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Long-Term Discolouration Modelling for Cast Iron Mains

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Water companies have been working to introduce strategies to reduce discolouration customer contacts via non-specialist 'business as usual' practices. A greater understanding of discolouration material behaviour however is still needed to accurately inform the mobilisation response and regeneration rates in mains of different materials. The Variable Condition Discolouration Model (VCDM) that tracks both accumulation and mobilisation processes, has been validated in some pipe materials using long term time series data. This paper investigates calibration for a 15 km cast iron main, using daily turbidity responses with VCDM parameter sensitivity and temporal stability investigated using a statistical approach comparing three periods of the data.

Results highlight the VCDM as widely applicable to determine long term discolouration behaviour and improved behavioural understanding. In this case, analysis of different time periods indicates flow-conditioning not only improves network resilience but can also reduce mobilisation rates and discolouration risk.

Keywords: Discolouration modelling, VCDM, discolouration material, water distribution systems, trunk mains conditioning.

Introduction

The accumulation of discolouration material on pipe walls of drinking water distribution systems (DWDS) is recognised as both continuous and complex, Van Summeren and Blokker (2017) and Vreeburg et. al. (2008). The research by Douterelo et. al. (2014), Fish et. al. (2015), and Husband et. al. (2011) has shown that accumulation rates of material are a function of distributed water quality and pipe material, while the behaviour and structure of the biofilm that develops on the pipe wall is dominated by hydraulic conditions in the pipe. Pipe wall accumulations consist of organic and inorganic material that leads to deteriorating assets and continual water quality risk with threat of mobilisation. The primary mobilisation cause is via hydraulic changes that increase wall shear stress, detaching particulate material from the pipe wall to become entrained in the flow before exiting via customer taps, Husband and Boxall (2010). Companies use many different approaches to remove or mitigate the risk of discolouration with no single solution. Of these approaches, there are those that require expensive capital spending, like pipe replacement and invasive pipe cleaning operations, and others that require little capital but more operational focus like network flushing.

With continual accumulation there is no such thing as a clean pipe and discolouration risks are therefore always present, particularly in response to planned or unplanned hydraulic changes. As a result it is no surprise the largest water quality related customer complaint in many countries is discolouration. Reducing the number of discolouration contacts is subsequently considered a very important target, and Yorkshire Water, who supply over 5 million customers in the north of the UK, has been promoting innovative maintenance strategies to support their aging water distribution systems, Al-Saffar and Husband (2018). One of the pro-active discolouration risk management practices identified that can be conducted on a larger scale within the business is conditioning of trunk mains through frequent non-specialist business-as-usual flow increases. Using managed flow increases in DWDS, such as by increasing pump output, controlling valves and reservoir inlet flows, manipulating flow directions in looped networks and even via flushing hydrants, has been proven as a method to mitigate the risk of discolouration and improve resilience, Al-Saffar and Husband (2018), Husband and Boxall (2016) Husband and Boxall (2017), Cook et. al (2016), and Cook and Husband (2017). Although a major component of the trunk main network, little understanding of cast iron mains has been recorded compared to studies such as on lined or non-corroding pipes. In non-corroding assets, the Variable Condition Discolouration Model (VCDM) has been successfully calibrated with standard parameters established and shown capable of predicting turbidity responses and subsequently planning of long term maintenance strategies to manage discolouration, Furnass et. al. (2014), Al-Saffar and Husband (2018), Husband and Boxall (2017), and Furnass et. al. (2019). However, the accumulation rate of the discolouration material with respect to different pipe materials within DWDS is still not well understood and this is mainly because of the lack of long term turbidity monitoring combined with accurate flow logging tracking hydraulically induced discolouration.

Monitoring turbidity levels for a long term (months or years) in different parts of the drinking water supply system is still not common for multiple reasons. For example non-permanent turbidity monitoring instruments may be unsuitable for long term data collection. Reasons include maintenance requirements for these scientific instruments, particularly battery charging, issues in finding viable connection points to the study main with suitable drainage for sample lines and communication problems when transmitting data from remote units that are typically underground. For this reason, techniques that allow modelling of accumulation and mobilisation in different pipe materials, ideally without the need to collect long term data or use multiple sections within DWDS, could provide valuable understanding to inform best business practices. Using a dataset from a cast iron trunk main, this work firstly investigates if the VCDM can be used to simulate the long term discolouration behaviour in pipes of this material, and then for the first time a sensitivity analysis is conducted to explore the possibility of using shorter period daily turbidity responses to verify VCDM parameters. The behaviour of the cast iron trunk main is initially simulated using parameters transferred from non-corroding mains with subsequent further calibration using visual interpretation. Sensitivity of the modelling parameters is then investigated using statistical analysis between measured and modelled turbidity across three periods, each of 21 days, at the beginning, middle and end of the dataset.

Background

Field Work

A company investigation into discolouration issues found a trunk main as a likely source following hydraulic incidents that resulted in a significant number of widespread, yet temporally clustered, customer contacts in an urban area in the North of England. The main identified was a 15 km cast iron 18” (≈457 mm) diameter main which is partially gravity fed from a service reservoir that has a treated surface water supply. To reach a second reservoir supplying the distribution system there is a pumping station to boost the head. A schematic of the system is shown in Figure 1 with hydraulic information in Table 1. To reduce the discolouration risk from the main, a plan was proposed to increase the daily peak flow, and hence resilience, via managed incremental steps (termed *flow-conditioning*) to remove material such that further hydraulic events would not mobilise sufficient material to generate a significant discolouration response. Prior to starting the flow conditioning operations, turbidity loggers were deployed to monitor the turbidity responses during the flow increases and to collect evidence as the operation progressed. The initial improved resilience was achieved by conditioning the main with an increase in daily peak flow from 80 l/s to 100 l/s over just over one week by increasing the pump output during peak demands. The flow profile during this study is shown in Figure 2A, with the conditioning phase highlighted in Figure 2B. During and post the conditioning a daily turbidity response was recorded following the typical demand increase from around 60 l/s to the peak flow of 100 l/s. This was observed to continue for 7 months but with a declining trend in magnitude. Turbidity data was collected during the monitoring period using ATI Nephnet instruments with infra-red nephelometric measurement processing and a functioning range set to 0 - 20 NTU. These were calibrated with standards under laboratory conditions and set with a sampling frequency of 1 minute. This allowed good visualisation of the discolouration responses, in particular trends with multiple small turbidity events (< 0.1 NTU) for each daily peak flow. By applying VCDM modelling it was planned to gather more information to help understand the discolouration material behaviour. This could help appreciate the longevity of the turbidity responses, the accumulation rate of material causing asset deterioration, and moving forward facilitate future discolouration hydraulic risk boundaries and scheduling of mitigation interventions.

Method

Modelling the Discolouration Response

The discolouration response at the end of the 15 km main was modelled over the entire monitoring period using single extended period VCDM simulations. VCDM is a modelling tool package that uses just three parameters to model both the simultaneous mobilisation and accumulation of discolouration material. Detailed explanation of the model formulation and parameter derivations can be found in Furnass et al 2015 and 2019. Two parameters describe mobilisation, represented by a material removal rate factor (mobilisation or erosion rate factor), and material release coefficient. The third parameter is a rate term representing accumulation, or regeneration, of discolouration material. Accumulation is assumed to happen continuously and at a constant rate. Model input requires pipe length, diameter and roughness. A flow time series is required which the model transforms into shear stress (the force perpendicular to the pipe wall, calculated using hydraulic head loss, a function of pipe roughness and diameter), which provides the driving force for material removal from the pipe wall. For plotting purposes a default background turbidity level can also be added, in addition to the number of equal sized shear stress bands (sufficient to cover the entire shear stress profile) into which discolouration material on the wall is divided. Mobilisation occurs when the applied shear stress exceeds a defined band value, with a rate relative to the extent of excess shear stress. Material mobilisation continues until the material in the defined band is entirely removed or if the excess shear stress drops below the band rating. By appending to a hydraulic model, the turbidity predicted by the model at the downstream node is calculated as the sum of all material removed from each band and for each time step and then transported along the pipe. The model also assumes that once entrained, no settling occurs. In 2019, Furnass et. al. (2019) stated that due to the limited number of case studies, further operational VCDM model cases are required for tool verification, in particular to investigate parameter transferability. VCDM is currently written as a base version in the Python programming language (although available in commercial software, such as DNVGL Synergi) and model runtime is typically only seconds on a standard computer. The user definable output is nominally a turbidity time series determined directly from the applied shear stress as defined by input flow data. To facilitate model calibration, measured data (where available) can be included and presented along with modelled output.

From visual inspection of measured data with modelled, an empirical best fit parameter calibration can be established. With turbidity data it is common for there to be a lot of non-hydraulically derived responses (noise), such as material emanating from upstream, deposits around fittings being mobilised or optical fouling. As a result, computational based calibration has historically been prone to difficulties. Visual matching therefore provides a quick and simple technique that can be done without time consuming and potentially debateable data cleansing. Visual inspection however remains subjective and in many cases when investigating longer term simulations, can also induce fitting bias. This can occur for example when focussing on significant events, such as flow conditioning exercises, and as a result lower magnitude, but equally important background events can get overlooked. To avoid this and provide an approach that facilitates statistical analysis to be applied, , a method to test the model simulations was developed. This could also allow investigation of parameter interdependencies and temporal variations, for example seasonally or after changes in treatment or network management. In this approach, three time periods, each of 21 days at the beginning (March), middle (May) and end (October) of the full data period were selected for comparison, as shown in Figure 3. Across the three representative periods, comparison between the measured and modelled data was undertaken by comparing resulting mean and variance values. This approach also facilitates investigating if shorter periods of data can be used to verify the VCDM functionality in specific pipe sections. Best fit calibrations were determined for each of the three parameters whilst the other two were kept fixed. This was done for each parameter and for each of the three time periods and across the entire simulation. The parameters giving the best fit between the measured and the modelled data could then be used as a reference for modelling pipes of similar properties.

Results

By monitoring the turbidity, the discolouration risk in this cast iron trunk main as it responds to hydraulic fluctuations can be assessed. Figure 3 shows the results of the VCDM modelling over the entire modelled period for both standard parameters and subsequent visual calibration, with sections from the beginning, middle and end periods selected for detailed analysis. The three sub-plots of each model output have the same time period x-axis and from top to bottom show the value of the flow translated to the applied shear in N/m^2 (Pascal), three example tracked shear strength bands selected to represent a cross-section of the shear stress range (defined by the input flow range and example bands in this case the 25th, 50th and 75th percentiles, the y-axis being amount of material present where 0 = no material and 1 = a fully developed material layer), and the measured and predicted turbidity in NTU.

During the flow-conditioning at the beginning of monitoring period, the turbidity response can be seen as safely managed to remain below 2 NTU (4 NTU at the customer's tap is UK regulatory limit). This response highlights material being mobilised and subsequently the declining response provides evidence demonstrating the increased resilience being delivered. During the beginning, turbidity responses peak around 1.5 NTU, the middle period at around 0.6 NTU and at the end 0.2 NTU. Initial extended period simulation results using VCDM standard parameters, transferred from non-corroding mains, demonstrate VCDM as a tool capable of predicting long-term discolouration behaviour. What can be observed using these parameters is that the VCDM simulates with a high accuracy the initial mobilisation at the start of the flow-conditioning Figure 3B, but then describes material as being removed too quickly. This can be observed from the tracking of individual bands of material, in particular from the behaviour of the 75th percentile band where all material is rapidly removed. As a result, the model under-predicts measured turbidity during the second part of the beginning Figure 3B, and the middle phase Figure 3C. Once the material has been removed, and this behaviour is seen as taking far longer in this cast iron main than would be expected in non-corroding assets based on the use of these calibrated parameters, the VCDM simulates well the low-level (less than 0.2 NTU) daily responses during the end period, Figure 3D.

With results indicating VCDM is a viable tool to safely manage the turbidity and can explain the behaviour of discolouration material over long periods in cast iron mains, maintenance scheduling and business as usual strategies can be developed. However, this work highlighted further considerations may be required, in this case site specific empirical calibration to address concerns regarding model fit and potential temporal changes in discolouration behaviour. To achieve improved measured to modelled fit, visual calibration was therefore undertaken with the VCDM mobilisation parameter ultimately reduced 100-fold from a widely used ductile iron pipe value of 0.0004 $Pa^{-1}s^{-1}$. This would seem counter-intuitive as cast iron pipes would be expected to have a greater discolouration risk. At the same time however these results were achieved with the material releasing coefficient increased from a default value of 1 to 3. No change was made to the regeneration rate with simulation results shown in Figure 3 (right hand column). These parameter changes support the high turbidity mobilisation and also slow the rate of removal, as evident from the more gradual decline in the 75th percentile compared to the standard parameters, Figure 3A. With reduced rate of material loss, a much improved fit is obtained throughout the beginning and middle phases, Figure 3B and 3C, although the end phase, Figure 3D, appears less accurate. Accepting which parameters therefore return the best fit falls between selecting either a better initial and middle fit (i.e. across a greater time period) with larger turbidity responses and hence greater potential discolouration impact, or the lower magnitude and across a shorter timeframe. This difference in turbidity magnitudes is also exaggerated in Figure 3 due to y-axis scale differences, and a difference of +0.1 NTU following almost a year's simulation can still be regarded as exceptional.

With each day partially removing material at a greater rate than accumulating, this can explain the declining trend in the daily turbidity response seen across the monitoring period. The measured and predicted turbidity data in the three 21-day periods are shown in detail in Figure 4 – 6. For this visually calibrated simulation the model parameters used were a regeneration rate of 6 months, a material release coefficient (α) of 3 NTU $Pa^{-1}m^{-2}$ and a removal rate of 0.000005 $Pa^{-1}s^{-1}$.

An additional benefit from this work during the flow-conditioning was the ability to use flow-conditioning associated pressure changes to determine pipe roughness, critical for shear stress determination. This identified the Darcy-Weisbach pipe roughness to be around 0.01 m, significantly greater than the default value of 0.001 m used for ductile iron mains. This may also be a factor responsible for the different behaviour identified in this cast iron main compared to non-corroding mains and highlights that for water quality modelling a key requirement is an accurate hydraulic model.

Investigating parameter effect on model output

With the VCDM defined by three parameters, the sensitivity of each was investigated by comparing mean and variance values as objective functions between measured and modelled turbidity data for each of the three periods and across the entire dataset. The results of changing individual parameter values, whilst fixing the others at the initial calibrated values, are shown in Figure 7. A best fit using this approach occurs when the mean or variance for the respective modelled parameter and time period bisects the horizontal constant for measured data for the same time period. The results indicated in most cases comparable outcomes using either mean or variance analysis, but significant variation between time periods analysed. In all cases differences are most distinct between the beginning and end periods, with the middle period reflecting an average outcome with greatest similarity to analysis across the entire dataset.

Results show the regeneration rate ranging between 2 and 6 months for all periods except the end when 18 months gives the best match. A similar discrepancy is shown in the material release coefficient (α) values that range between 3 and 4 NTU Pa^{-1}m^{-2} except for the end period with a value of 1. For the removal rate parameter, the best-fit for the end period is less than other periods with values ranging between 5 x 10^{-6} and 5 x 10^{-8} Pa^{-1}s^{-1}

For the degree of the three parameters affecting the modelling results, results indicate in this case the effect of regeneration rate is not very effective after 12 months for all of the time periods. The material release coefficient and removal rate is more sensitive on the beginning period when compared to the other time periods and this is a reflection of the higher turbidity values observed.

Assessing the VCDM parameter performance from Figure 7, and in particular using differences determined through analysis of mean turbidity, a good correlation with values obtained through the visual interpretation is found. This is particularly evident when examining the beginning period. This is important as with the higher turbidity responses generated here due to the initial flow increases, it may be considered as the most critical operational stage and also most sensitive to model fitting. Using this agreement, it is suggested VCDM values for this cast iron trunk main are a regeneration rate of 6 months, material release coefficient value of 3 NTU Pa^{-1}m^{-2} and removal rate of 0.000005 Pa^{-1}s^{-1}.

Discussion

The turbidity data collected in this study showed that there was a continuous turbidity response at every peak daily flow, but a declining turbidity response was observed over the monitoring period. The reason for not removing the entire discolouration layer it can be suggested was because of the short duration peak flow, lasting less than an hour, being insufficient to allow all material to be mobilised. Parameters determined from VCDM calibrations in non-corroding assets however did not predict this, suggesting a difference in discolouration behaviour between pipe materials. This is shown with the lower removal rate parameter. It is possible this may be associated with differences observed in pipe roughness and the effect this can have on system shear stress. There is also clear effect of different parameters on the model performance at different periods across the entire dataset. This would indicate that short period calibration tests in cast iron mains may be beneficial but may not reflect the long term behaviour. From assessment of the sensitivity analysis results, it is suggested that using the difference between measured and modelled turbidity means provides a suitable objective function for verifying VCDM model parameters. The sampled period ideally should correspond to a significant event when turbidity responses are greatest, in this case at the beginning. With best calibration results and confidence in model simulations established, the VCDM is then a powerful decision support tool that justifies flow-conditioning as a widespread business-as-usual discolouration management strategy.

Investigating how the parameters change during the sensitivity analysis returns some interesting findings. Of note is that the more the regeneration rate is increased, the less simulation results are affected. This highlights that irrespective of intervention applied or costs involved, in less than a year the discolouration risk will return for this cast iron asset. From this it may be questioned if invasive cleaning strategies, or even pipe renewal, can be justified as sustainable to protect delivered water quality. On the other hand, it also highlights how periodic maintenance maybe essential, especially where network hydraulic changes may be expected. Mobilisation parameters show higher values during the beginning phase, suggesting that following the flow-conditioning material layers are potentially more stable and hence pose less discolouration risk. This work therefore supports the use of flow-conditioning as not only valuable in increasing network resilience, but also delivering longer term operational benefits.

Conclusions

The results of this study show;

- Flow conditioning is an effective strategy to increase network resilience.
- The Variable Condition Discolouration Model (VCDM) is a viable operational tool to inform discolouration management including maintenance scheduling and business-as-usual practices.
- Standard VCDM parameters developed from non-corroding mains may be transferred to cast iron mains.
- Site specific VCDM verification improves simulation accuracy and can highlight differences in discolouration behaviour between pipes of different properties.
- Short-term selected period calibration may provide VCDM parameter verification, particularly around key hydraulic events using means of measured and modelled turbidity as an objective function.
- Mobilisation and hence discolouration risk reduction is identified as a longer term operational benefit of flow-conditioning.

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Table 1. Flow characteristics in the main

Flow (l/s)	Velocity (m/s)	Reynolds number at 10 ºC	Wall Shear Stress (Pa)
60	0.365	127,680	1.5
80	0.487	170,350	2.0
100	0.609	213,030	2.5

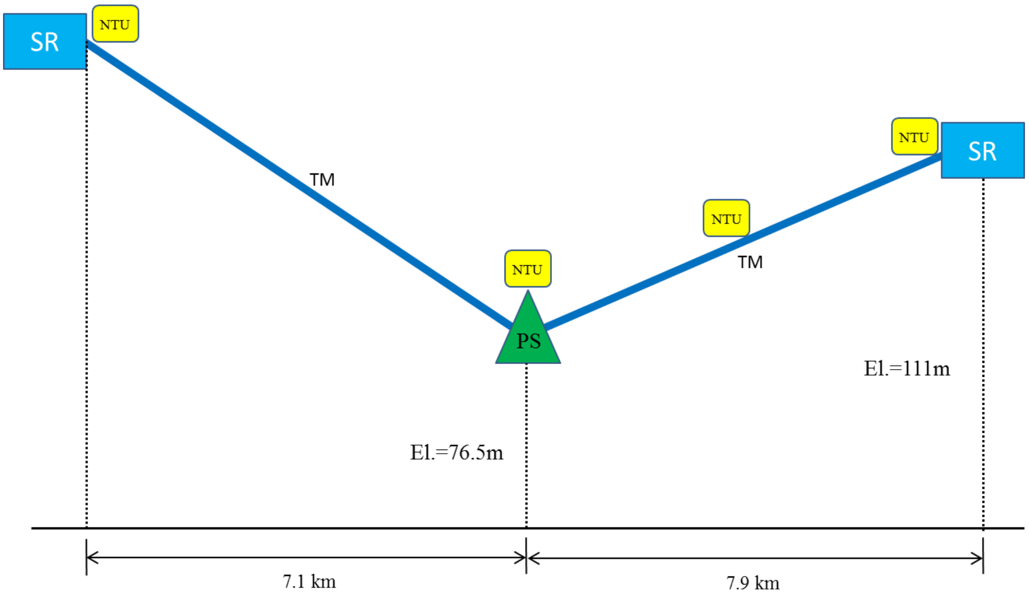


Figure 1. A schematic showing the studied 15 km 18” diameter CI main between two service reservoirs and the pumping station. Turbidity and flow monitoring points indicated.

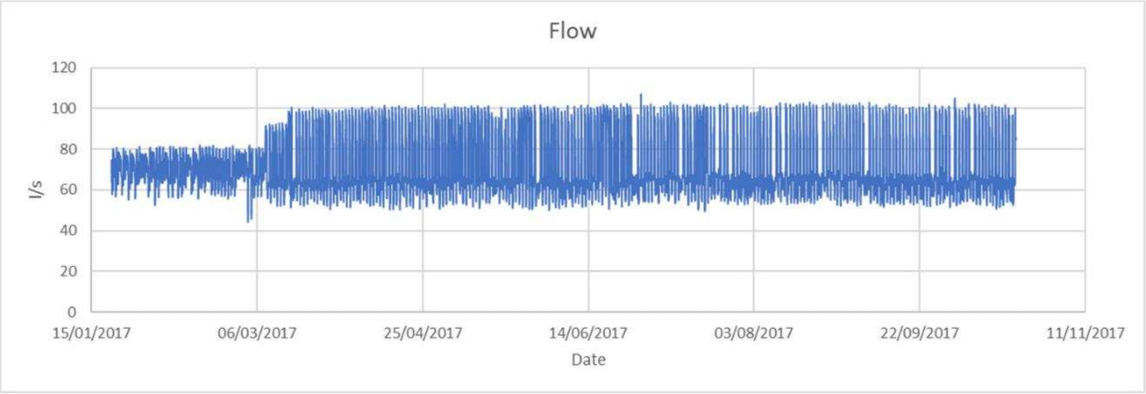


Figure 2A. The flow profile for the study period in the 18” CI main

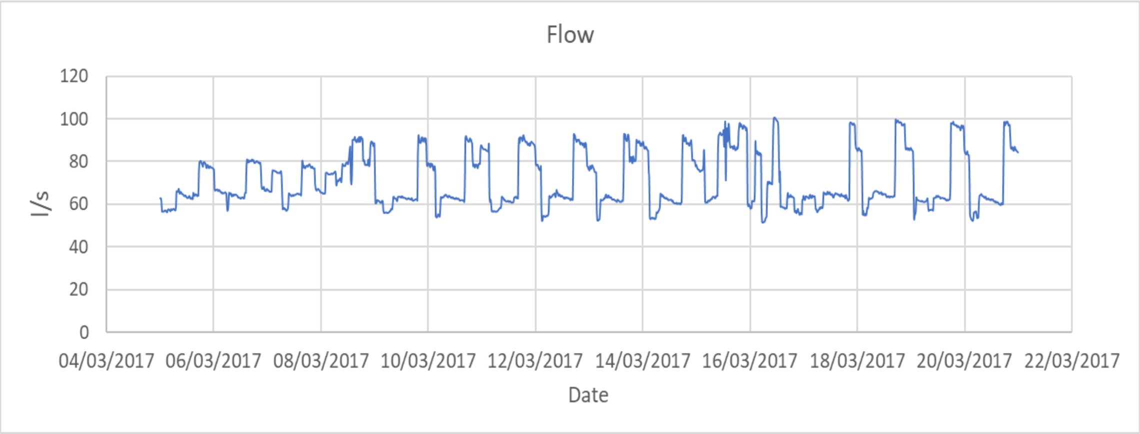
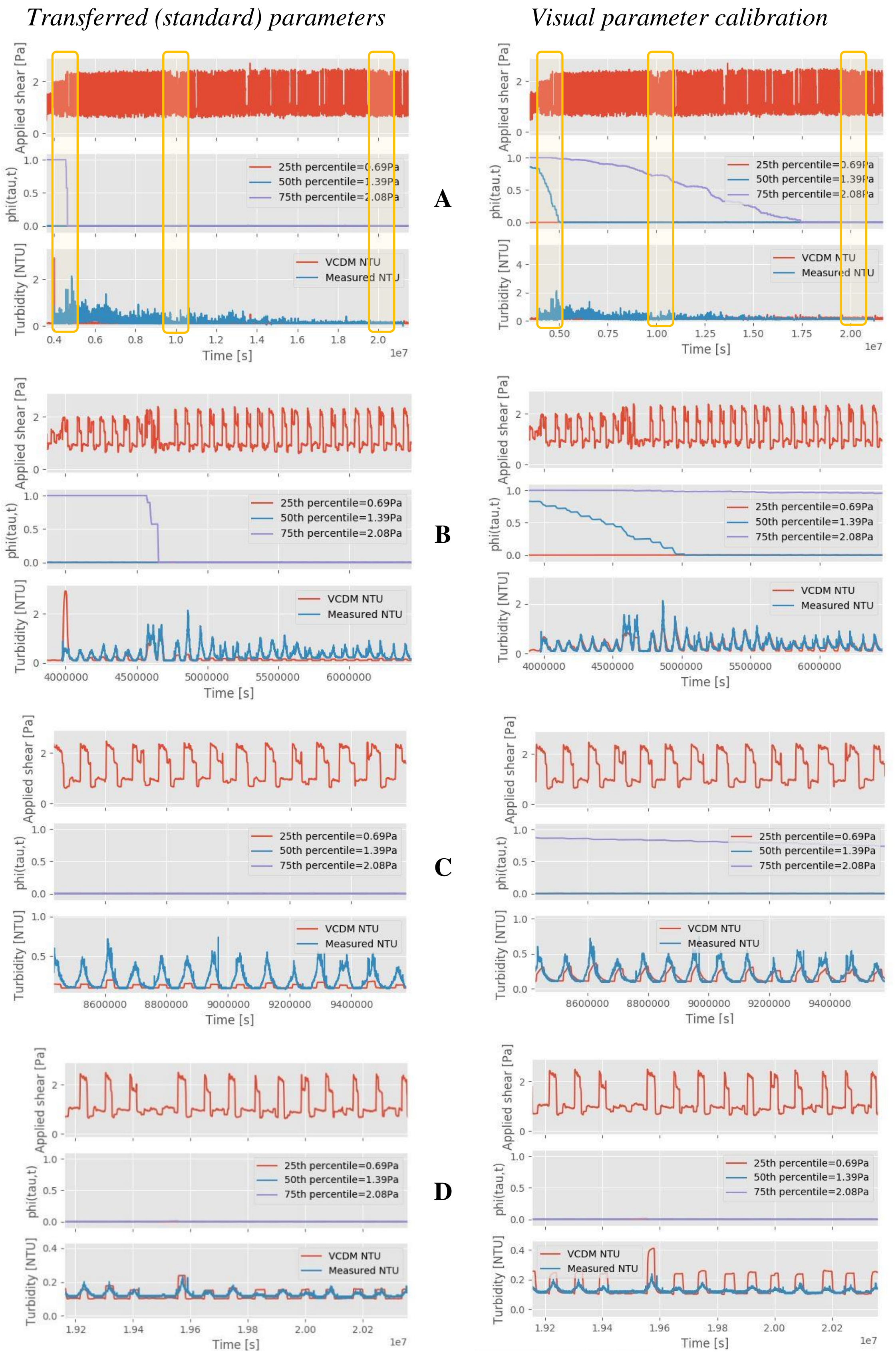


Figure 2B. Flow profile with gradual flow increase from 80 l/s peak to 100 l/s peak in the 18” CI main



Transferred (standard) parameters

Visual parameter calibration

Figure 3. Results of VCDM modelling using standard parameters and visually calibrated results, showing entire dataset and the 3 analysis periods at beginning, middle

and end (A). Each model output has 3 components, the top showing the applied shear stress profile (as determined by measured flow), middle shows the state of 3 representative shear stress bands (25th, 50th and 75th percentile, with y-axis 0 representing no material and 1 fully developed material layers, effectively maximum risk). beginning period (March, B), middle period (May, C) and end period (October, D).

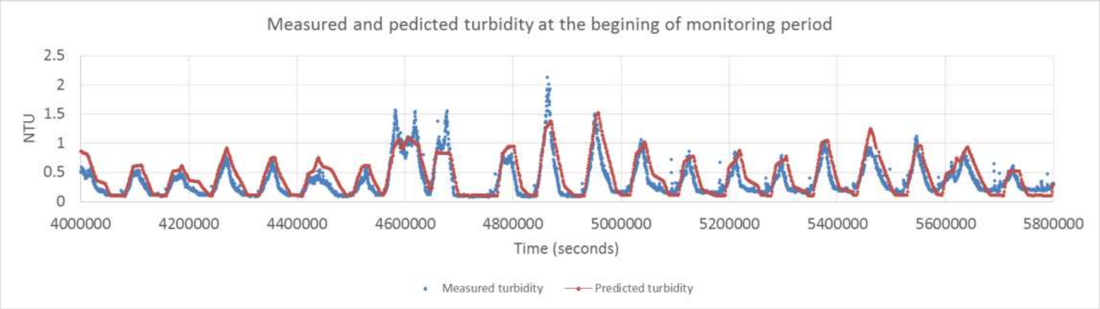


Figure 4. Measured and VCDM predicted turbidity in the beginning 21 day period.

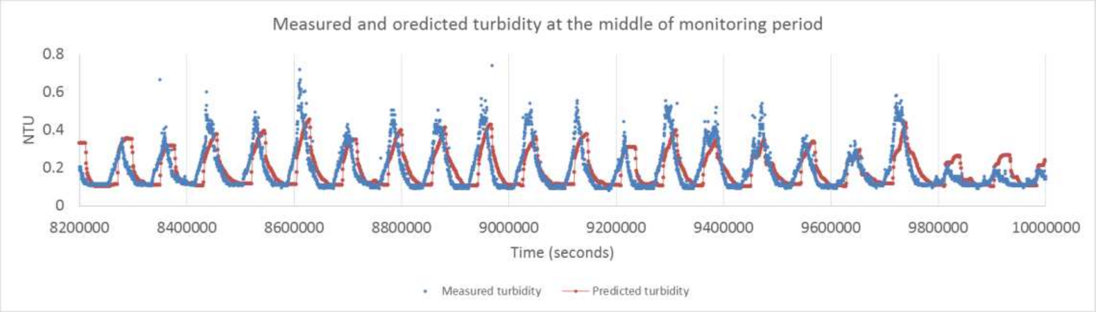


Figure 5. Measured and VCDM predicted turbidity in the middle 21 day period.

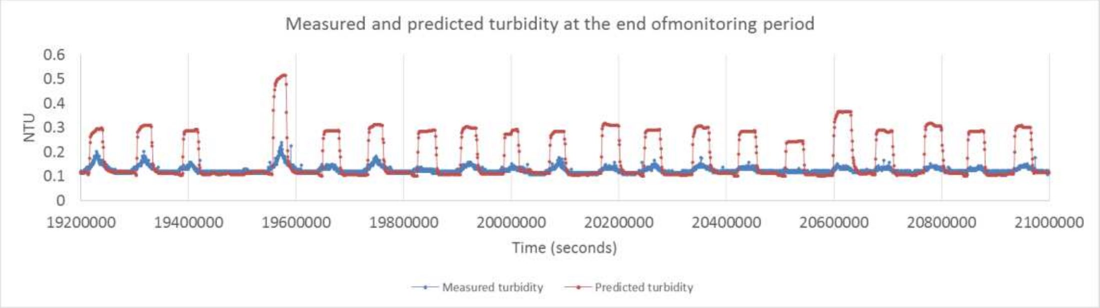


Figure 6. Measured and VCDM predicted turbidity in the end 21 day period.

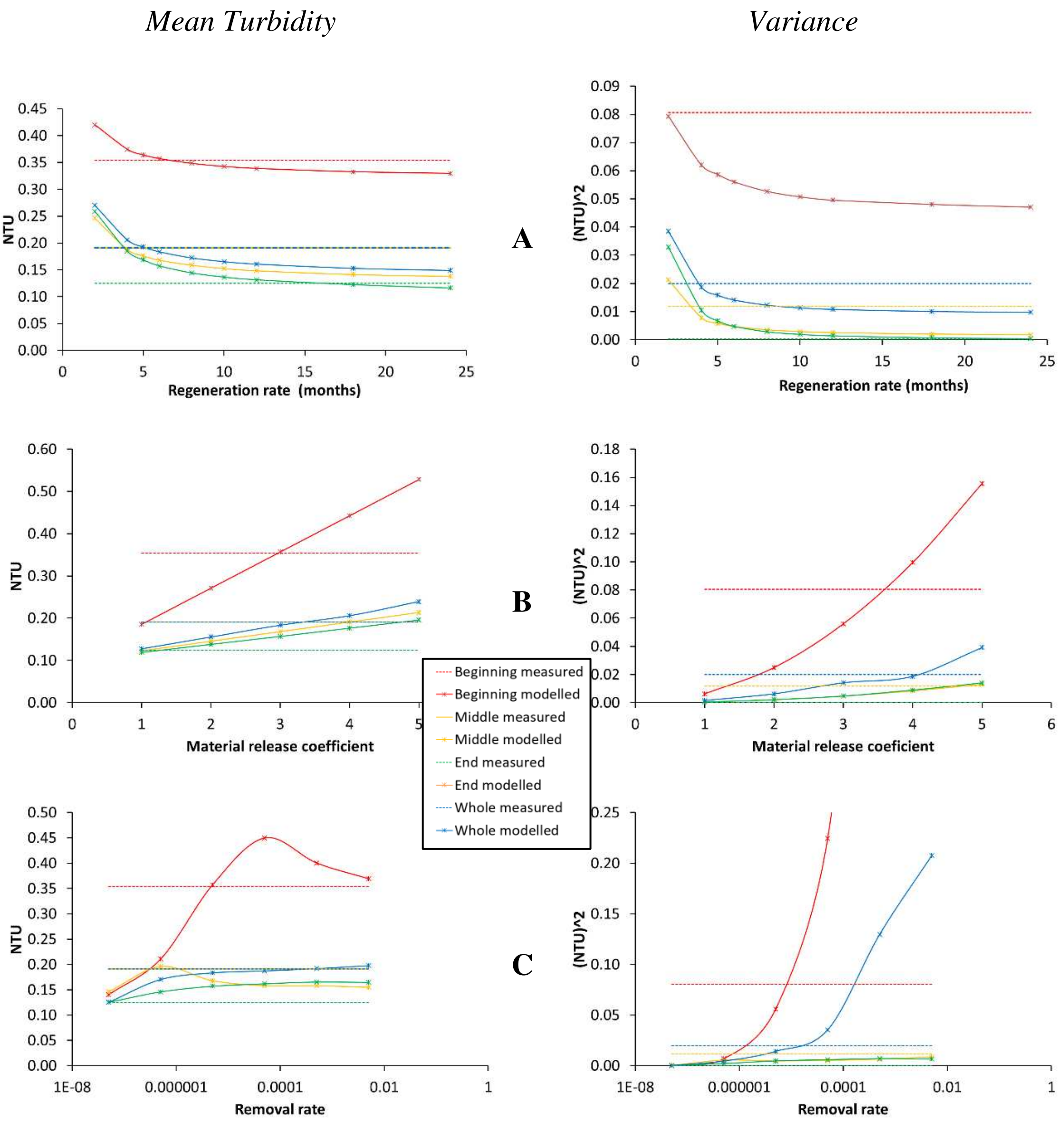


Figure 7. Relationship between the measured and modelled turbidity time series for regeneration rate (A), material release coefficient (B) and removal rate (C), showing comparison of means (left column) and variances (right column) for beginning, middle, end, and whole dataset.

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