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Identifying material accumulation processes in drinking water distribution systems with extended period EPANET MSX turbidity simulations

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Abstract

Discolouration is an international phenomenon in drinking water distribution systems due to erosion of particulate material layers. In the UK water companies are implementing hydraulic layer conditioning for maintenance and resilience with significant cost benefits, despite limited understanding of the material accumulation processes. In this paper 18 months turbidity data from a 4 km trunk main is simulated using four extended period Epanet MSX model formulations. The measured data demonstrates recurrent regeneration of discolouration risk and hydraulic conditioning as pro-active mitigation. Modelling facilitates investigation of layer regeneration processes, helping inform future discolouration models and operational strategies to safeguard water quality.

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Keywords: Discolouration; shear stress; conditioning; Epanet MSX

1. Introduction

Regulators of the privatised water suppliers in the UK now use customer contacts as a measure to rank company performance. With discolouration in drinking water distribution systems (DWDS) the principle observed water quality failing [1], reducing the occurrence of these events is therefore a key operational target. Research has demonstrated that discolouration is primarily a result of rapid hydraulic mobilisation of particulate material layers that accumulate ubiquitously on pipe boundary surfaces [2]. Understanding the factors and processes influencing this accumulation is therefore important for future discolouration model development and water treatment/DWDS

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managers to mitigate discolouration incidents, thereby reducing customer contacts and improving performance rating.

DWDS are complex chemical, biological and physical systems. Many factors influence the rate at which the serviceability of these assets deteriorates as material accumulates [3]. Together with the known inorganic constituents such as iron and manganese [4, 5], current research is highlighting biofilms as a principle component [6, 7]. Hence factors such as temperature, disinfectant residuals and organic content are likely to be important in addition to the hydraulic loading [8-10]. For layers of material to develop there must also be a source. Studies in distribution systems identified that discolouration risk in surface water sourced sites, with typically poorer bulk water quality, regenerated quicker than groundwater sites [11]. In addition sites with higher background metal concentrations (typically associated with corroding pipes or fittings), also returned higher regeneration rates[12]. This indicates bulk water quality as a key factor. One method to reduce the rate at which discolouration risk develops is therefore to improve the bulk water quality prior to distribution. This however has potential significant capital cost implications and only longer term discolouration risk reduction benefits. Alternatively DWDS operators may obtain immediate and long term benefits by managing the generation and erosion of discolouration causing material layers within DWDS, such as by hydraulic conditioning [13]. Understanding the factors and processes influencing discolouration material accumulation is therefore vital to develop computational models that can inform future risk and operational strategies to safeguard water quality.

In this paper 18 month turbidity data from a 4 km trunk main is collected and analysed. The measured data demonstrates discolouration risk regenerating and how hydraulic conditioning can be used as a simple and cost-effective pro-active mitigation strategy. The measured data is then used to calibrate four successive extended period Epanet MSX model formulations to investigate different modes of material layer behaviour. In the first model, only stripping of material layers is simulated, analogous to the existing PODDS model (see below). The second formulation then allows a percentage of the disturbed material to reattach when flows are reduced. With water quality an implicated factor, the third simulation adds the source water as a regenerator. In the first three MSX models, a single linear profile covering all shear strengths is used. In the final simulation this single profile is discretised allowing simultaneous erosion and regeneration for different shear strengths. Examination of the calibrated modelling results from the different formulations indicates factors governing regeneration. This helps inform future discolouration modelling requirements that can be used to develop long term DWDS maintenance programs.

2. Modelling Discolouration

In 2001 a novel approach to understanding the phenomenon of discolouration was published termed PODDS (Prediction Of Discolouration in Distribution Systems) [14]. The PODDS model describes the mobilisation of particulate material layers leading to discolouration. It was proposed that layers with a defined profile of cohesive strength properties accumulate continuously on boundary surfaces and are conditioned by hydraulic forces, the system shear stress. Although a constant low-level background flux of particulate material exists in the bulk water [15], it was proposed elevated concentrations visible to consumers was due to erosion of these material layers when the applied shear stress exceeds the cohesive conditioned state. This concept was coded as a user function into the 1D hydraulic modelling software EPANET [16] as a force balance between cohesive material retention and system mobilising shear stress. Since its publication over 1000 field and laboratory trials have been conducted that have verified its application within DWDS [17]. The PODDS model depicts single layers of material with defined shear strength τ_c (Nm^{-2}) and the erosion mechanism can be summarised as follows:

- Increase in flow causes increase in pipe wall shear stress, τ_a
- Material eroded is entrained in bulk flow at a rate that is a function of τ_a-τ_c if $\tau_a>\tau_c$ (note for simplification purposes and assumed due to particulate nature, the PODDS model includes no reattachment or dispersion processes of material eroded)
- Material (discolouration potential) at wall decreases but its strength τ_c increases.

With the knowledge DWDS, or more specifically the material layers on pipe walls, respond to hydraulic changes and the PODDS model is able to simulate this, effective maintenance strategies have been developed. Example strategies from project affiliated water companies include trunk main flushing, where water is disposed to waste (no strict flow control required), or *conditioning*, the use of controlled flow increases to incrementally remove material whilst the main remains in operation (i.e. increasing τ_a above prevailing conditions to remove material weaker than *target* τ_a). Both these approaches allow network managers to manipulate flows for resilience purposes or discolouration risk mitigation. Some example applications and cost benefits are listed in Table 1. Incorporation into 'business as usual' stratagems has also helped prevent discolouration incidents and associated remedial costs. As the material layers that have the potential to cause discolouration have been shown to develop continuously [11], there is effectively no such thing as a 'clean' pipe. Replacing mains, re-lining or invasive cleaning (all typically expensive and logistically challenging) are therefore not effective stand-alone long term discolouration control solutions. This is highlighted by Figure 1 showing evidence of material regeneration in a strategic 800 mm main only 12 months after cleaning. Note material can be observed around the full pipe circumference, commensurate with PODDS modelling results and biofilm research observing the microbial community to be ubiquitous and unaffected by position in pipe [18, 19]. A further 3 years after this picture, this network is reporting the discolouration issue back to levels recorded prior to the £25 million cleaning program. Ongoing maintenance is therefore essential, but at what frequency and optimal strategies are yet to be established.

To further improve management strategies for long term discolouration risk mitigation it is necessary to understand and model the rate at which assets deteriorate due to material accumulating on pipe walls. While the PODDS model is a proven tool for modelling the mobilisation of discolouration material, it does not specify the material responsible, the source of the force retaining this material to the pipe wall, or its rate of accumulation. No realistic regeneration mode is included and so long-term maintenance plans, with associated costs and justification of optimal investment strategies, cannot be evaluated. Current research developing the PODDS model to incorporate both the continual erosion and regeneration of discolouration material in DWDS is however progressing [20]. To ensure these second stage models are fit for purpose and accurately describe the behaviour, trials to elucidate factors governing regeneration are required. Given a suitable long-term data set that includes a variable flow and a subsequent turbidity response from a known length of pipe, it is possible to investigate by calibrating models emulating different behaviours. Although not feasible in the coded EPANET version, the PODDS model can be written as an EPANET-MSX (Multi-Species eXtension) model. EPANET-MSX allows for the consideration of interacting species, such as the particles causing discolouration in the bulk flow and on the pipe walls, to be coded as a customisable stand-alone executable program [21].

Table 1. PODDS facilitated operational savings.

Pipe properties	4km 600 to 400mm Mixed	7km 450mm AC	6km 350mm Unlined DI	10km 500mm and 18" Mixed	4km 800mm DICL
Proposed strategy	Swabbing	Swabbing	Main replacement	Flushing infrastructure	Jetting
Proposed cost	£490K	£530K	£2M	£1.3M	£300K
PODDS strategy	Overnight flushing	Trunk main conditioning	Trunk main conditioning	Trunk Main conditioning	Trunk Main conditioning
PODDS cost	£227K	£150K	£40K	£40K	[2]£5K
Savings	£263K	£380K	[1]£2M	£1.3M	£295K

[1]Savings deferred, £40k due to control valve and turbidity monitor installation
[2]£5K is water cost, already planned pump refurbishment and control valve installation

Fig. 1. Evidence of material regeneration around full pipe circumference in 800 mm main 12 months after invasive cleaning

3. Field Data

In this paper 18 months of turbidity data from a 4 km 450 mm DI trunk main is simulated based on the measured flow in extended period EPANET-MSX models. During the 18 month data collection period the main was subjected to a number of flow conditioning trials where hydraulic shear stress was increased in managed increments as part of normal operation. This strategy returned good temporal and turbidity magnitude variations facilitating calibration of different model formulations. Figure 2 shows a sample 16 days flow and turbidity data including four conditioning steps. For studies of this nature this site has a number of advantages, as identifiable from the flow pattern. Primary amongst these is that this main supplies a reservoir. This means flow magnitude can be controlled and a steady value obtained simply by valve or pump setting. Customer supply mains are typically more challenging to target or maintain specific flow values due to the dynamic nature of demands. In addition the reservoir allows water to be isolated for later discharge if required. This is advantageous as although the generalised mobilisation behavior from pipe walls can be predicted, every network is unique and the rates of material accumulation currently unknown. Trials can therefore mobilise unexpected material deposits such as may accumulate around fittings or low-flow zones including dead-ends and looped network tidal points.

As part of resilience planning, this trunk main was required to supply a flow of 40 l/s, higher than the current typical peak 18 l/s. Risk analysis and history from this site had identified that this would incur a risk of discolouration. With accurate remote flow control and monitoring available at this site, conditioning was selected as a viable and effectively low-cost strategy to achieve this target. Predictive PODDS modelling assuming complete material accumulation (in equilibrium with normal daily hydraulic conditions) and initial trials identified the scale of flow steps required to produce a 1 NTU response. This turbidity target was selected as a significant safety margin below the UK 4 NTU regulatory value. This allows the trunk main to remain operational, yet an effective cleaning step. The data in Figure 2 highlights how this managed process of stepped flow increases was able to gradually condition the main to accept higher flows whilst material is removed.

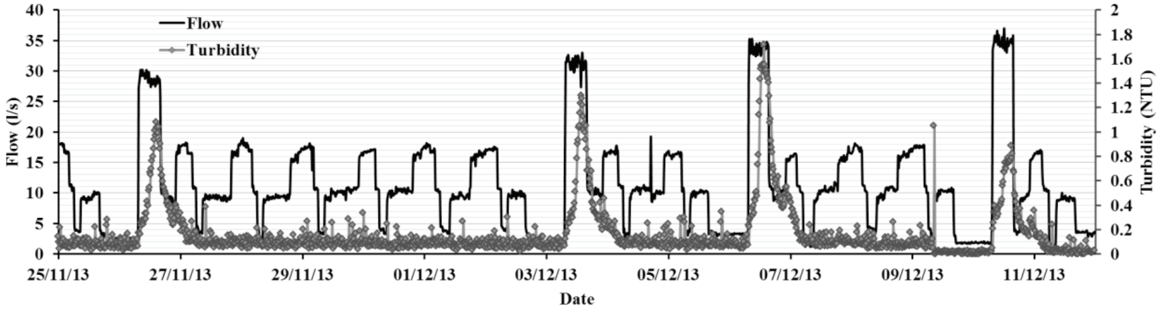

Fig. 2. Flow and turbidity data from flow conditioning trials

4. EPANET-MSX Modelling

With the customisable nature of EPANET-MSX different modes were coded to investigate factors influencing the material regeneration. Figure 3 shows three different measured turbidity and model calibrated turbidity outputs from 18 month, single pipe length, single period, MSX simulations. Each simulation is represented by three consecutive plots (note x-axis not consistent) to focus on key aspects during the data collection period. The first section (top) covers the conditioning period, hence the number of distinct turbidity responses. The remaining two sections cover a number of events with defined turbidity response. For all the simulations in Figure 3, accumulated material was defined as a single layer with explicit shear strength. For all simulations calibration quality is based on visual interpretation. Figure 3a shows the basic model in stripping mode only with no reattachment or regeneration. This is effectively the current PODDS EPANET model. As expected good simulation results are obtained for the initial flow increases. As time progresses however the model is unable to accurately reproduce the magnitude of the observed responses. This is because in this model mode material has already been eroded. Based on the PODDS concept, it can therefore be concluded that 'new' material must be present, i.e. layers are regenerating.

When material is eroded into the bulk flow, it has been suggested that if the flow is then reduced this causes some reattachment as this particulate cloud travels downstream. As radial processes bring flow entrained material into contact with the pipe wall allowing attachment [22], elevated concentrations would be expected to increase the attachment rate. This can be investigated by defining a simple relationship in the MSX code that allows a portion of the disturbed material to reattach when flows are reduced. The calibrated results of this are shown in Figure 3b. This shows improved calibration covering the conditioning trial period. However the later events are not simulated accurately. The turbidity responses from these events show initial model fit, but not full duration response. This indicates regeneration of material in the downstream sections (closest to the monitor) but not upstream. This is expected as material travels downstream but is not replaced. The results however supports the idea reattachment occurs when flows are reduced. It also suggests that for accurate long-term model calibration there must be a source of regenerating material. Based on this, an inlet source of material matching typical background levels was added to the MSX model from 3b and the results are shown in Figure 3c. This gives an acceptable calibration for the entire 18 month simulation although a number of anomalies remain.

These results from calibrating different modes of modelling discolouration response to measured data highlight a number of key aspects. Firstly the shear defined material layer concept is an accurate portrayal of the mobilisation process as shown accurate over the extended period. Secondly, layer generation is continuous and also a function of shear stress. In addition it demonstrates that bulk water quality directly informs DWDS material layer regeneration rates. This demonstrates the requirement for holistic water treatment and DWDS management strategies if water quality is to be maintained.

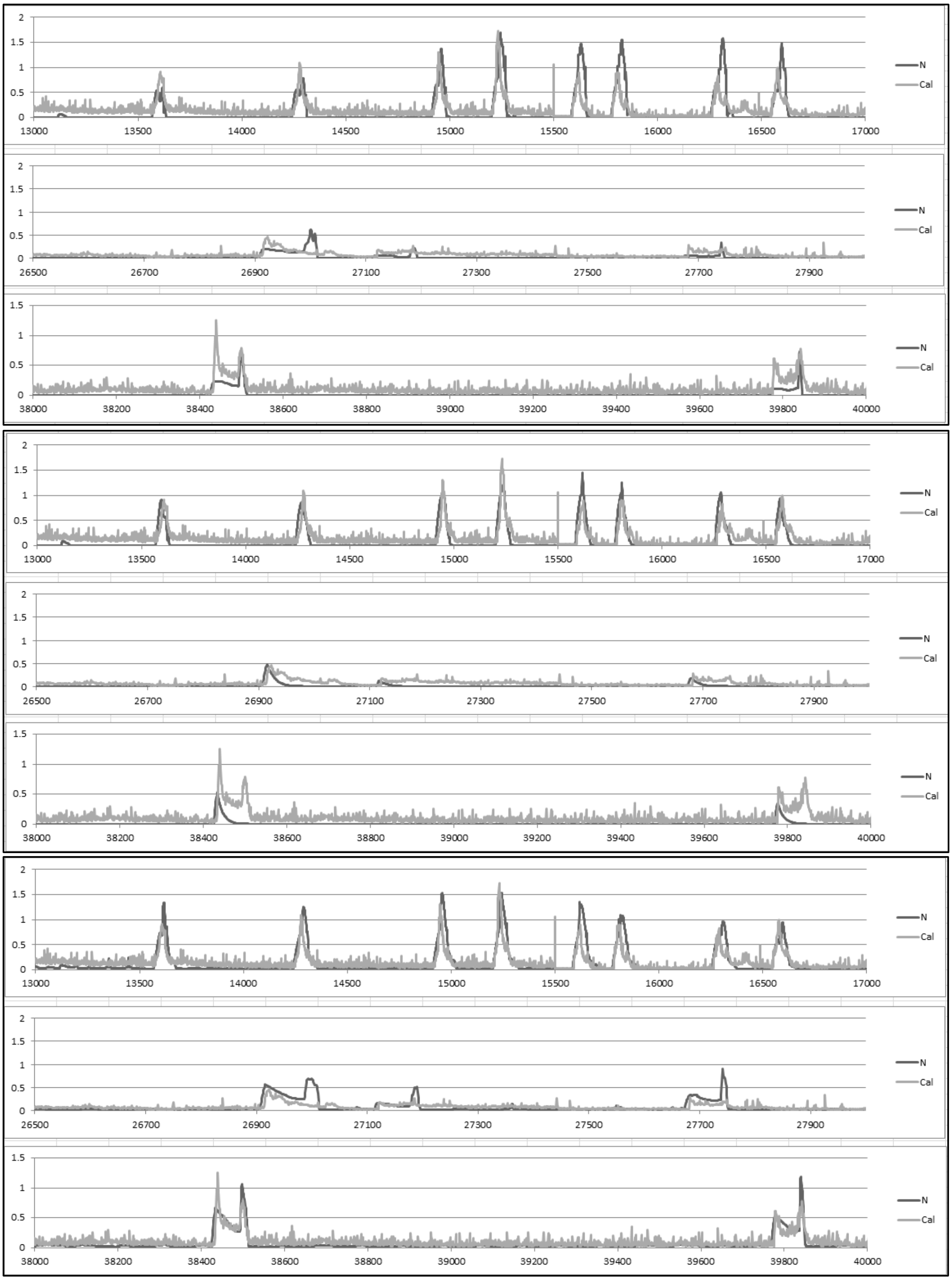

Fig. 3. EPANET MSX 18 month single layer, single model run, x-axis simulation time steps, y-axis turbidity in NTU. Darker line is measured *N*TU, grey line model *Cal*ibrated NTU a) Model in stripping mode only, no reattachment or regeneration, b) Model allowing disturbed material to reattach when flows reduced, c) Model with reattachment and source water acting as regenerator.

The MSX models above use a simple, linear relationship between the scalar shear strength and the discolouration potential during mobilisation. As with the original PODDS formulation, material is eroded in a sequential manner starting with the weakest layers. This approach has an operational value as it returns a single conditioned shear stress (Tc), an applied shear stress (or equivalent flow rate) below which no material is present. This value can be tracked producing a realistic operational flow limit in annually flow variant networks that can be used to prevent mobilisation events. A plot of the conditioned shear stress from the 18 month flow profile is shown in Figure 4a. It is unlikely that sequential material shearing occurs homogenously, yet with the PODDS model proving reliable it suggests it describes sufficiently well the general behaviour. This is perhaps a result of the large DWDS surface area involved in this process and the empirical nature of the PODDS model. Regeneration however has been shown to occur over a range of shear strengths simultaneously [20]. This simultaneous regeneration of discolouration material could be modelled if the amount of material at the wall is tracked over time for an array of discrete shear strengths [20]. An MSX model was coded by discretising the shear profile into 10 layers. The code for layer 2 of the 10 layer model where Tc2 is the conditioned shear for this layer, Ta the applied shear stress, D diameter, Z pipe length, N (NTU) the turbidity, K a turbidity factor, P is the mobilising (erosion) factor and P1 the regeneration factor is;

```
FORMULA    Te2    ((sgn(Ta-Tc2)+1)/2)*((sgn(L3-Tc2)+1)/2)*(Ta-Tc2)
FORMULA    Tr2    1/(Tc2-Ta)*((sgn(Tc2-Ta)+1)/2)*((sgn(Tc2-L2)+1)/2)
RATE       Tc2    Te2*P-Tr2*P1*NTU/Z
RATE       N2     Te2*P*4/D*K*DL2-(Tr2*P1*4/D*K*DL2*NTU/Z)
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Unlike the previous models this does not produce a single conditioned state but tracks the 10 layers. This is shown in Figure 4b. The coding of these individual layers reveals the model eroding and regenerating each layer simultaneously. Using this formulation, the simulation shown in Figure 5 is produced. This replicates well all aspects of the turbidity response to hydraulic changes. It can be noted from Figure 4b that layer discretisation was based on simple numeric division based on the shear profile, although effectively less than half the 10 layers are impacted during the trial. Further work remains to assess the number and size of layers and if variable mobilising or regeneration factors are required. At present however this work indicates discolouration causing material layers should be considered simultaneously eroding and regenerating constantly across a range of shear strengths with the regeneration rate based on background water quality including reattachment of material following mobilisation.

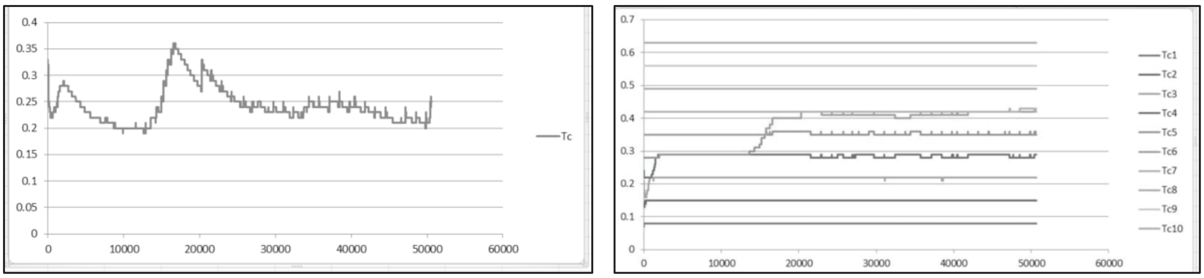

Fig. 4. EPANET MSX plot of simulation time step (x-axis) against layer conditioned shear strength (y-axis) for a) single layer model b) 10 layer model

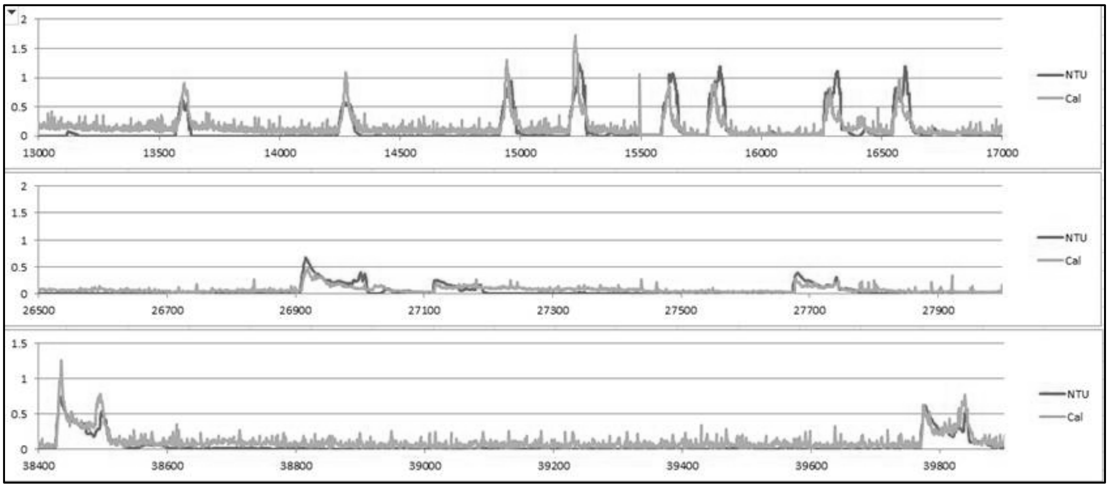

Fig 5. EPANET MSX 18 month 10-layer, single model run; x-axis simulation time steps, y-axis turbidity in NTU. Darker line is measured *N*TU, grey line model *Cal*ibrated NTU

5. Conclusions

Long term flow and turbidity monitoring demonstrates the regenerating behaviour of material layers in DWDS that when mobilised by increasing shear stress cause discolouration. By controlled tactical flow step increases, the eroding characteristics (as described by the PODDS concept) can be used as a simple and cost-effective pro-active discolouration risk mitigation strategy. Modelling of the data facilitates improved understanding of the erosion and generation processes and indicates that material layers with the potential to cause discolouration in DWDS should be considered simultaneously eroding and regenerating constantly. Furthermore, modelling indicates the regeneration rate a function of background water quality including reattachment of material following mobilisation.

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