at a flow rate of 20 l/s. This work allowed the boundary valve to be opened and the main put back into service.

During the flushing operations turbidity was seen to rapidly fall as the flow rate reduced. During night one when the flow rate was reduced from 20 to 10 l/s, the turbidity dropped by 100 NTU in 10 minutes or 0.1 pipe turnovers and only took 2/3 of a pipe turnover in total to fall to 4. This suggests that a settling mechanism may have been occurring. This is somewhat contradictory to the cohesive layer theory developed by Boxall (Boxall et al. 2001), whereby the particles captured during flushing operations remain entrained such that even small flows resulting from leakage would be enough to prevent settling. However this main had been stagnant for a number of years and therefore conditioning theories may not be as relevant due to accumulation and formation of larger size and density particles. Unfortunately no discrete samples were collected to investigate this.

The unplanned secondary additional 0.5l/s flow increase that occurred on night 2 of flushing, mobilising additional layers of discolouration material in a unlined cast iron main, indicates the limitations of flushing as a mains cleaning technique on larger diameter mains. In larger diameter mains the flushing forces are limited by the flow rates that can be achieved through a hydrant, and the ability to safely dispose of the water produced. Thus a flow rate higher than the main was flushed at will mobilise additional discolouration material. In this application flushing was only employed to bring the main into service, and once the main was re-commissioned, the planned stepped flow increases would manage the risk of higher flow rates, when the water would safely enter supply.

Field Operations

Flow control was planned to be obtained by incremental changes in valve position. When undertaking modelling to convert the required flow rates to number of valve turns however it was noted that the required flow steps were all achieved in the final 2 turns of the valve. This sensitivity meant that the plan would be hard to achieve without a high level of control, but the principles could be followed. The valve on the 21” main was closed by 27 of 36 turns in one operation and a further 6 valve operations were undertaken over 30 days to fully close the valve (note the valve was on an 18” bypass, thus there were only 36 turns to closure - instead of expected 42 for a 21” main).

Turbidity was closely monitored in the field to determine the number of valve turns per operational step. An example of the turbidity response recorded during one of the valving operations is shown in Figure 17. It can be seen here that although the recorded turbidity was below regulatory limits it was above the designed level of 1

NTU. This is because of the difficultly in applying a sensitive theoretical plan to field activities where flow monitoring was unavailable. In addition, the required 7 days to completely recondition the main between valve operations was not always followed due to the availability of personnel and operational pressures to deliver the scheme sooner than planned.

The 21” main was successfully closed and the additional flow transferred along the 18” inch main without impacting customers or causing discolouration customer contacts. This was achieved without any interruption to supply or capital spend and resulted with a £70K cost saving over traditional line stop techniques.

This operation highlighted the feasibility but some of the practical difficulties, of being able to increase flows in a main in a controlled manner yet minimising discolouration risk. Flow conditioning can be useful in increasing the resilience and operational capacity of a main, or by inducing higher flows on a regular schedule can be used as a mains cleaning technique.

Industry Implications

Analysis of in line turbidity monitor data and clustered discolouration customer contacts demonstrate that trunk mains pose a risk to discolouration in the distribution system. When analysing the data from the long term deployment of turbidity loggers, the standard deviation of the daily turbidity cycle is shown to be a good method of eliminating drift in loggers whilst still capturing short term effects and could be used as a method of resampling the data and assessing relative change pre and post rehabilitation. Analysis of such data from 5 different DMAs over a three year period showed that between 30 and 50% of turbidity spikes were associated with imported discolouration material.

Cluster analysis of discolouration customer contacts is an extremely effective desk top method able to broadly classify the source of customer contacts and thus to target interventions appropriately to either DMA or trunk mains. It is unwise to rely on customer contacts alone to target interventions as they only facilitate reactive management. A forward, proactive, looking DOMS approach (DWI 2002) must investigate where material is accumulating rather than where it has been recently mobilised.

The trunk main discolouration event presented here highlighted the need for a pro-active trunk main risk assessment program. The PODDS model can be used by water companies as a tool to assess trunk main discolouration potential. This is achieved by recording the turbidity response from a small induced flow on a trunk main and using this information to calibrate the PODDS model. The model can then be used to predict the turbidity response from further increases in flow such as operational or burst scenarios. This information can then be used to accurately calculate and rank trunk main discolouration risk based upon turbidity response, likelihood of flow event and number of downstream customers.

Operational flow increases (re zoning, demand increases etc.) have been shown to have a higher discolouration risk than mains bursts on large diameter trunk mains. This is possibly due to the infrequency of mains failure and that the burst location provides an exit point for the discolouration material. It is therefore essential to manage and reduce the discolouration risk of planned works within trunk mains. The PODDS model is a powerful tool that enables both discolouration risk assessment for planned works and management and risk mitigation of operations through the planning and design of stepped flow increases, whereby the turbidity response due to such operations can be kept below regulatory limits.

Conclusions

- Turbidity monitors at DMA level indicate that 30 to 50% of discolouration events recorded were likely to have originated upstream from the DMA inlet.
- Clustering of discolouration customer contacts show an average of only 9% linked to trunk mains, but the range in correlation indicates that some trunk mains pose significantly greater discolouration risk than others, thus providing a means of prioritisation.
- Analysis of large diameter mains bursts indicate that few result in customer contacts, and it is suggested operational activities have a higher risk of causing discolouration customer contacts.
- PODDS modelling was used to determine the source of discolouration material following an incident. This unexpected event highlighted the need for pro-active trunk main discolouration risk strategies.
- Proactively manipulating flows through trunk mains in a controlled manner can be used as a non-invasive and low cost mains cleaning technique. This is particularly feasible in situations where there are dual trunk mains that can facilitate the manipulation of flows.
- PODDS modelling can be used to plan regular operational maintenance strategies of stepped flow increases. This can be designed to mobilise discolouration material at levels below regulatory limits and unperceivable to customers. The result is improved network resilience and mitigated discolouration risk in the event of planned, or unplanned flow increases.

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Figures

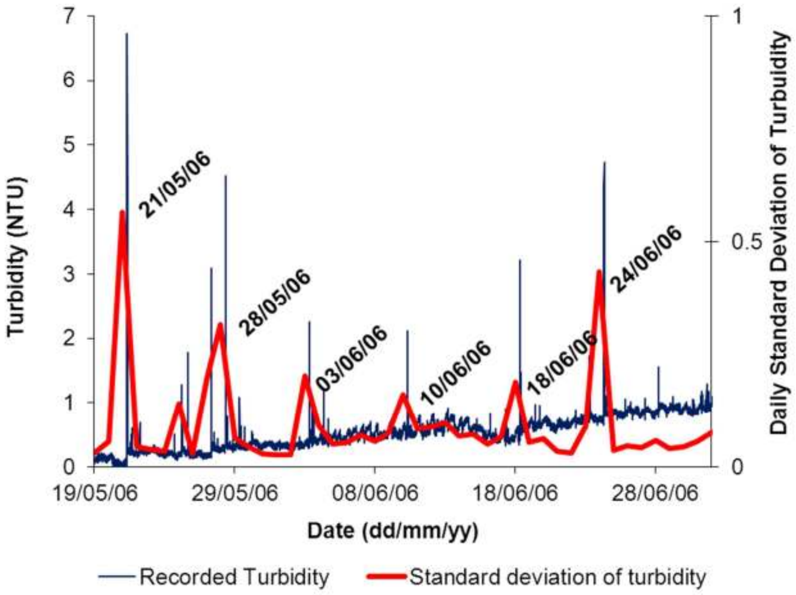

Figure 1 Example of time series turbidity data and analysis by standard deviation method.

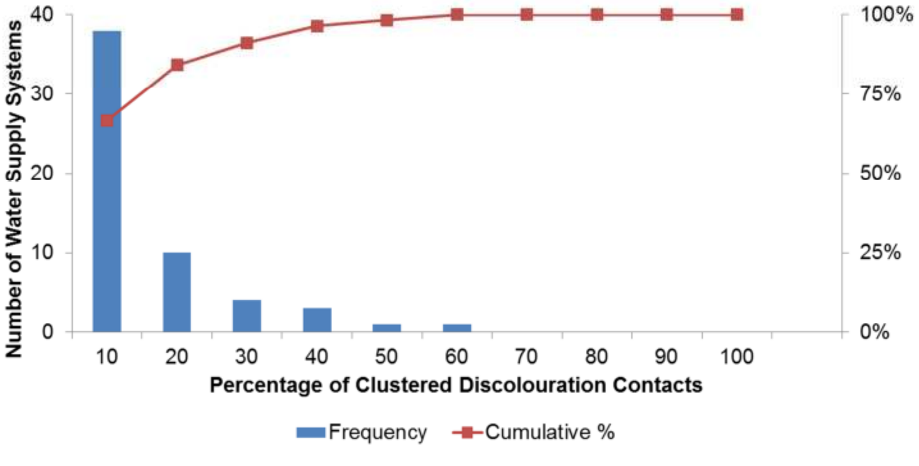

Figure 2 Percentage of trunk main discolouration customer contacts per month

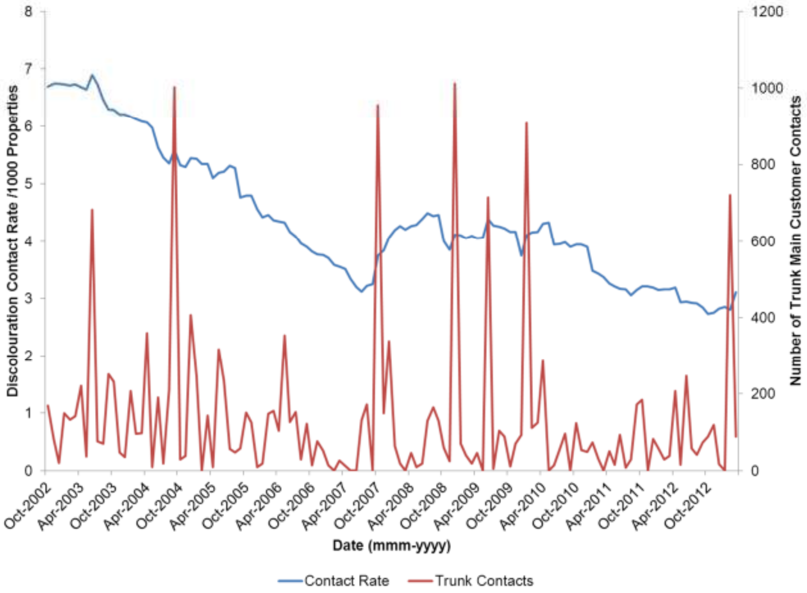

Figure 3 Trunk main discolouration contacts (identified by cluster analysis) compared to the overall companywide customer discolouration contact rate

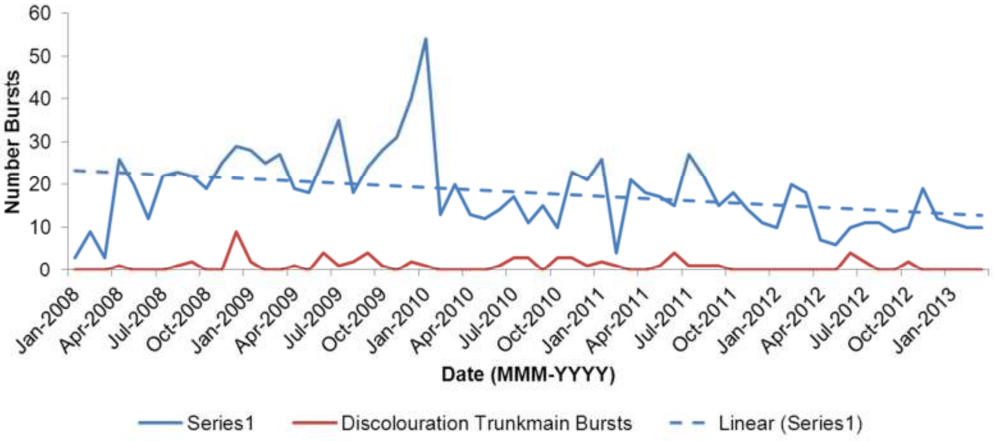

Figure 4 Number of discolouration causing and non-discolouration causing bursts per month

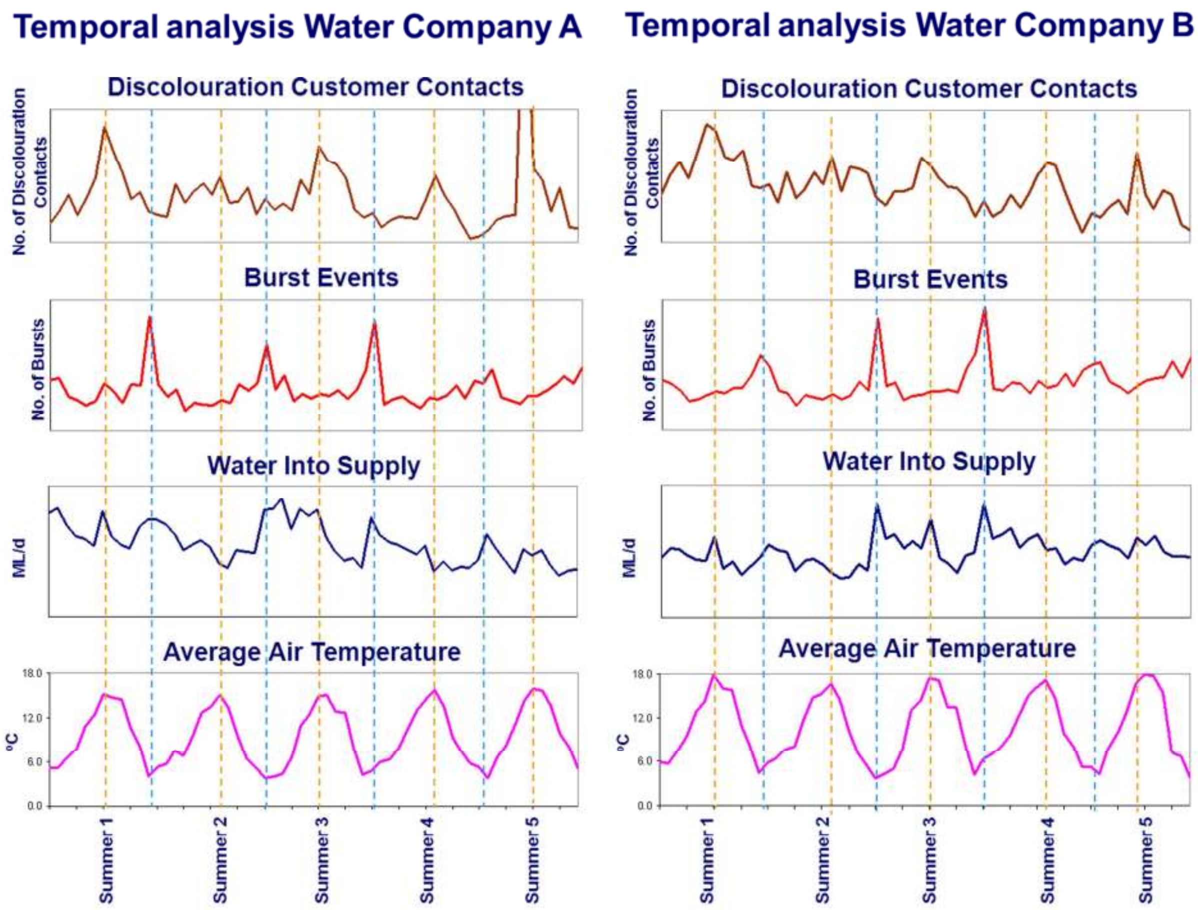

Figure 5 Seasonal trends in discolouration contacts and burst events (Cook 2005)

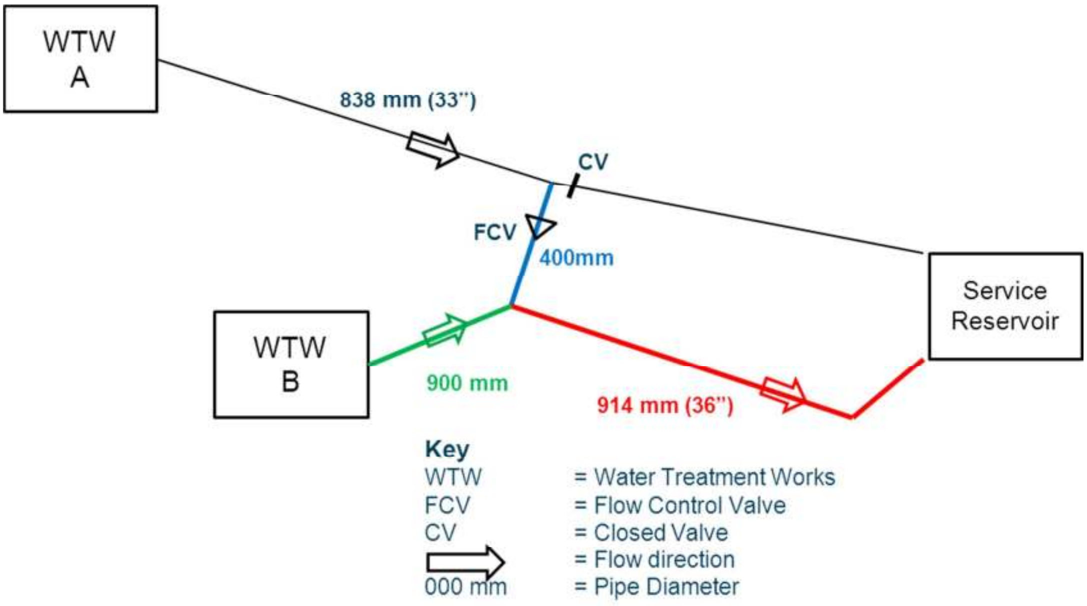

Figure 6 Trunk main transmission system

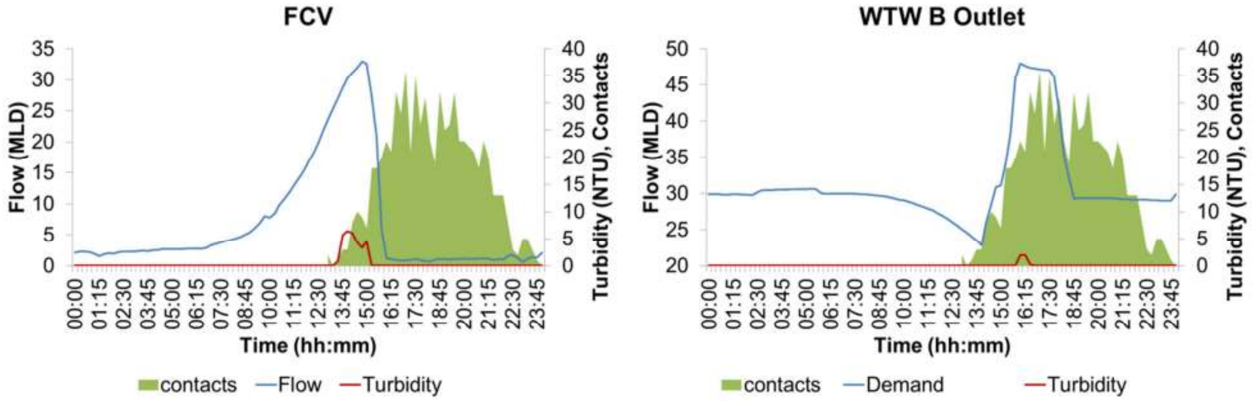

Figure 7 Flow, modelled turbidity and customer contacts for pipes not considered to have caused the discolouration event

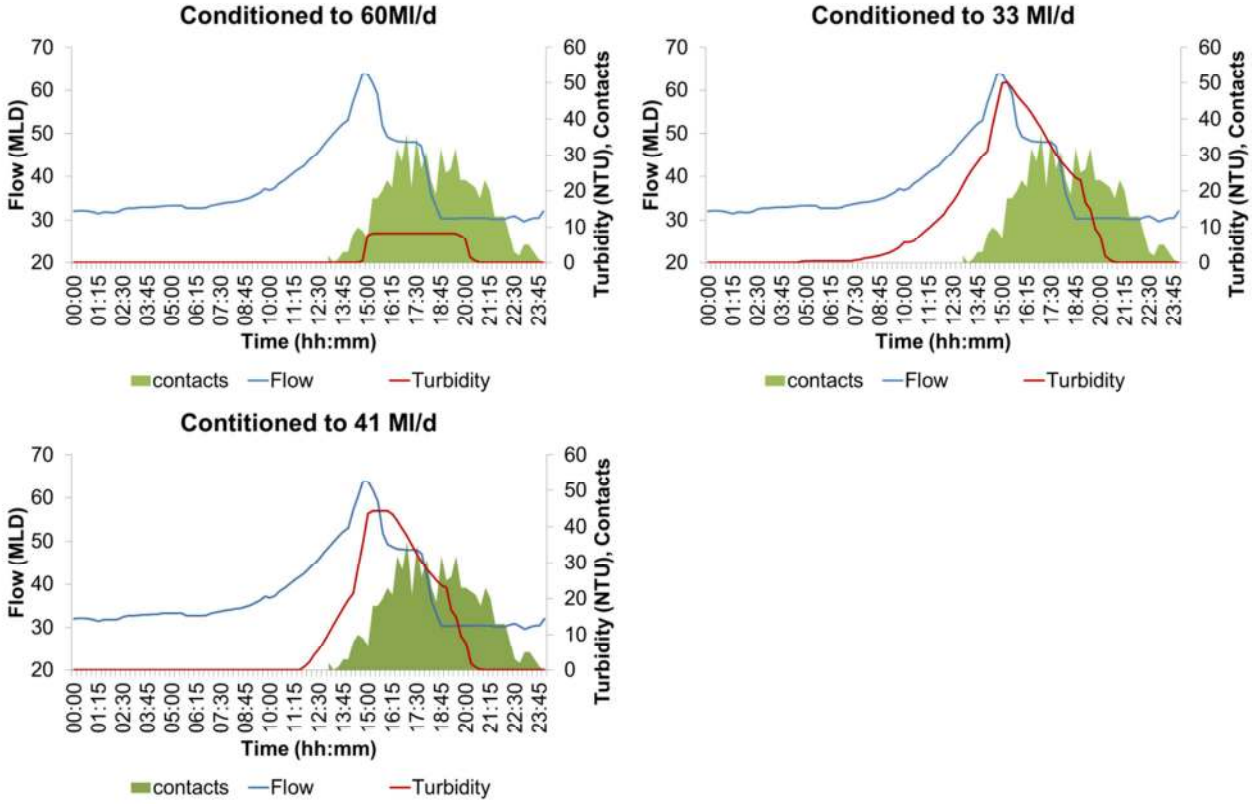

Figure 8 Flow, modelled turbidity and customer contacts using different conditioning parameters for the 36" Main

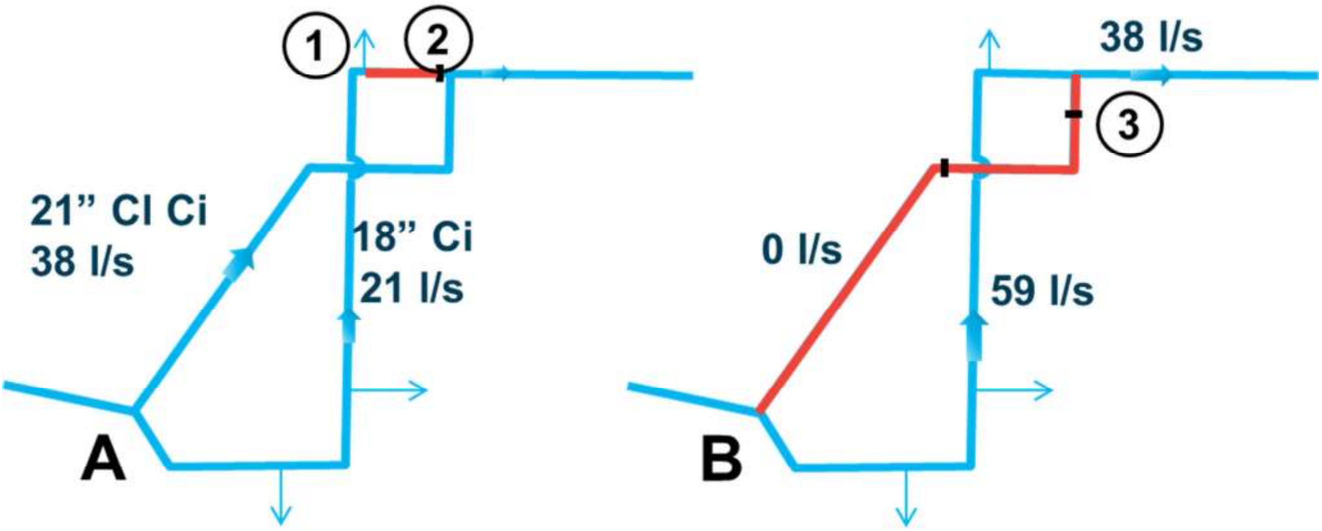

Figure 9 Trunk main diversion schematic A) normal/current operation B) required to facilitate main shut off

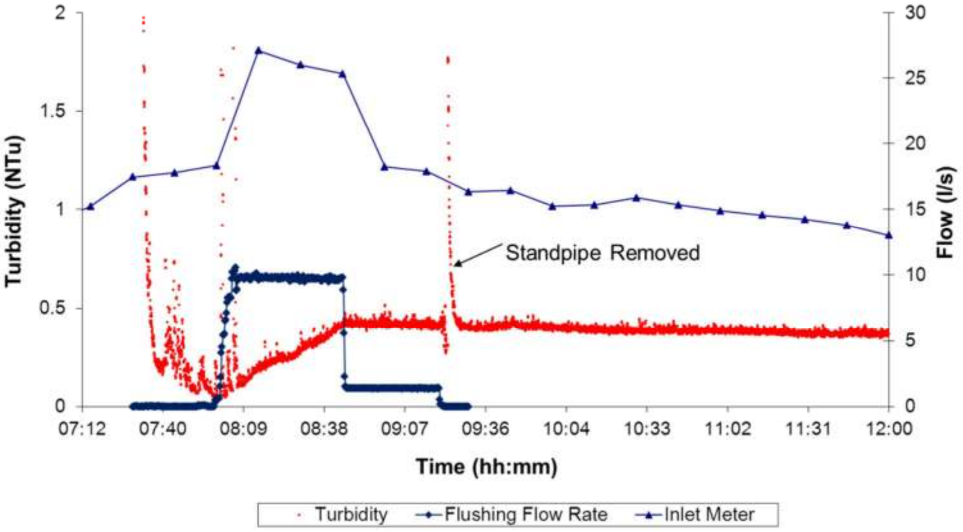

Figure 10 Turbidity response and flow regime of 10 l/s field trial.

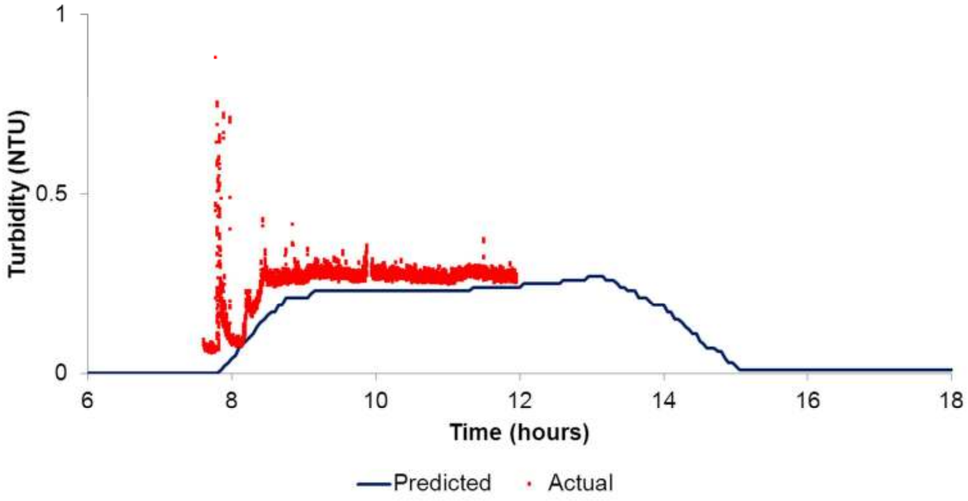

Figure 11 Example of predicted and actual turbidity response for the 6 l/s field trial

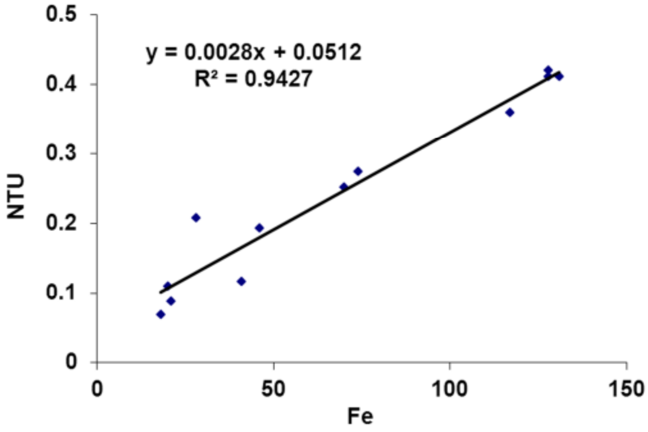

Figure 12 Relationship between iron and turbidity

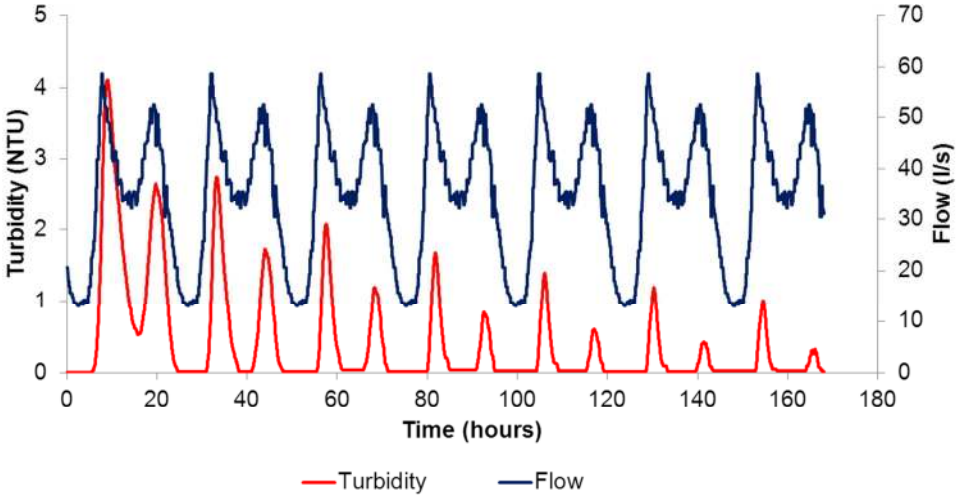

Figure 13 Predicted turbidity response of 21" main in one operation

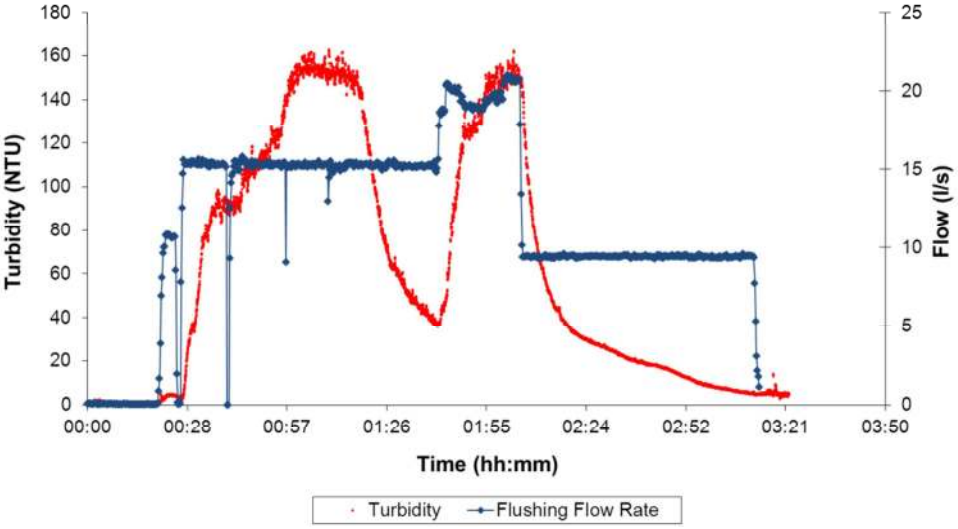

Figure 14 Flushing night 1

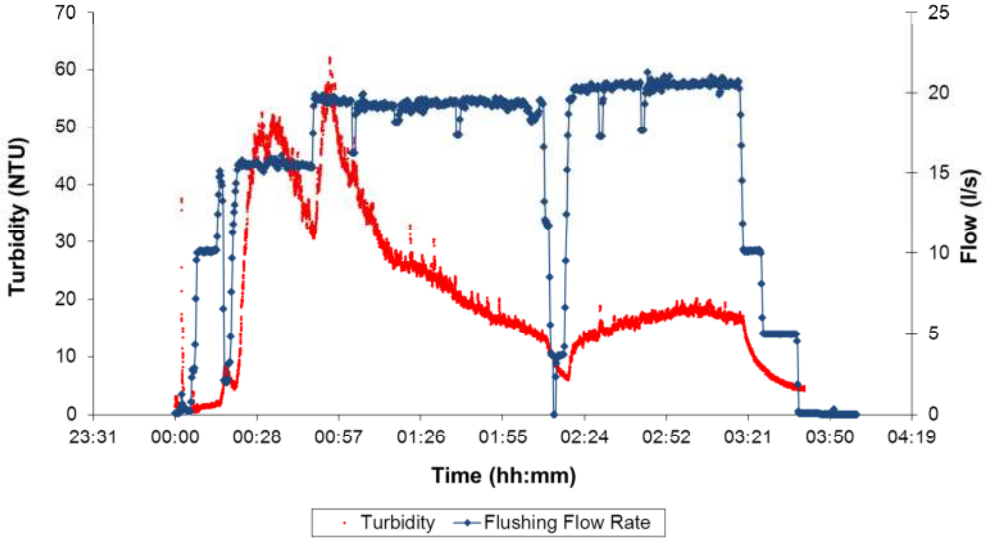

Figure 15 Flushing night 2

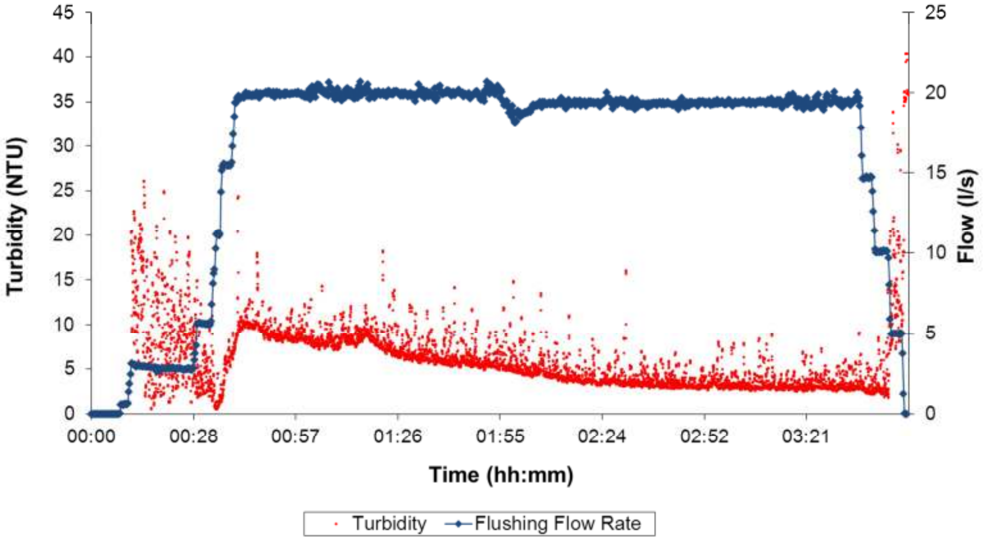

Figure 16 Flushing night 3

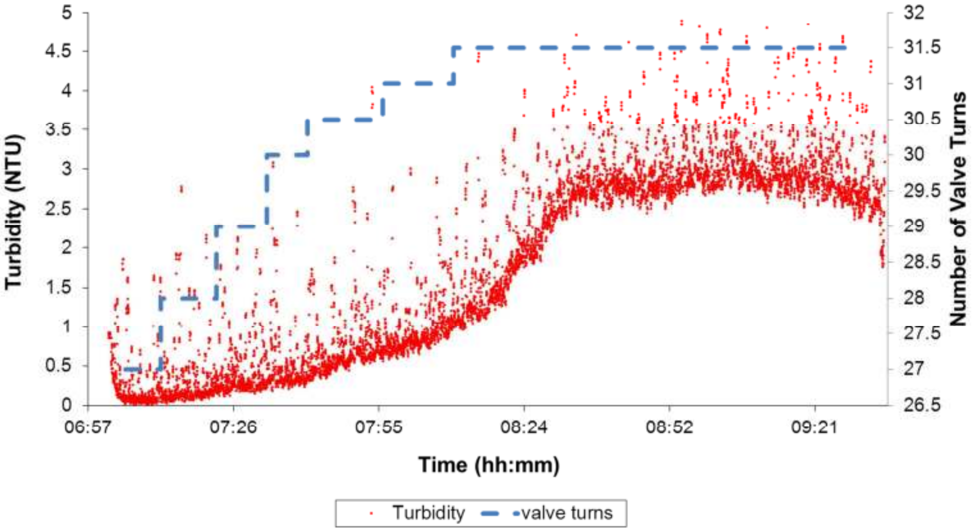

Figure 17 Example of turbidity response during one valve closing operation

Tables

Table 1 Discolouration event classification for 5 DMAs over 3 years

	A	**B**	**C**	**D**	**E**
Localised Event	16	3	0	0	0
DMA Demand Increase	2	2	8	5	2
Imported Material	0	3	5	6	2
Unknown	0	1	1	2	0

Table 2 Discolouration event classification

No. of properties	**Required No. of discolouration contacts on the same day.**
<500	2 or more
500-1000	3 or more
>1000	4 or more

Table 3 Trunk main bursts linked to clustered discolouration customer contacts

	Number of trunk main bursts		**Discolouration contacts caused by trunk main bursts**	
Year	**Non Discolouration**	**Discolouration causing**	**Total**	**Average per Burst**
2008-2009	278	15	1190	9.3
2009-2010	326	16	990	61.9
2010-2011	187	17	436	25.6
2011-2012	205	8	291	36.4
2012-2013	126	7	340	48.6

Table 4 Parameters used to calibrate PODDS model

Parameter	**Value**
k	-3
b	1
P	0.00005
n	1

Table 5 Valve schedule required to maintain peak turbidity <1 NTU according to PODDS predictions.

Day	**Proportion of Additional Demand %**	**Flow at 7.45 am l/s**	**Flow Increase l/s**	**Max Turbidity NTU**
1	25	28.65	10.01	0.80
7	40	34.66	6.01	0.97
14	54	40.27	5.61	1.02
21	66	45.08	4.81	0.97
28	78	49.89	4.81	1.01
35	89	54.30	4.41	1.00
42	100	58.70	4.40	1.03