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Practical Paper

Modelling discolouration in a Melbourne (Australia) potable water distribution system

J. B. Boxall and R. A. Prince

ABSTRACT

Reducing customer complaints of discoloured water is a major challenge for the water industry. The ability to predict the spatial probability and severity of discolouration events in distribution systems could lead to the implementation and optimisation of proactive operational and maintenance strategies to minimise discolouration. This paper explores the transfer of a predictive, semi-empirical model developed to describe iron dominated discolouration problems in the UK to an Australian system, where discolouration is primarily associated with clay type material. The paper presents the application of the model to a large diameter water main that forms part of the Melbourne system within a single source water quality zone. The model is based on cohesive transport theory and for this application includes the concept of a 'self-cleaning threshold', defined as a shear stress that the pipe experiences regularly, due to normal daily demand, that prohibits the accumulation of sufficient material within the pipe and hence poses no discolouration risk.

Results presented here show that the model can be calibrated to simulate the turbidity response measured in real systems due to changes in hydraulic conditions, for clay driven discolouration problems. These changes in hydraulic condition resulted from various 'natural' events which occurred during the available data period. Through such simulation the semi-empirical model parameters were evaluated. These simulations demonstrate the capabilities of the model, which could be applied to operational and maintenance practice. For example, to identify and prioritise network cleaning operations to minimise discolouration risk, at pipe level, through simulation of discolouration responses to various possible events (burst, fire fighting etc) and ranking the resulting predicted discolouration, or through prior simulation to identify the cleaning necessary to mitigate discolouration risk of planned operations such as valve movements.

Key words | discolouration, modelling, water supply

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INTRODUCTION

The occurrence of discoloured water within potable water distribution systems is a major source of customer complaints worldwide. Discolouration events have been widely reported in the USA and Canada (Deb & Hasit 1995; Ellison 2003), the United Kingdom (Childs 1987; Boxall *et al.* 2001), Australia (Prince *et al.* 2003*a*), the Netherlands (Slaats 2002) and France (Gauthier *et al.* 1999).

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Discolouration events are rarely due to true colour but rather suspended particulates (Prince *et al.* 2000; Boxall *et al.* 2001). Sources of materials causing discoloured water are as variable as the composition and characteristics of the systems within which discoloured water occurs. However there is agreement that nearly, if not all, systems foul eventually (Slaats 2002; Ellison 2003; Boxall *et al.* 2003*a*,*b*). Major material sources are thought to be long term exposure of the water distribution system to low, acceptable background concentrations of organic and inorganic material entering from the source water (Lin & Coller 1997; South East Water 1998; Kirmeyer *et al.* 2000; Slaats 2002; Ellison 2003), material from treatment processes (Gauthier *et al.* 2001; Slaats 2002; Ellison 2003), processes within the distribution system itself, such as pipe and fitting corrosion and lining erosion (Stephenson 1989; Gauthier *et al.* 2001; Clement *et al.* 2002; Slaats 2002; Boxall *et al.* 2003*a*), biological growth (Le Chevallier *et al.* 1987; Stephenson 1989; Clark *et al.* 1993; Meches 2001), chemical reactions (Stephenson 1989; Sly *et al.* 1990; Walski 1991; Lin & Coller 1997; Kirmeyer *et al.* 2000), external contamination that may occur during operations such as pipe repairs (Gauthier *et al.* 1996; Slaats 2002), intrusion (Gauthier *et al.* 1999; Kirmeyer *et al.* 2000; Prince *et al.* 2001) and backflow. These sources rarely contribute directly to discolouration events, but facilitate the gradual accumulation of material within the distribution system.

In simple terms it is thought that material accumulates during low flow conditions and becomes entrained into the bulk flow by a hydraulic disturbance (Walski 1991; Boxall *et al.* 2001; Prince *et al.* 2003*a*). Factors which may influence the specific mechanisms of collection and release of the material are the characteristics of the individual particles: material type (iron, manganese, clay etc.) and the associated particle properties of size, density, zeta potential (electric potential at the solid liquid shear plane) and the strength of electrochemical interactions. These interactions are complicated by the effects of particle concentration and effects of interactions between different materials and particle sizes; biological activity within the bulk water and at the pipe wall; corrosion rates and other particle supply rates; water quality parameters and effects on precipitation of metals and biological activity, flocculation; turbulent flow interactions with the pipe wall; and hydraulic regime. Thus the antecedent mechanisms of material accumulation and the subsequent triggering of the release of material leading to discoloured water are complex and are dependent on many system and material specific factors that are unknown, uncertain or hard to measure.

Predictive modelling of discolouration has the attraction that it may be used to optimise system operation and planning of proactive maintenance, minimising cleaning volumes, return frequencies and customer complaints. In Melbourne, Australia, for example operational maintenance for the control of discolouration events costs hundreds of thousands of Australian dollars a year, yet customer complaints of discoloured water persist (Prince *et al.* 2003*a*). There is potential for large savings and reduced complaints if the risk, location, severity and timing of discoloured water could be predicted, modelled, and managed.

This paper describes the transfer of a predictive, semi-empirical, cohesive transport model developed for predominately iron dominated discolouration problems in the UK to an Australian system, where discoloured water is primarily associated with clay type material. The model does not consider material source, accumulation or mobilisation mechanisms explicitly as it is empirical and is calibrated to take account of all of the relevant mechanisms and processes. The principal of the model is that the underlying interactions are consistent with the approaches adopted in cohesive transport modelling.

BACKGROUND

Cohesive transport model

From particle size analysis of material collected during flushing operations and discolouration events in the UK, Boxall *et al.* (2001) showed that under normal operating conditions the material causing discoloured water was held in suspension. In addition it was unlikely that quiescent conditions of a sufficiently long duration would occur in any part of the distribution system for gravitational settlement of the material to occur.

Boxall *et al.* (2001) proposed a new modelling approach based on the fundamental principle that discoloration material was held in stable cohesive layers attached to pipe walls within distribution systems. With the strength characteristics of these layers conditioned by the shear stresses that are imposed by the normal hydraulic performance of the system. The layers are assumed to have a defined profile of discolouration potential versus layer strength, with an increase in discolouration potential corresponding to a decrease in layer strength. The ultimate strength of the layers is dictated by the shear stress imposed within each pipe at the time of peak daily flow, hence peak daily flow controls the discolouration potential. The occurrence of disequilibria hydraulic conditions, for example caused by a burst event, operational or maintenance activity such as re-zoning or due to an increase in peak daily flow, may expose the layers to shear stresses in excess of their conditioned cohesive strength. This may lead to a mobilisation of the layers resulting in a discoloration event. The duration, magnitude and profile of discolouration events are hence a function of the strength vs. potential relationship defined for the layers, the conditioning hydraulics and the disequilibria or disturbing hydraulics. The strength vs. potential relationship within the model is defined by equation 1.

$$\tau_s' = \frac{C^b - C_{\max}}{k} \quad (1)$$

Where τ_s' (N/m^2) is the material layer yield strength, which varies as the layer is eroded and regenerated. C (NTUm) is a measure of the turbidity potential or stored turbidity volume of the layer. This may be visualised as shown in Figure 1. C_{max} defines the limits of the layer, k (NTUm^3/N) the gradient of the relationship and b (−) the order of the relationship. Mobilisation of the layers is described by equation 2.

$$R = P(\tau_a - \tau_s')^n \quad (2)$$

Where τ_a is the applied shear stress, hence $(\tau_a - \tau_s')$ is an 'excess' shear, which must be positive for erosion to occur. The coefficient P (NTUm^3/Ns) and exponent n (−) may be used to describe the effect of the eroding force. The source of the material is not considered explicitly within the modelling approach, but different material sources may be simulated by the selection of layer description parameters. R (NTUm/s) is the rate of supply of stored turbidity. This is used: i) to calculate the change in turbidity of a parcel of water under consideration through multiplication by the surface area (m^2) of pipe affected by the parcel of water during the simulation time step and division by the flow rate (m^3/s), and ii) to update the layer strength for the start of the next time step through multiplication by the time step. Supporting evidence for the selection of model type, consideration of the material source and full mathematical formulation of the model are presented in Boxall *et al.* (2001). The model approach is consistent with the variable strength concept developed to help describe erosion of cohesive estuarine mud (Parchure & Mehta 1985) and the model form is comparable to that developed to describe erosion of in-sewer deposits with cohesive properties (Skipworth *et al.* 1999).

The model uses turbidity as a surrogate for discolouration and the element of the model that is used to predict turbidity has been termed PODDS (**P**rediction **O**f **D**iscoloration in **D**istribution **S**ystems) and has been coded into EPANET (Rossman 2000). PODDS runs as a water quality element that utilises the EPANET substance tracking and transport algorithms. As such the model is subject to the assumptions of quasi-steady state modelling within EPANET, i.e. no transient or acceleration effects are considered.

The incorporation of such a modelling approach with a calibrated hydraulic model facilitates the prediction of the discolouration risk (potential and impact) posed by different network areas and pipe level activity. Once calibrated the model may be used to plan pro-active management strategies, for example the flushing of systems to reduce the risk of discoloration including flushing routes, clean water fronts, and optimum flushing rates through the simulation of likely system responses.

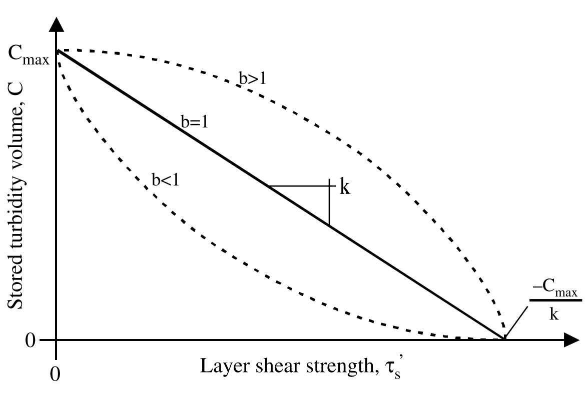

Figure 1 | Representation of layer strength versus stored turbidity volume relationship assumed in the PODDS model.

Self-cleaning threshold

Self-cleaning mains are those that achieve a critical shear stress (self-cleaning threshold) during normal daily operation such that material in the pipe is removed at low back ground levels on a daily basis and/or forces are sufficient to inhibit the initiation of layers such that cohesive layers cannot develop. Water companies in the Netherlands have been implementing the concept of a self-cleaning threshold for the design of new systems since 1999 (Vreeburg & Van Den Boomen 2002; Slaats 2002; Van Den Boomen *et al.* 2004). The work was originally based on laboratory results for smooth pipes and non-cohesive material, with subsequent fieldwork validation. The concept of the self cleaning threshold can be readily incorporated into the PODDS model by setting P in equation 2 to zero if the daily shear stress is above a defined value, hence prohibiting material mobilisation and turbidity generation from that pipe.

System comparisons

The PODDS model has been validated for a number of UK field sites, using turbidity data collected during network flushing operation, Boxall & Saul (2005). The main constituent of the material responsible for these discolouration events in the UK has been found to be particulate iron, irrespective of pipe wall material and with a mean particle size of around 10 μm. Similar size distributions were observed at all study sites (Boxall *et al.* 2001, 2003*b*,*c*). Model parameters have been quantified for different pipe materials including plastic, asbestos cement and cast iron pipes with diameters up to 150 mm. Within the PODDS model these parameters have been grouped as a function of pipe material and diameter.

In Melbourne, Australia, discolouration events have been found to be predominately associated with clay, silt and sand materials, originally from the source water (Prince *et al.* 2000). Clay size particles typically exhibit cohesive properties (Mehta & Lee 1994), and as long as over 10% of the material is clay with a particle size less than 2 mm, the material will exhibit cohesive properties (Raudkivi 1990). Hence the materials responsible for discoloured water in the Melbourne system may be expected to exhibit cohesive properties, and hence it was considered appropriate to investigate the application of the PODDS model to the Melbourne system.

THE MELBOURNE DATA SET

System characteristics

The Wantirna Water Quality Zone (WQZ), managed by South East Water in Melbourne, Australia was selected for the study. This WQZ is a small, self contained, gravity fed system, detailed in Figure 2. The system supplies 8890 properties and is predominantly residential. The resultant daily demand pattern is therefore consistent. Most of the system was constructed later than 1977 and as a consequence there are no unlined cast iron mains in the system. The source water (treated and disinfected by Melbourne Water) is unfiltered, as is 80% of Melbourne's water supply, relying on long detention times in reservoirs and selective depth withdrawal (to compensate for temperature stratification effects) from reservoirs to manage the quality of the water that enters the distribution system. Wantirna is supplied by Silvan reservoir, which has the highest historical turbidity readings of Melbourne's major reservoirs, 0.7–2.3 NTU (Prince *et al.* 2001). Since the totally quiescent conditions and long residence times of large reservoirs is insufficient for gravitational settling of the

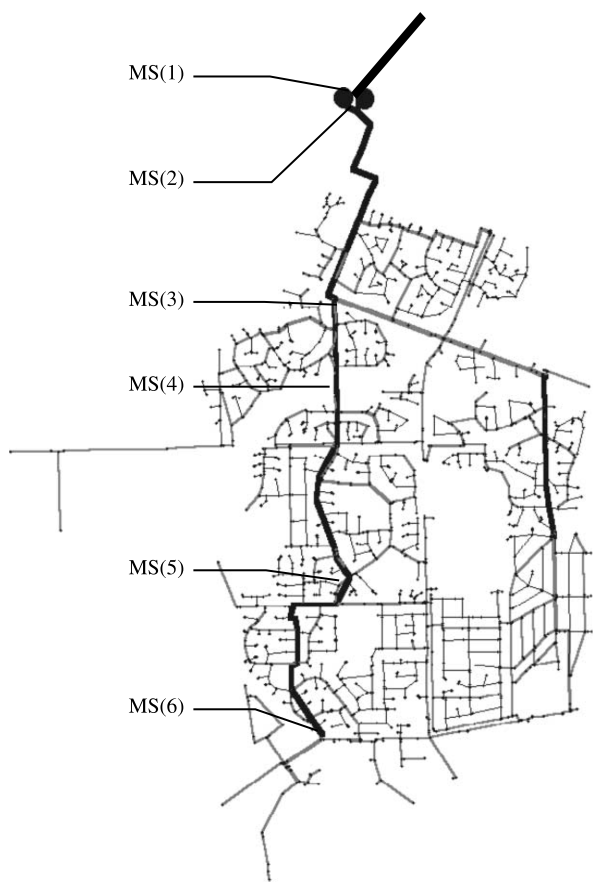

Figure 2 | Complete network schematic of Wantirna WQZ showing continuous online monitoring site (MS) locations.

material that is being continually supplied into the distribution system, it can be inferred that this material is unlikely to settle and accumulate due to gravity alone in the presence of network hydraulic conditions and retention times. The source water is dosed with chlorine, fluoride and lime. The zone has an above company average rate of customer complaints for discoloured water with six complaints per thousand properties per annum compared with a company average of three point four (Prince *et al.* 2003*a*).

Monitoring data

Six monitoring sites (MS) were installed down the west 450 mm 'backbone' transfer main of the Wantirna system (Figure 2). Data was collected with a temporal resolution of 10 minutes over the period February 2001 to June 2002. MS(1) serves as a monitor for the inlet to the system as a whole, while MS(2) as a monitor for any changes occurring through the storage reservoir. Data from MS(2) was therefore utilised to define the upstream, turbidity boundary conditions for this study. A number of additional measurement points were established as detailed in Figure 2, and at each point readings of flow and turbidity were recorded using COLT units containing a Hach 1720D low range turbidity meter. MS1 utilised an existing ultrasonic flow measurement device, MS2 an orifice plate device and the remainder Great Lakes Instruments flow meters. Further details of data collection and instrumentation can be found in Prince *et al.* (2001).

MS(6) is situated at the extremity of the transfer main. Downstream of this site demand is extremely low resulting in an excessively oversized pipe with low conditioning shear stresses and long detention times between MS(5) and MS(6).

Event data

During the 16 months monitoring period 30 turbidity spikes with turbidity greater than 4 NTU were detected. The cause of these events and the relationship to customer complaints were investigated and reported in Prince *et al.* (2003*b*). Many of these were unsuitable for model calibration for a number of reasons: short duration, due to disturbance upstream of the storage reservoir, cause of disturbance unknown, uncertain instrumentation response at two or more instruments or disturbance affecting only small sections of the system. Of the remaining events, five were selected to evaluate the PODDS model. Selection was made to cover a range of attributed disequilibria hydraulic trigger events (burst, accidental damage, fire sprinkler system and authorised and unauthorised hydrant operation), thus covering a range of magnitude and duration of measured turbidity responses.

MODEL APPLICATION

The model was set up and applied to simulate 6 states:

- The operational conditions prior to system events
- Event 1, a mains burst down stream of MS6
- Event 2, a burst hydrant between MS5 and MS6
- Event 3, a short duration event attributed to a fire sprinkler system malfunction down stream of MS6
- Event 4, due to use of hydrants by the fire department between MS5 and MS6 and after MS6
- Event 5, unauthorised hydrant use down stream of MS6.

Simplification of the network model

To reduce model simulation times and to simplify the calibration procedure, the hydraulic model was simplified to include only the monitored pipeline. The network shown in Figure 2 was simplified to that shown in Figure 3. The total length of the modelled pipe line from the reservoir to the final monitoring point is 5.5 km, the majority of which has a diameter of 470 mm and a Hazen-Williams roughness of 110. Off-take demand patterns and factors simulating the relative flows through each off-take were based on the outputs of the full hydraulic model. Comparison of pre- and post- simplification hydraulic solutions was undertaken to ensure no errors were introduced during this process. Figure 4 shows an example of the comparisons made for the modelled flow rates at each monitoring sites. However, from Figure 4 it can be seen that the flow rate in the original model is greater than that in the final simplified model, with a consistent error between all of the sites, up to a maximum of approximately 10 l/s. This discrepancy was not introduced through the model simplification and was

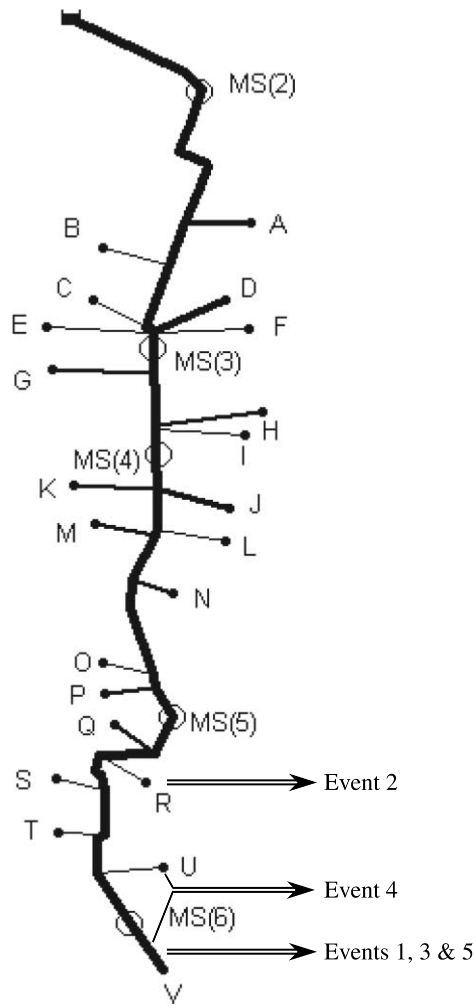

Figure 3 | Reduced network schematics of Wantirna WQZ, showing continuous online monitoring site (MS) locations and locations of hydraulic events.

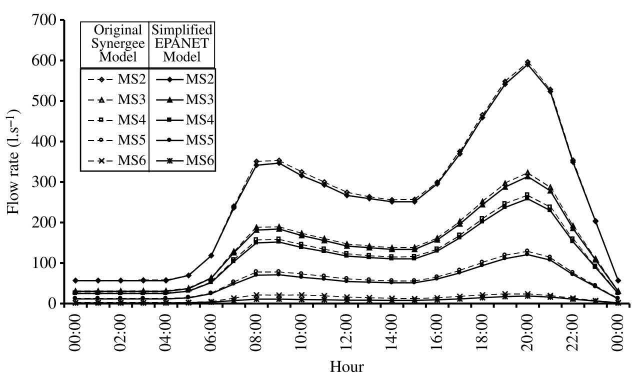

Figure 4 | Comparison of modelled flow rates from the original full system model in Synergee and the final simplified model in EPANET.

present in both the original full and initial simplified models. This discrepancy arises from a slight over estimation of the flow rate at MS(6) during the original model build, due to the fact that the flow rate was around the detection limit of the monitor. This was subsequently corrected in the simplified model. This correction is supported by the fit of the hydraulic predictions for the simplified model to measured data during the modelled events.

Calibration of the hydraulic model

In order to apply the PODDS model it was necessary to define two hydraulic states: 1) the hydraulic history prior to the disturbance, as this provides details of the shear stress that condition the strength of the cohesive layers within each pipe (conditioning hydraulic model); and 2) the disequilibria hydraulics that create a boundary shear stress that is in excess of the conditioned strengths, thereby resulting in a discolouration event (event hydraulic model).

From application of the PODDS model in the UK it was found that the conditioning hydraulics could be evaluated from calibrated daily hydraulic models, with the provision that no unusual hydraulic events had occurred in the preceding interval. The duration of this interval is a function of the rate of accumulation of material and the magnitude of the disequilibria hydraulics. The flow profiles measured in the study pipeline of the Wantirna system were observed to exhibit seasonal variation and a number of frequent small disequilibria events. As a consequence, it was found that flow data recorded in the week prior to each of the five monitored events examined in this study should be used to establish the conditioning hydraulics. The hydraulic conditions of each unique event were simulated by adjusting demand profiles at specific off-takes within the system, plots of this hydraulic validation for the five selected events are shown in Figure 5 to Figure 9. The hydraulic modelling was validated against flow data from monitoring sites and times not used in model set up.

Calibration of the turbidity model

In addition to the calibration of the hydraulic model, it is also necessary to calibrate the parameters used within the

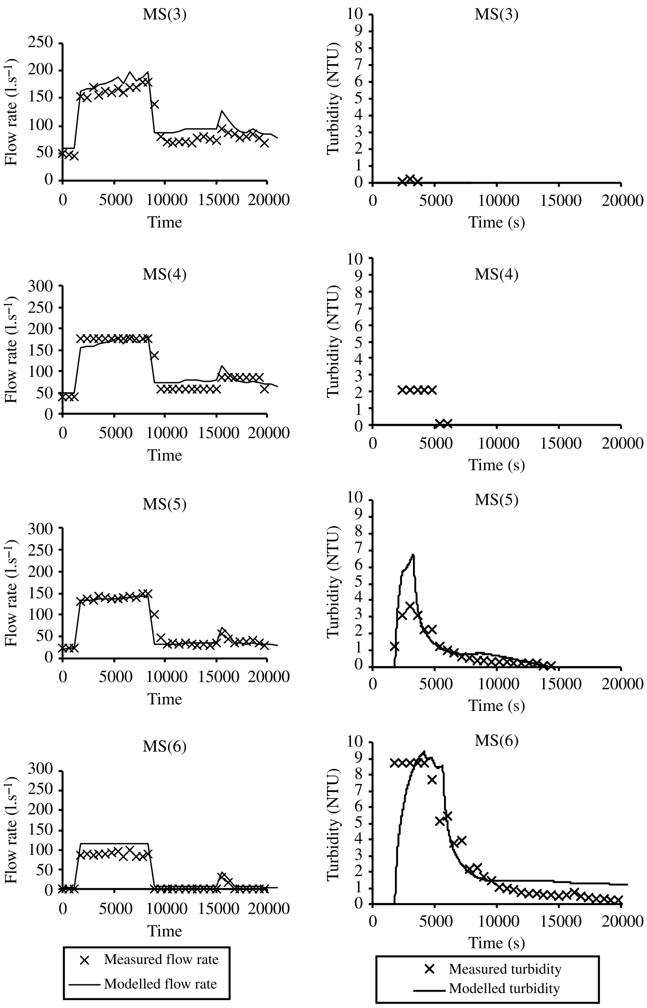

Figure 5 | Event 1, showing measured and simulated flow rate and turbidity.

PODDS model to produce simulations of the measured turbidity response. These are the PODDS parameters used to define the layer strength versus turbidity potential relationship (k, C_{max} and b) and the parameters that define the mobilisation of the cohesive layers (P and n), equations 1 and 2 respectively. The turbidity data from each event was utilised for calibration in a progressive manner. Parameter values were established for event 1, these values were then used as the basis for simulation of event 2, and revised parameter values then derived to best simulate both events, then event 3 was added, and so forth. Hence all event data was utilised for calibration purposes, no 'blind' simulation tests were performed with the dataset studied. However, the parameter values were found to converge naturally and little or no revision was made in producing the simulations shown for the last events. Hence events four and five were effectively verification tests, although minor revisions to some parameter values were made following these simulations. The simulations results presented here were obtained using the final parameter set.

Turbidity data used in this paper are of event turbidity, turbidity above a background datum; the average background datum is 1.4 NTU. Further explanation of event turbidity can be found in Prince *et al.* (2003*b*). This persistent background level of turbidity was not considered here, however it could readily have been accommodated in the model using standard EPANET functionality to define the source turbidity concentration for the duration of the simulation and throughout the system at simulation time zero. When assessing these results it should be noted that turbidity monitors had an upper limit of 9 NTU event turbidity, instruments at monitoring sites 3, 5, and 6 having a resolution of 0.2 NTU whilst monitoring site 4 had a resolution of 2 NTU.

Turbidity calibration was undertaken using the PODDS model within the EPANET software. Spreadsheet and macro functionality was used to facilitate the adjustment of model parameters for the pipe lengths on a global or local basis and visual and mathematical evaluation between measurements and prediction. Calibration was an iterative process, employing both manual techniques and Evolver© Genetic Algorithm (GA) search techniques.

SIMULATION RESULTS FOR EACH EVENT

Application of the PODDS model with calibrated parameters showed that there was a good fit between the model simulation and the measured data for all events (Figure 5 to Figure 9). The same values of PODDS model parameters were utilised throughout the pipe length. This was desirable to prove the ultimate usefulness, in particular the transferability of the model. Uniform parameters should be expected given that the pipe length monitored and modelled from the Wantirna WQZ is of consistent diameter, material, age and roughness, and assuming that the material layer characteristics within these pipes are spatially and temporally uniform. The same value of self-cleaning threshold was used for all of the events, however this results in different extents of the self-cleaning zone for each event, dependent on the shear stresses predicted by the conditioning hydraulic model.

Event 1, shown in Figure 5, was attributed to a mains burst that increased flow for a prolonged period in the distribution system downstream of MS(6). This event resulted in a hydraulic disturbance imposing shear stresses that were significantly greater than the peak conditioning forces and resulted in relatively high turbidity. At sites where the monitoring instrumentation was operating at an accuracy sufficient to provide meaningful data (MS4 was only accurate to a resolution of 2NTU) a good fit of simulation to measured results was achieved.

Figure 6 shows the measured and simulated turbidity results for Event 2, attributed to a burst hydrant. The event resulted in an atypically high demand for a prolonged period in the distribution system between MS(5) and MS(6). As can be seen the simulated turbidity response at MS(5) is good and the predicted response at MS(4) is adequate, taking into account the resolution limitation of the measured data at MS(4). At MS(3) the self-cleaning threshold eliminated the prediction of any turbidity response in the model, this compares well to the small measured response, hence this was considered an adequate fit. At MS(6), downstream of the event, the model simulates the eventual propagation of the turbidity spike from MS(5) virtually unchanged other than a small amount of additional turbidity due to the short pipe length between the measurement site and the event location. The measured trace shows lower turbidity than the simulation during this period, suggesting that decay in the peak turbidity occurs during the long (~14 hours) travel time to MS(6). The measured data also shows a turbidity response prior to the model prediction. Such an early response may be due to mobilisation by surge effects, caused by the sudden

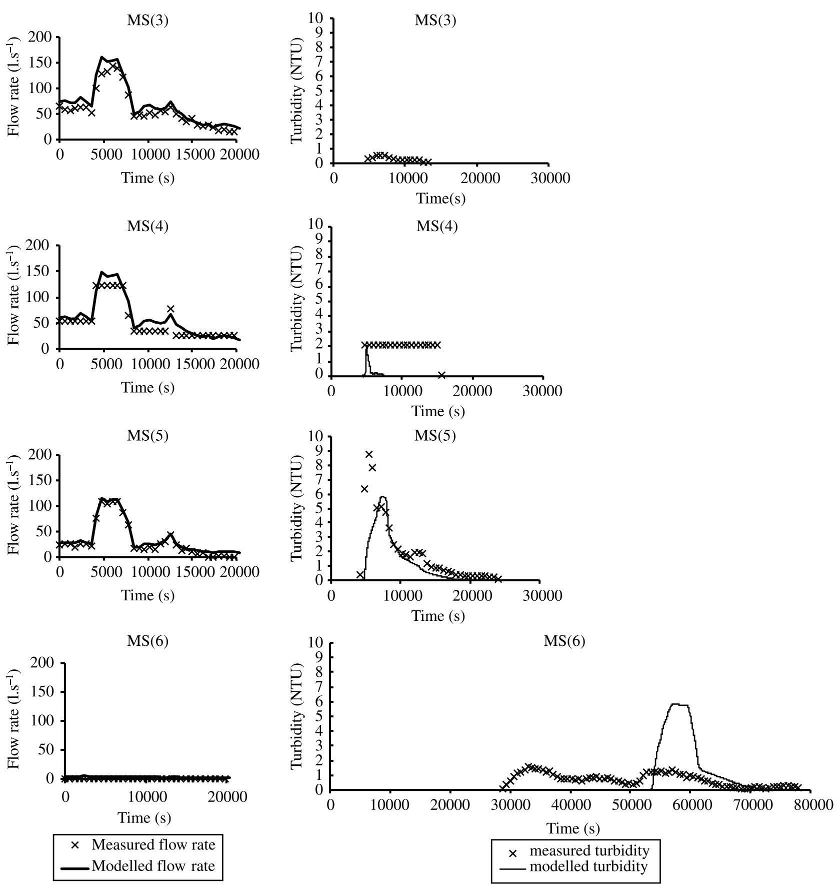

Figure 6 | Event 2, showing measured and simulated flow rate and turbidity.

burst event. Such surge events are not simulated by the standard EPANET hydraulic model utilised in the study and hence the model predictions do not estimate the influence of surge effects.

Figure 7 shows results for Event 3, attributed to a fire sprinkler malfunction in a factory. Event 3 resulted in a short duration (only measured by two data points ~20–30 mins) increase in flow downstream of MS(6). The measured and simulated data gave a good response at MS(3). No data was measured at MS(4). At MS(5) and MS(6) the simulated turbidity responses were dominated by slow propagation of the turbidity produced further upstream in the system, by the usual hydraulic conditions in that part of the system. The measured data does not display these propagation effects,

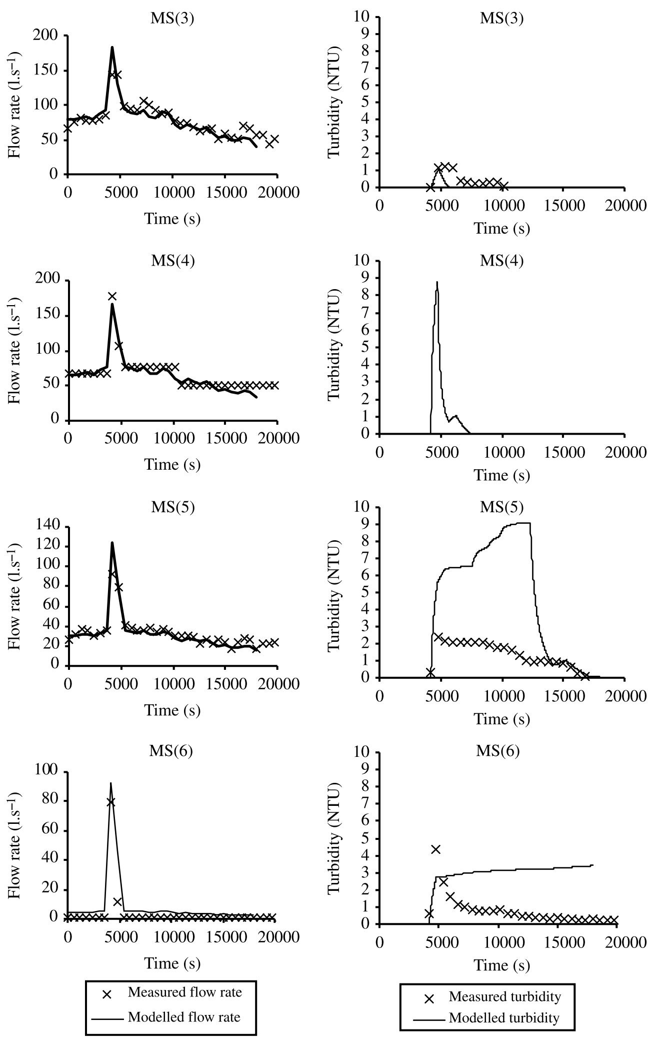

Figure 7 | Event 3, showing measured and simulated flow rate and turbidity.

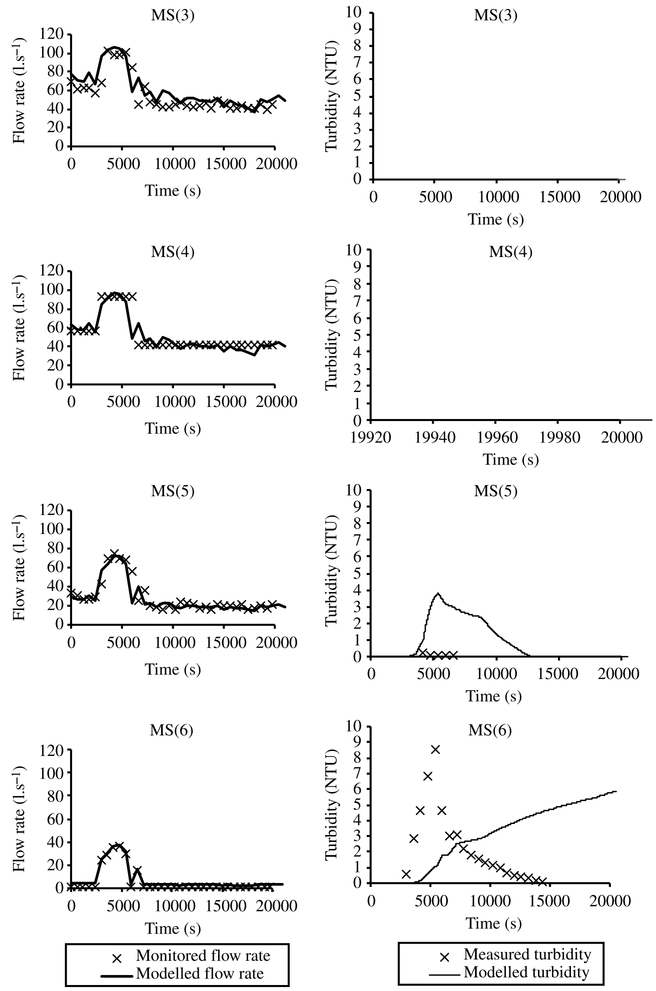

Figure 8 | Event 4, showing measured and simulated flow rate and turbidity.

although the measured and prediction end times of the event at MS(5) are consistent. Comparison of the measured data between MS(3) and MS(5) suggests that material is lost to the pipe wall during prolonged transport, evidenced by a reduction in measured turbidity.

Figure 8 and Figure 9 show results for Event 4 and Event 5 respectively. Event 4 is attributed to the fire department using hydrants in the distribution system downstream of MS(6) and in the system between MS(5) and MS(6). Event 5 was suspected to be caused by unauthorised hydrant use in the distribution system downstream of MS(6). Both these hydraulic events are of lower magnitude than the previous events. Minimal or no turbidity was measured at MS(3) to MS(5) during these disturbances, and the PODDS model has

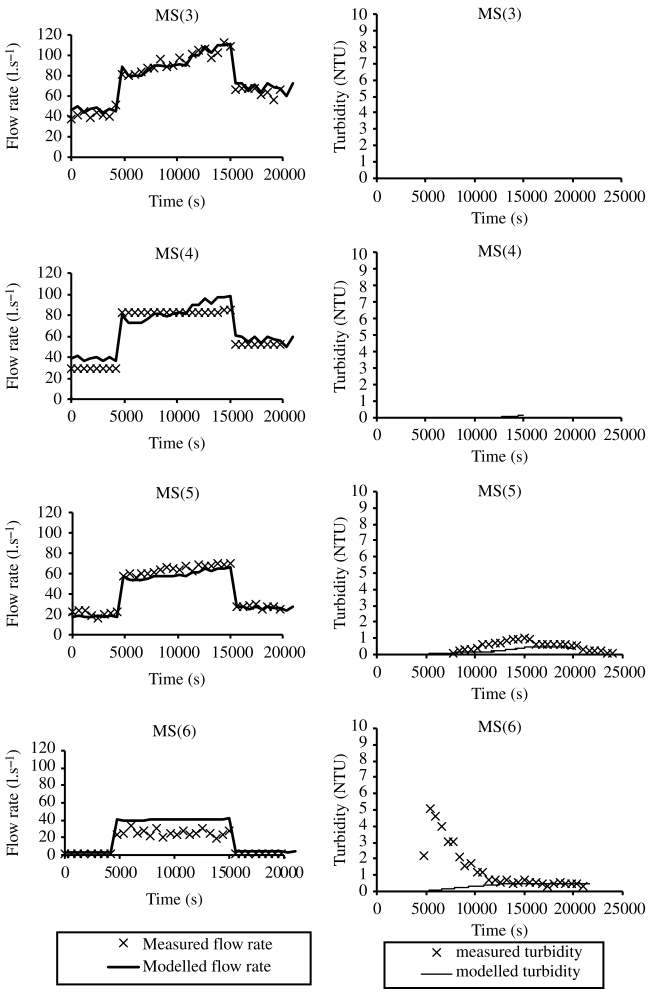

Figure 9 | Event 5, showing measured and simulated flow rate and turbidity.

simulated this limited response, for example event 5 at MS(5). For both of these events (and indeed events 2 and 3) the measured response at MS(6) was not well simulated. It is suggested that the extremely weak hydraulic forces and long residence times of this section of the distribution system may result in different material accumulation processes and layer strength characteristics compared to the rest of the pipe length.

OVERALL DISCUSSION AND INTERPRETATION

Acceptable simulation of the measured turbidity responses were observed in the transfer main upstream of the various hydraulic disturbances for the duration of the events. These predictions were based on a conditioning shear stress, calculated for the flow regime in the system one week prior to each event, and consistent PODDS parameters (k, C_{max}, b, P and n) and self-cleaning threshold shear stress. The consistency of the values used suggests that the processes leading to discoloured water are temporally and spatially consistent for that part of the system upstream of the disturbances. These results give confidence in the application of the model to other pipes and systems, however work in the UK suggests that the PODDS parameters are a function of pipe material and diameters. Further calibration work should therefore be undertaken prior to the transfer of the methodology to other systems. Once calibrated the PODDS model is able to predict the performance of systems with clay like particles when disturbance effects are local and travel times are relatively low.

Application of the PODDS model led to the quantification of the self-cleaning threshold shear stress that occurs in the Wantirna system. A single value of $1.12\,N/m^2$ was found for all the events examined. This is more than double the value of $0.47\,N/m^2$ suggested by Slaats (2002). This difference could be due to the derivation of the value reported by Slaats 2002 from laboratory studies with non-cohesive sediments, although this value has subsequently been validated against field trials, could be due to differences in material characteristics between the Wantirna and Dutch distribution systems. Quantification of the self-cleaning shear stress threshold has significant implications without the need for further model development. For example system management, operation and design can be optimised to maximise the occurrence of shear stresses in excess of the threshold, maximising the area of the system maintained in a clean state, cleaning programs can be planned to target only potentially dirty pipes and a clean water front for spot flushing readily identified.

Simulations for both events 2 and 3 provide good agreement to monitored turbidity data for the duration of the events and upstream of the event locations. The PODDS model predicts well the short term turbidity response to hydraulic disturbance, but does not predict the loss of material from the bulk flow during prolonged transport in the pipe line downstream of the hydraulic disturbance. This is because the PODDS model assumes that material remains as a permanent suspension once mobilised. This assumption has been appropriate for data collected and the events modelled to date in the UK, but appears inappropriate for the long residence time and the clay driven processes of the Wantirna WQZ, as some accumulation, flocculation, or other process appears to occur within the pipeline. Defining the rate of turbidity losses from the bulk flow after the disequilibria event would enable the prediction of discoloured water response downstream of the event location. This would enable whole system scenario management and risk assessment. The apparent loss of turbidity from the bulk flow could be due to flocculation, electrochemical, particle to particle or particle to wall interactions, or interactions with biofilm. This would require further research into the processes and development of the PODDS model, a first step would be to include reactive substance decay models, such as already included within EPANET.

Development of a table of PODDS parameters based on available information such as source water quality, pipe material and diameter would enable the model described in this paper to be applied to any system for scenario management to predict discolouration formation upstream of an event. For example the model could be used to predict the upstream water quality response of a system due to planned operational procedures, or to estimate the discolouration risks posed by different pipes, and cleaning programmes planned accordingly. Such a table could readily be developed from monitoring of existing flushing programmes or other turbidity data.

Calibration of the cohesive layer regeneration parameters already built into the PODDS model would facilitate long-term risk assessment and allow for the calculation of cleaning repeat rates, maintenance intervals (Boxall *et al.* 2003*a*). This is currently being investigated by the University of Sheffield for UK systems. Regeneration rates and the increase in available material from the transport and recollection of upstream turbidity would also seem important for modelling the extremity of systems such as at MS(6).

The results of the comparative study show that the PODDS model, including a self-cleaning threshold, is applicable to the Melbourne system and could be a useful tool in operational planning and management. Some additional research and development would allow for further application of the model for risk assessment and mains cleaning repeat rates.

CONCLUSIONS

- The PODDS model has been used to simulate the low turbidity response measured as a result of 'naturally' occurring hydraulic disequilibria in relatively large diameter transfer pipes for the clay dominated discolouration problems of Melbourne, Australia. Good agreement was observed for hydraulic events that did not allow any accumulation of clay particles.
- The PODDS model utilises consistent parameters to describe material layer characteristics and critical shear stresses over the complete pipe length and between different events, suggesting good potential transferability.
- Some consistency was found between the model parameters required to simulate iron dominated UK systems and clay dominated Australian systems.
- A consistent self-cleaning threshold value was found for all events. This could be used to facilitate the development of operational maintenance strategies, for example changing flow routes in existing systems such that this threshold is regularly achieved. By doing this no material could accumulate within those sections of the system and hence poses no risk of discolouration what ever the imposed event hydraulics.
- Further research is planned to refine and simplify the PODDS model for practical application and for the development of look-up-tables of parameter values to allow for easy, system wide, predictive use of the approach. For example for the simulation of discolouration resulting from planned operations or expected changes in demand (i.e. seasonal variation) such that the cleaning necessary to mitigate associated discolouration risk can be evaluated.

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