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The use of high resolution monitoring in the management of water quality failures caused by discolouration

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Water quality failures caused by discolouration has become a serious problem for water service providers as they seek measures to comply with increasingly stringent standards from regulatory authorities. Such measures include tools that would enable them predict discolouration events before they occur, so that they can act in a more proactive manner. This paper demonstrates how high temporal monitoring of the distribution networks could be a useful tool for better prediction and management of discolouration. The turbidity results from high temporal measurements show that the bulk of sediment movement across networks are at low concentration; 75% of sediment movement caused by hydraulic disturbance was of low quantity (< 2 NTU), why 13% was of higher quantity (> 4 NTU). This suggests that during normal operations, distribution networks are in most cases, self-cleaning. Monitoring of sediment movement at low concentration proved to be useful in predicting discolouration risks as an increase of the former by 37 to 50% resulted in a quality failure in most cases. Such observation of sediment movement in a network was possible with measurements at high temporal resolution. High temporal resolution data was also used to map sediment budget of 0.032 kg in a section of a 400 m length network, which was equivalent to 1.04 $gm^{-1}y^{-1}$. It was also possible to monitor turbidity with residual chlorine concentration which gave a weak positive r^2 value of 0.107. Overall, the results suggest that a great deal of water quality information could come from high resolution monitoring of networks and therefore could help to proactively reducing discolouration risk.

Key words: Water quality, turbidity, sediment movement, discolouration, hydraulic disturbance.

INTRODUCTION

Failures in water quality can be defined as an event of exceedance in one or more quality standards set by regulatory authority. Management of these failures in drinking water quality have become a subject of strong concern for regulatory authorities in many parts of the world (Sadiq et al., 2008; Andreas et al., 2008). Among the various customer complaints about water quality failures, those with regards to its aesthetic qualities are in

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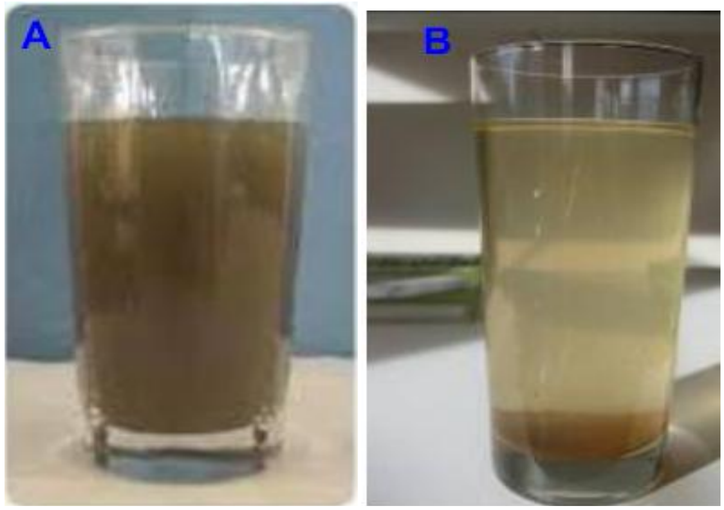

Figure 1. Showing discoloured water before (A) and after (B) it had been allowed to stand for a while with a partitioning of the water into its clear (upper) and sediment (bottom) phases.

most cases, highest on the list of reoccurring issues. This is because many of such water quality failures, for example discolouration and chlorine-induced odour are largely unpredictable and measures to manage them are only carried out after it has been called for by several complaints from customers. The risk of the unpredictable re-occurrence of these events is likely to put more pressure on companies in the water sector, or water service providers (WSPs) as they are called in the UK, given that they are required to ensure the provision of water of high quality to customers at all time. Furthermore, the Water Service Regulatory Authority (WSRA) in the UK requires WSPs to provide these services to customers at minimum cost. WSPs that do not comply with regulatory water quality standards could however, face fines and requirements to make commitments to improve on the quality of their water. Despite the huge investment within the water sector, the risk of failures in critical water quality parameters like discolouration (Figure 1) still remains a key cause for concern within the UK water sector (Cook et al., 2005).

Consequently, there is a likely problem of increasing operational and administrative cost as regulatory authorities become stricter on their quality requirements. Hence, there is an urgent need on the part of WSPs for proper management of the issue of water quality failures. However, for the issue to be properly managed, it would be necessary to be able to predict its occurrence with greater confidence. Accurate prediction would require a better scientific understanding of the causes of these failures which are at the moment high on the complaint list. In a recent study carried out to explain the possible mechanism of discolouration, Husband and Boxall (2011) proposed a two-phase process requirement for discolouration events. These are:

1. A supply of material to the distribution network (which could come from the treatment process) and material accumulation (which could be likened to a depositional zone in hydrological terms).
2. Material mobilisation which at sufficient quantity, could ultimately result to a discolouration event.

The proposal therefore suggests that for discolouration to occur, there must be a sufficient amount of particulates (or sediments) available within the distribution system ("sediment availability"), whereas mobilisation or suspension would require hydraulic disturbances like an abrupt change in flow or pressure (Boxall et al., 2001; Prince et al., 2003). This became the underlying concept on which some established models used in predicting discolouration risks were based. An example is the Resuspension Potential Model (RPM) which uses changes in unidirectional flow as obtainable in water-distributing pipeworks in studying the risk of particulate resuspension (Vreeburg et al., 2004) and the risk of discolouration using the discolouration risk model (DRM) by Dewis and Randall -Smith (2005).

Another model known as PODDS (Prediction of Discolouration in Distribution Systems) which was developed by Boxall et al. (2001) adopts a similar "hydraulic" approach to predict discolouration. Whilst it has been possible for many decades to record hydraulic disturbance at high spatial and temporal resolution within the inaccessible pipework of the water distribution system there has been no way to get similar information about sediment availability. Thus far, management practice has relied solely on hydraulic changes in predicting discolouration events. There is little doubt about the possibility of hydraulic disturbance having some control over sediment movement which could result in discolouration

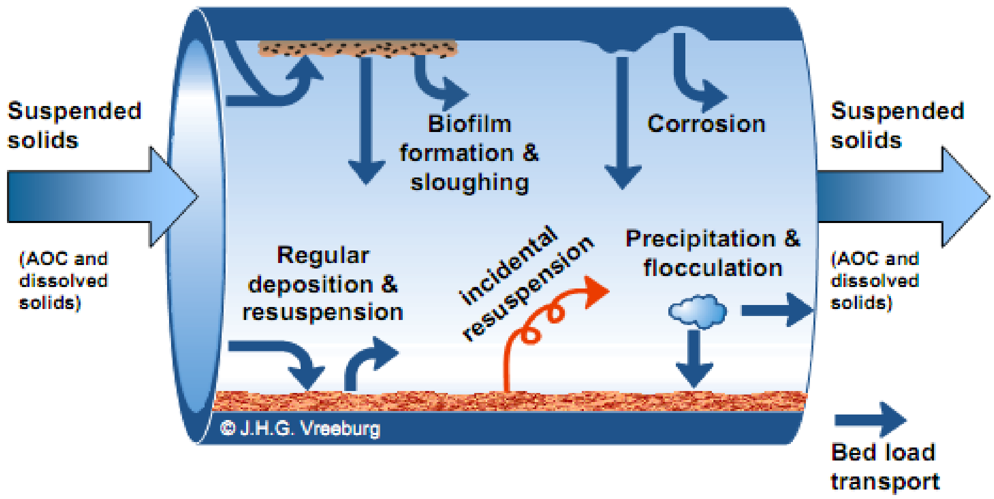

Figure 2. Showing the different types of sediment movements. Adapted from Newcombe and Dixon (2006), p281.

(Jānis et al., 2008; Vreeburg and Boxall, 2007). Some studies have even monitored the different mechanisms of sediment movement and sizes within a pipe under unidirectional flow (Figure 2) with much success (Subhasish and Athanasios, 2008; Cheng, 2006; Verberk et al., 2006; Seth et al., 2004; Gauthier et al., 2001; Paphitilis, 2001).

However, it is also likely that hydraulic disturbance alone may not give a consistently accurate prediction of discolouration. For example, when there is a hydraulic disturbance but insufficient sediments in the resulting suspension to cause discolouration. It therefore follows that the knowledge of sediment availability within a distribution network would be required in order to better understand and predict the likelihood and size of discolouration events after a hydraulic disturbance. However, the current method of managing discolouration falls short of this critical requirement. Currently, the process of managing discolouration has depended on information from customer complaints to verify the location and the subsequent sampling of water from taps within those locations. Relying on customer complaint or tap sampling, apart from the bare risk of fines from regulatory authorities, cannot provide sufficient data that could help in understand the processes that leads to discolouration. This is because discolouration events in most cases are high magnitude and short period events. Hence, low temporal resolution sampling, as currently obtainable is likely to miss those critical events that could render a more robust scientific understanding of the process.

Hence, the need for high temporal resolution monitoring of the process therefore arises. Since discolouration events still remains largely unpredictable even with a good understanding of high resolution hydraulic data across the network, it therefore suggests that knowledge of hydraulic disturbances may have a limited control on discolouration. Hence, the knowledge of sediment availability and extent to which hydraulic disturbances may affect its movement would give a better scientific understanding of the controls of discolouration events. However, such high resolution data are hitherto scarce. The reason for the paucity of high temporal resolution field data for turbidity (or sediment availability) is not farfetched since there is a practical difficulty in assessing water within the pipelines in a distribution network.

Also, the technology to carry out high temporal resolution monitoring required to better understand this process was previously not in existence. Such technology now exists and observing sediment movement at high temporal resolution can now be made possible. It is therefore important to demonstrate whether these new instruments can be used to improve the prediction of water quality failures by monitoring turbidity along with hydraulic disturbance at high resolution. An initial requirement for the success of such study would then be to understand the hydraulics of the water distribution system so as to note the likely areas where hydraulic disturbances could be more frequent. Water, on leaving the treatment plant is normally transported to the end users through a system of trunk mains, reservoirs and pumps (or booster stations). Trunk mains are generally used to transport water to several districts which are known in the UK as district meter area (DMA). From the DMAs, water is distributed via smaller mains and finally to service pipes that goes to end users. Trunk mains tend to maintain a high and relatively stable (or undisturbed) flow when compared to distribution networks in a DMA.

Some studies have suggested that the difference in flow between trunk mains and normal distribution pipes could be as high as a factor of a hundred (Blokker et al., 2008). The lower velocity makes distribution networks

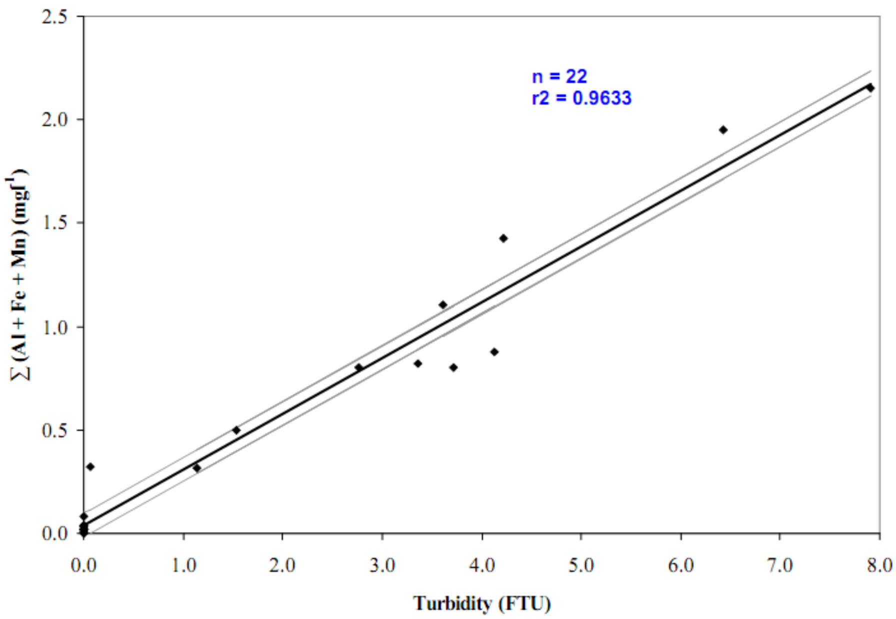

Figure 3. Calibration curve for turbidity events with sediment concentration. Adapted from Gaffney and Boult, 2011.

an ideal location for sediments to accumulate and therefore a possibility of resuspension during, say a sudden hydraulic change. Also, these areas normally witness sharp changes in flow or pressure (which are the only hydraulic disturbance within the network) during peak and low demands; a phenomenon known as the 'diurnal effect' (Gary, 2008) which could help in understanding sediment movement even better. This then suggests that distribution pipes within DMAs could be a very useful location to study the behaviour and movement of sediments in relation to hydraulic changes.

Hence, with the use of these new instruments, the likely relationship between discolouration (caused by sediment movement and measured as turbidity) and hydraulic disturbance can be observed at high resolution. High resolution turbidity monitoring will allow the relative importance to discolouration events of hydraulic disturbance and sediment availability to be determined. This knowledge is required in order to determine the amount of resource that should be allocated to the collection of each type of data in order to best be able to predict discolouration risk. However, it has been observed that there is a continuous movement of sediments at low concentration within the distribution network (Gaffney and Boult, 2012).

It therefore follows that a deeper understanding of the likely relationship between sediment movement and hydraulic disturbance could be established if observations are made based on the size of the turbidity event per hydraulic disturbance. Furthermore, turbidity monitoring at high temporal resolution would provide ample data that could be used to monitor sediment mass balance and spatial resolution were high enough to map sediment sources and sinks. This would also help improve prediction of discolouration since it affects the aesthetic quality of water and reduces confidence of customers. However, discolouration may not be solely an aesthetics concern as several studies have suggested, discolouration could also render aid to microbial activities (Bishop, 2007; Bachmann and Edyvean, 2006; Ainsworth, 2004).

Gaffney and Boult (2012) demonstrated the possibility of using high resolution data to estimate sediment budgets within a DMA. More importantly with regards to this work, was the development of a working curve which was used in the conversion of turbidity into particulate matter (or sediment) as shown in Figure 3.

Since this work is an extension of the previous study carried out by Gaffney and Boult (2012), the calibration curve above was also used in conjunction with flow (or 'discharge') data to determine sediment budget within a section of a DMA. In determining the sediment budget, it is important to ascertain whether a mass balance approach, that is, input and output fluxes, similar to the concept used in production engineering can be used to calculate sediment flux by using the working curve above as the medium for converting continuous turbidity data into sediments. To achieve this, high resolution monitoring would be carried out using the Hydraclam (Siemens WT, UK) which can provide high resolution measurements turbidity data. The aim of this study is to determine whether high resolution water quality data could be useful in improving the management of water quality particularly discolouration. Achieving this aim would be the first step towards the future success of proactive management of water quality failures for WSPs which would reduce the potential risk of fines from regulatory authorities if such failures persist.

METHODOLOGY AND METHOD

The study was carried out in two stages. The first stage involved collection of continuous turbidity and pressure datasets from the hydraclam. This took a period of eighty days. Data collected from this first stage was used to analyse correlation between sediment movement and hydraulic disturbance and the likely influence on discolouration. The second stage then involved collection of turbidity and flow data in other to calculate sediment flux for the particular section of the DMA which was used to map the sediment in that section. Collection of this data took twenty eight days. Both data from stages one and two of the research were however amalgamated and the influence of hydraulic disturbances on discolouration was analysed. Unlike previous studies which had seek to observe for discolouration events that could be tied to hydraulic changes alone, this study also focused on those sediment movements that may not result to any noticeable discolouration and check if such low concentration sediment movement may have any role to play in an eventual discolouration. The Hydraclam was the principal instrument deployed for this study. Also, the period of the study was carefully selected so that datasets were collected during normal operations when no maintenance was schedule.

The Hydraclam has four sensors that are capable of capturing four different water quality parameters at fifteen minutes interval. The parameters measured are turbidity, pressure, temperature and conductivity. It has a range between 0-14 FTU (formazine turbidity unit) for turbidity with a resolution of 0.01 FTU, and can be screwed on a hydrant line within the network. As water from the network gets into the hydraclam, it passes through an internal column where the nephelometric turbidity sensor is positioned to measure turbidity every 15 min. Data is normally offloaded from the Hydraclam via software on the Palm ^{TM} PDA platform which could also be synchronised with a PC. The sensors in the Hydraclam that measures turbidity was calibrated with a 0 FTU and 4 FTU standard solutions, freshly prepared daily before it was sent for field measurements. The 0 FTU standard suspensions were 15 MΩ DIW. To prepare the 4 FTU standard suspension the remainder of the 0 FTU standard suspensions were divided into two portion of 1 L each. 10 g of Hydrazinium Sulphate (VWR International) was dissolved in one of the portion and 100 g of Hexamine (VWR International) was dissolved in the other portion. Both suspensions were then mixed and allowed to stand for 24 h in the dark, which resulted in a 4000 FTU standard suspension. The 4 FTU turbidity standard was then prepared by diluting a portion of the 4000 FTU standard suspension. Recalibration of the Hydraclam turbidity sensors was done each time it was removed from the distribution network using freshly prepared standard suspensions. Another instrument used was a Chloroclam. The calibration of the chloroclam sensor was done in the Siemens Water Technologies laboratory using standard chlorine solutions prepared from water in the network.

High temporal resolution data was used to analyse the correlation between discolouration and hydraulic disturbance. However, since sediments continuously move at low concentration along the distribution networks, the size of each turbidity event was compared to the hydraulic disturbance prior to that event so as to evaluate if the higher turbidity events were actually influenced by hydraulic disturbance. The size of turbidity events was divided into five size categories, which are: sizes of events >0.5NTU to <1NTU, >1NTU to <2NTU, >2NTU to <4NTU, >4NTU to <10NTU, and >10NTU (NTU is an acronym for Nephelometric Turbidity Units). The size of each event was determined by calculating the maximum hourly difference in turbidity concentration in a given location. The determination of the sediment budget was done within a pipeline that was unbranched as shown in Figure 6. The section of the pipe was carefully selected so as to ensure that no sediment ‘leaks out’ of the system under study thereby ensuring that the mass balance determined was as accurate as possible. The sediment budget was then calculated as the difference in sediment discharged into and out of the system.

In calculating the sediment flux, discharge data was collected at 15 min interval using a hydraulic model (SynerGEE, GL Water) and this was multiplied by the corresponding turbidity data after appropriate conversion to sediments in mg/l using the calibrated curve. The SynerGEE hydraulic model uses an input data that included household numbers connected to the network, consumption, both flow and pressure measurements. To account for slight systemic or operational changes, continuous data was collected over a large period of time (80 days for the first stage and 28 days for the second stage).

The calibrated hydraclams were deployed to the hydrant node locations ex-reservoir, each one of them was flushed to ensure the sensor is in full contact with the water in the pipes as shown in Figure 4. Data of pressure and turbidity were then collected at high temporal resolution at several locations within the distribution network. The nephelometric sensors in the Hydraclam were carefully monitored for fouling. When fouling of the sensor was suspected, cleaning of the sensor lens was done using 0.01M HNO_3 (Fischer chemicals) and re-calibrated using the procedure explained earlier. The turbidity in NTU was determined by calculating the difference between successive measurements. This approach ensures the elimination of errors associated with the measuring device.

Each turbidity event was counted and categorised by size of event in each location. Hourly hydraulic changes prior to each turbidity event were observed to check if it was causal or acausal to subsequent discolouration event. Hydraulic changes analysed and compared with turbidity was that of pressure and flow. Data collected from the second stage of the study was used to determine the sediment budget for that section of the DMA as displayed in Figure 4 using the working curve in Figure 2 to convert turbidity to sediment. The data from this stage was also used to develop a time series sediment balance graph for the section of the DMA. Also, continuous data of residual chlorine was collected alongside turbidity data at one of the locations where the Hydraclam is located with the Chloroclam. The flow of the water from the pipes into the tubing of the chloroclam was maintained between 120 to 160 ml/min. to ensure optimal chloroclam performance.

RESULTS

Overall monitoring period was 108 days with a total of 15,550 and 4922 datasets collected during the first and second stages of the research, respectively. There was no planned flushing of the networks all through the period of the study in order to ensure a favourable opportunity to study sediment movements during “normal operations”. Study of the data collected across all sites reveals a temporal variance of turbidity between 0 NTU and 14.6 NTU during the duration of the research. It was also found that 75% of suspended particles (measured as turbidity) ranged between 0.5 NTU and 2 NTU this can be compared with those with magnitude greater than 4NTU that was only 13%, which gives a spread of 62%. This then suggests that the bulk of suspended material fluxes within networks are being transported at low concentration which could be difficult to detect by mere customer observation. The hourly correlation between hydraulic

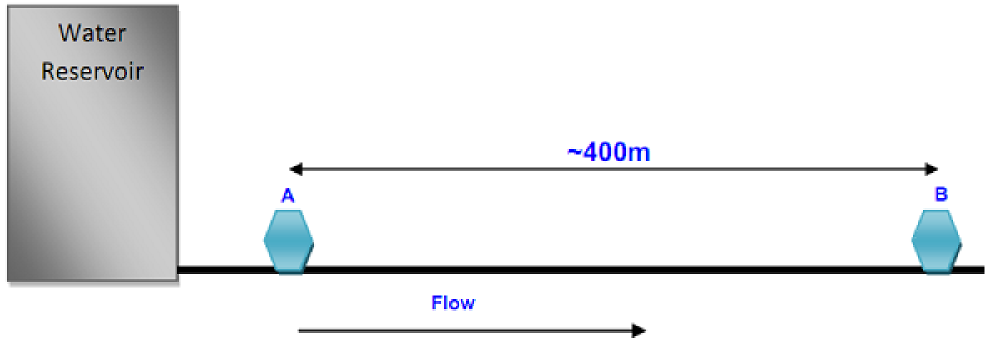

Figure 4. The set-up for the determination of sediment budget, necessary to demonstrate the possibility of sediment mapping within a DMA. A and B are Hydraclams (Siemens WT, UK).

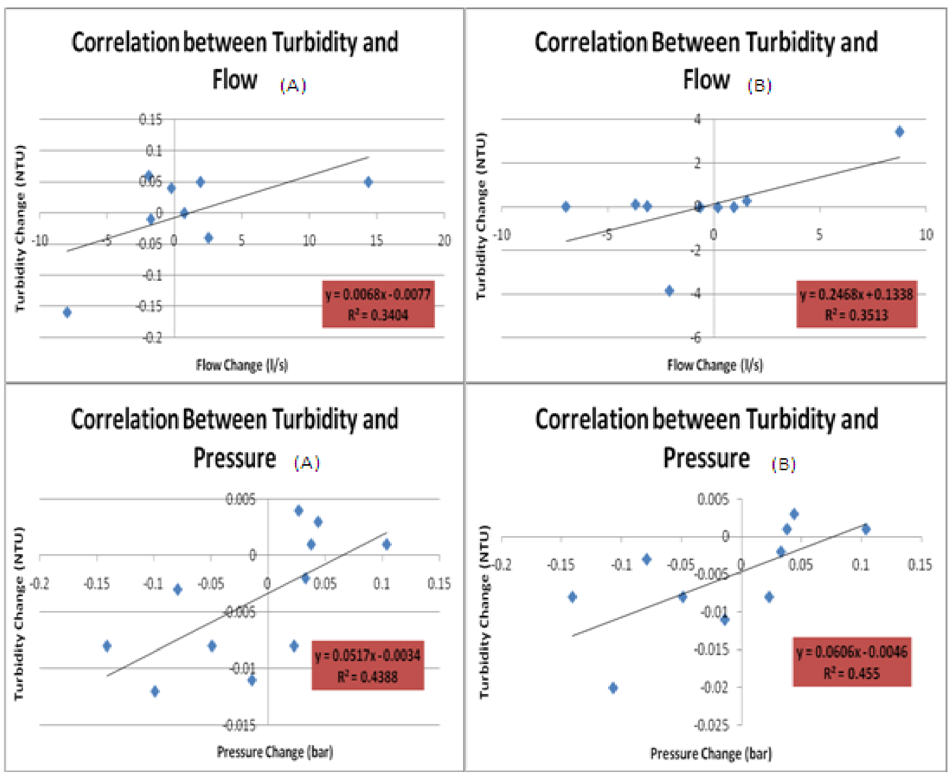

Figure 5. Showing general hourly graphs of hydraulic changes and turbidity.

changes and turbidity was found to be generally positive, but weak (Figure 5). Hydraulic disturbance caused by changes in flow was found to have an r^2 value between 0.34 (for changes occurring during periods of relatively low turbidity) and 0.35 (for changes occurring during periods of high turbidity). A similarly positive but weak correlation was also found with hydraulic disturbances caused by pressure changes with an r^2 of 0.44 (for changes occurring during periods of relatively low turbidity) and 0.46 (for changes occurring during periods of high turbidity), respectively. This weak correlation is likely to be as a result of turbidity events occurring at periods when there was no prior hydraulic change and *vice versa*. It then suggests that during "normal operating conditions" hydraulic changes may be playing a weak or passive role in causing or determining discolouration risk than initially observed.

The weak correlation between hydraulic disturbance and turbidity was also made apparent with respect to magnitude of sediment movement within the distribution network (Figure 6). Since there was a limited amount of data on sediment movement from a single site, datasets from all sites was combined so as to make a meaningful assertion on the data that is being analysed. The data

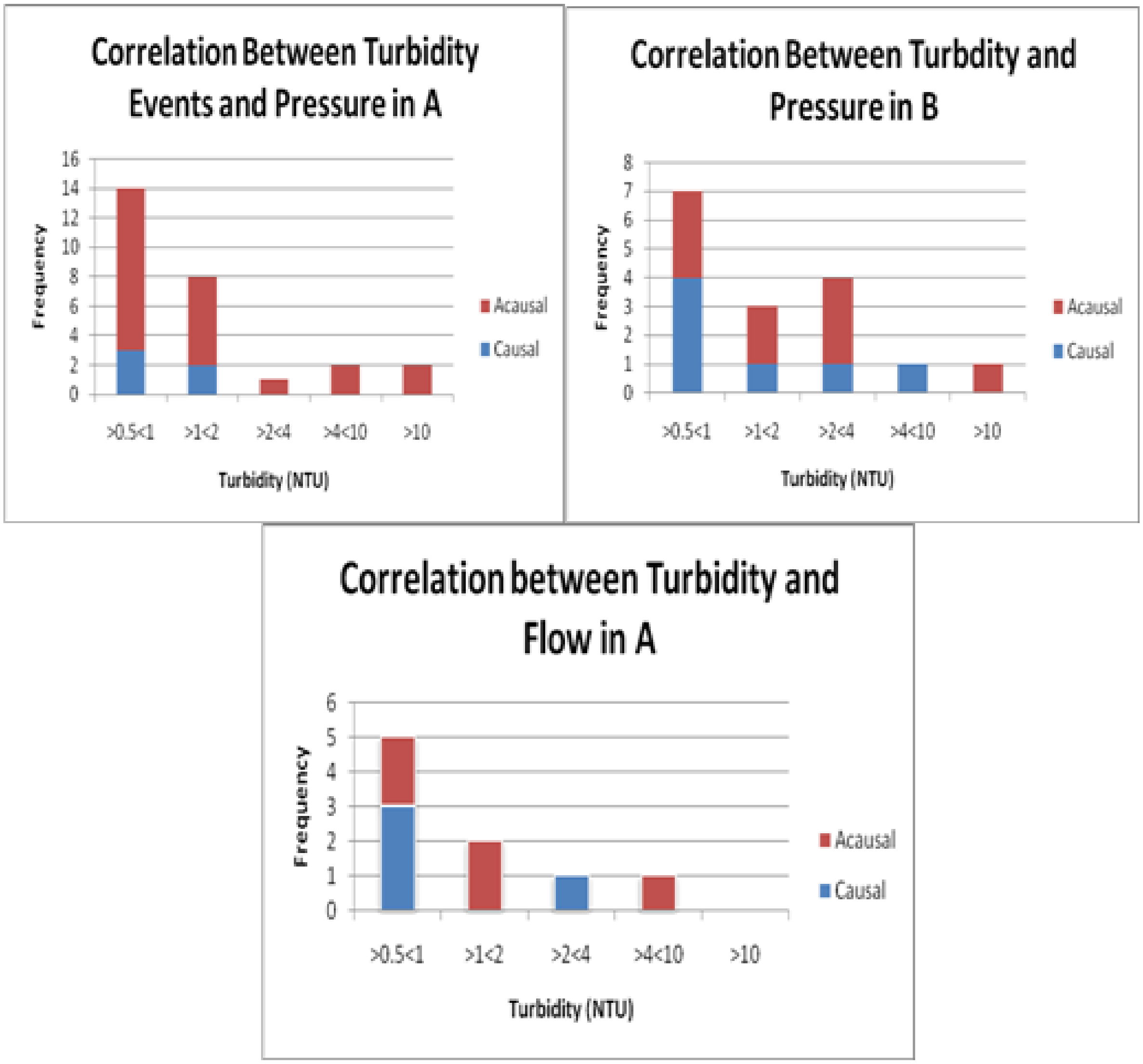

Figure 6. Causal and non-causal turbidity events occurring in the distribution networks.

collected across all sites showed that only 14% of the entire sediment movement was greater than the regulatory standard of 4 NTU (representing just 2% of the whole turbidity events of interest in this research) was actually caused by a hydraulic disturbance.

In a sharp contrast, the percentage of sediment movement below the magnitude of 4 NTU that was caused by hydraulic disturbance was 33% which represents 29% of the whole ranges of sediment movement events of interest in this study. It therefore follows that 69% of all the sediment movements analysed were not caused by any hydraulic disturbance. However, an interesting finding in the result was the manner by which turbidity varied over time.

The number of quality failures (that is, measurements above 4 NTU) was five (5) which is minor as seen from the percentage time exceedance graphs below (Figure 7). Although, continuous turbidity measurement during the period of the study revealed a high range, temporal variability (Figure 7), the temporal differences in the baseline turbidity (lowest turbidity measured) all through the period of the study was low and more "predictable". For example, for every 10% rise in the baseline turbidity, an occurrence of a turbidity event within the range of interest in this study was likely. At one of the sites, a 50% increase in the baseline turbidity was immediately followed by a quality failure while in another site similar water quality failures were observed when the baseline turbidity increased by 37 and 49% without any prior hydraulic disturbance to account for them.

The period within which the baseline turbidity accumulated to the amount capable of causing a quality failure averaged 10 days. It was also found however that turbidity events that was more than the regulatory

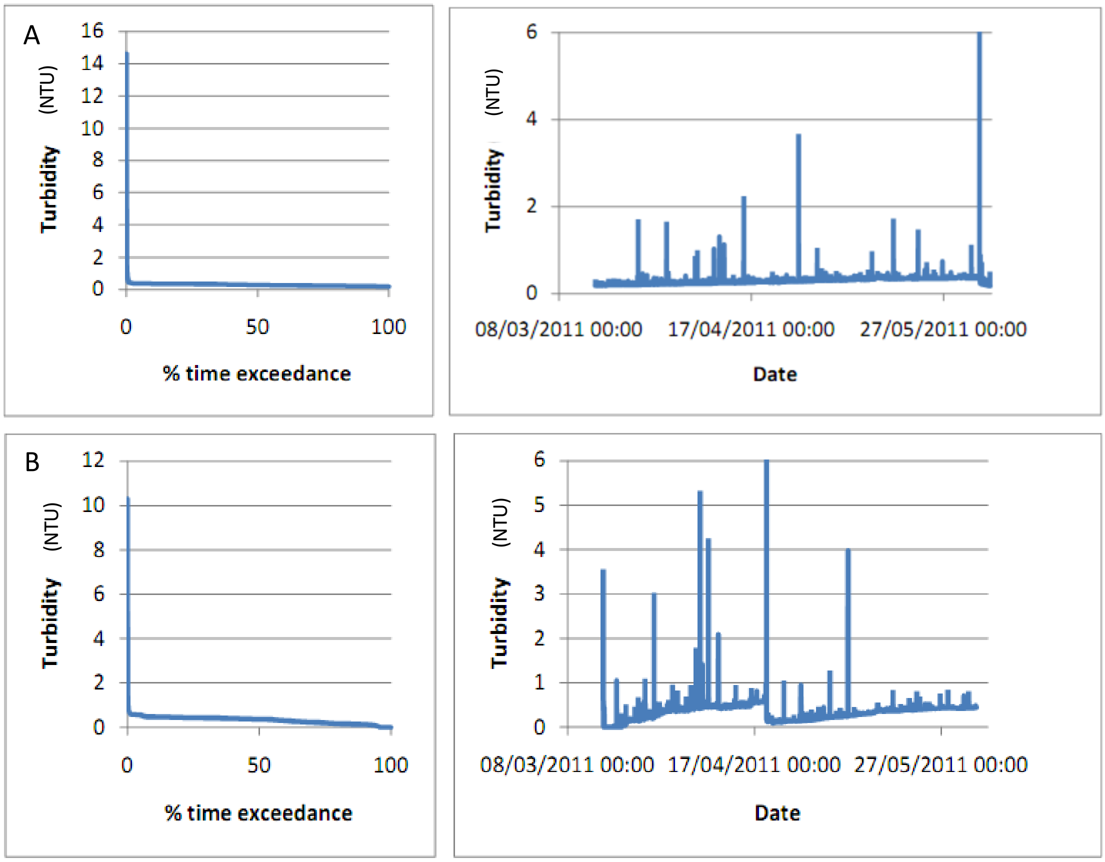

Figure 7 (A-B). Showing high temporal turbidity data collected from different sites, with the corresponding % time exceedance curves.

Table 1. Showing the sediment budget of a section of the DMA.

Sediment input		Sediment output		Balance		$gm^{-1}y^{-1}$
Mass (kg)	**Error (kg)**	**Mass (kg)**	**Error (kg)**	**Mass (kg)**	**Error (kg)**	
2.660	3.0×10^{-5}	2.628	3.0×10^{-5}	0.032	4.24×10^{-5}	1.04

standard was followed by a sharp drop in the baseline turbidity value. For example, at one site the baseline turbidity dropped by 44% immediately after a turbidity event of 14.6 NTU. At another site, a drop of 56% was observed after an event of 10.3 NTU. This behaviour suggests a self-cleaning process that goes on within the distribution network which can only be properly observed at such high temporal resolution as carried out in this study.

The section of the distribution network that was analysed in this study was found to be net accumulating with 0.0320 kg ± 4.24 x 10^{-5} kg of sediment budget accumulated over the period of the study (Table 1). The standard error in Table 1 is expressed at 95% confidence limit and includes only the regression line error from Figure 3, used in converting turbidity to concentration of metal oxides (which is a surrogate for sediments).

It is apparent from the results that sediment movement within the distribution network also proved to be temporally dependent (Figure 8). At some periods, the sediment balance (that is output-input budget) was depositional (that is net accumulating), whereby the input was higher than the output. In other periods the sediment output flux was much higher with an apparent mobilisation of sediments into other sections within the networks. However, when such mobilisation occurred, it was not as a result of any sudden increase in flow but just an increase in concentration of sediments within the system. The result also revealed the superimposition of output and input fluxes in most instances, which suggests a "steady-state" process going on within the network.

The results from the chloroclam displayed a sinusoidal pattern of residual chlorine concentration (Figure 9), with the maximum at 0.33 mg/l and minimum at 0.14 mg/l

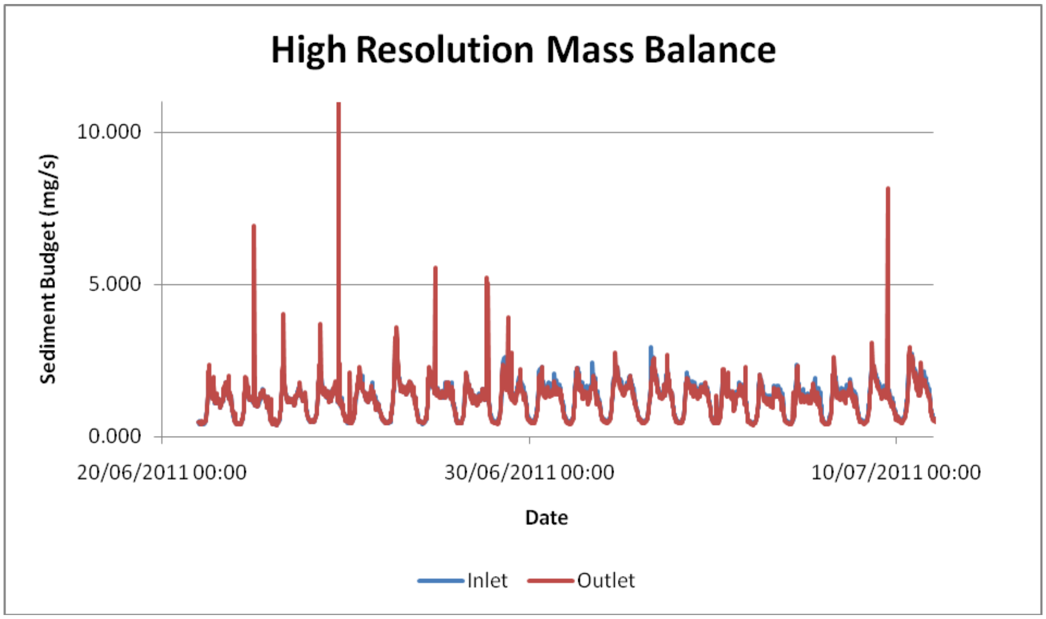

Figure 8. Showing high temporal sediment balance within a section of the DMA.

(Figure 10). However, when the changing chlorine concentration was compared with the varying turbidity there was no clear indication of decreasing residual chlorine caused by any change in turbidity. However, when the data sets for periods when residual chlorine concentration was decreasing and when it was increasing were compared with the corresponding turbidity (Figure 10), it was found that the correlation was positive. The positive correlation was also found to be order of magnitude stronger during the periods of increasing residual chlorine concentration than the period when chlorine concentration was decreasing.

DISCUSSION

As water service providers (WSPs) seek a more proactive approach in resolving issues of water quality failure, like those with regards to discolouration, the results from this study show that high resolution monitoring would play a very important role in achieving this aim. High resolution monitoring showed specific behaviours of sediments within distribution networks that would not have been otherwise observed. Such information would be useful in adopting a more proactive quality failure management and could provide an "early warning signal" for management to act upon before such failures gets to the customer's or regulatory authority's notice. How continuous monitoring could help to achieve this aim would be discussed below.

It is clear from the results of hydraulic changes and sediment movement during "normal operations" that there were a lot of instances where sediment movement resulted in a water quality failure without any apparent or significant hydraulic disturbance and *vice versa*. This could however either be as a result of the time lag between measurements in this study (which was every 15 min), which would have missed a hydraulic change that might have lasted only for some few seconds. It could also be that there was no mobilisation after a hydraulic disturbance because there were no sediments to be mobilised. Thirdly, it could be that sediments were just dislodged from an accumulation point without any requirement for a hydraulic disturbance. However important the first two possibilities are, since there were significant amount of sediment mobilisation that were unrelated to hydraulic disturbance, the latter case seems more likely. It suggests that the system is likely to be self-cleaning, a possibility that had also been proposed in some earlier studies (Vreeburg and Boxall, 2007; Boxall and Prince, 2006). To confirm this viewpoint would however require a longer period of monitoring and more data collection of high temporal and spatial resolution. However, the implication of such undisturbed sediment mobilisation across distribution networks is that better prediction of discolouration risks would require more resource to be channelled towards collecting data for sediment availability.

Nevertheless, the likelihood of a self-cleaning process as made evident with the varying turbidity results is suggestive of the possibility of sediments within distribution networks tending to behave like sand piles under "monotonic" or unidirectional loadings (Liu et al., 2011; Roul and Schinner, 2010). One explanation to this with regards to discolouration would be that; as the bulk sediment material increases due to accumulation, the increased "internal pressure" of the bulk (or "sand pile") results in a "crumbling effect". This crumbling of bulk

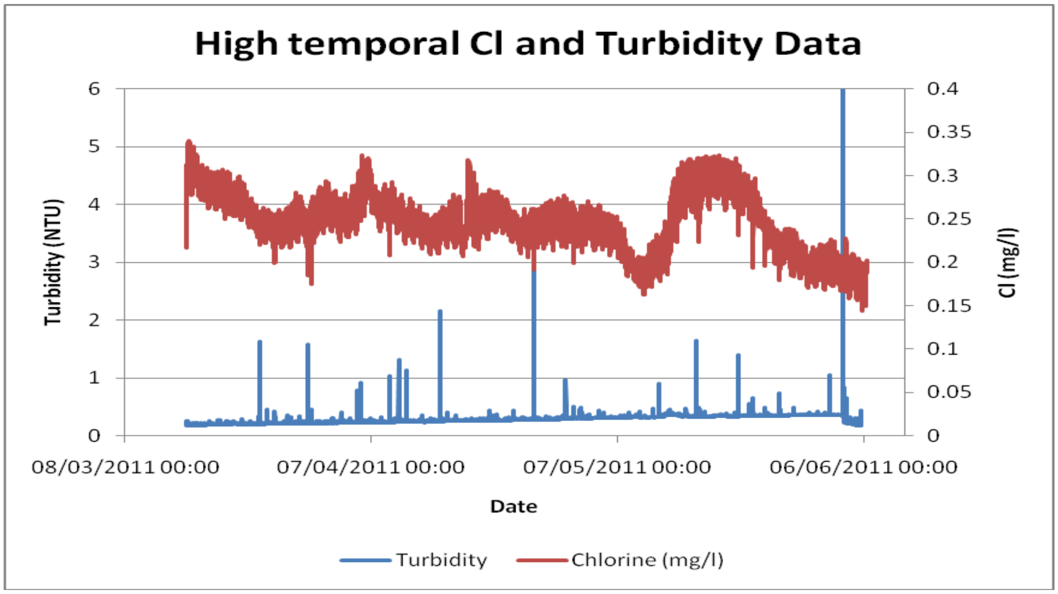

Figure 9. Showing high temporal changes in turbidity and residual chlorine concentration.

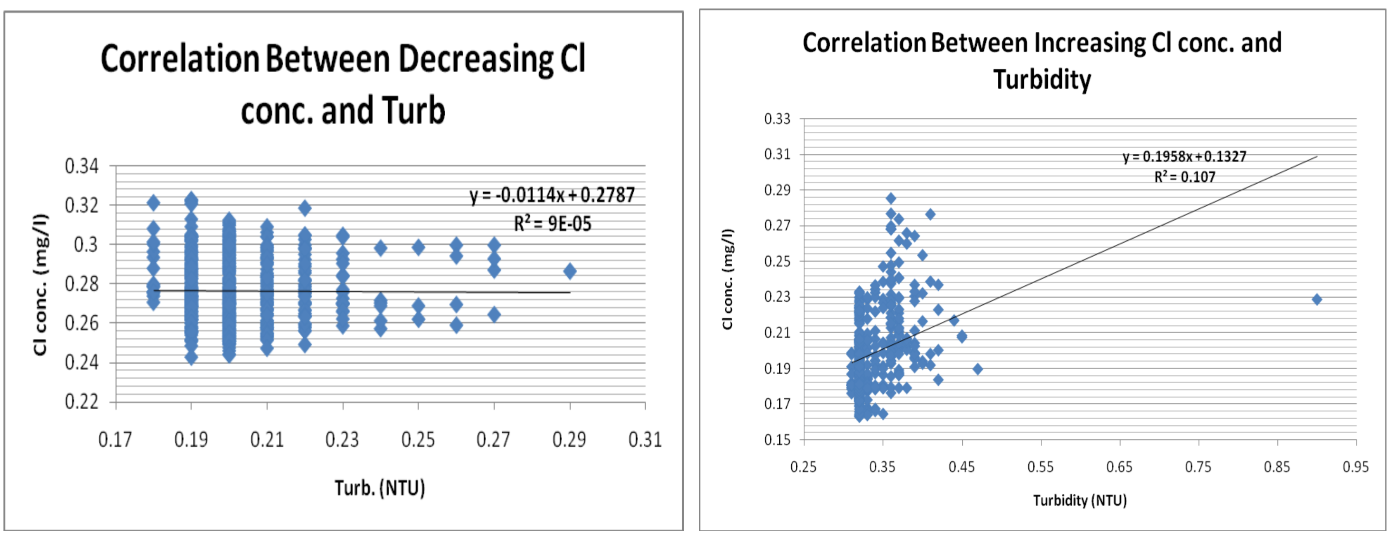

Figure 10. Showing the correlation between turbidity and changing pattern (that is, instances of decreasing and increasing) of residual chlorine concentration.

sediment would probably be observed as sediment mobilisation without any need for an additional external shear (or hydraulic disturbance). If this is true, as suggested by the weak correlation between hydraulic disturbance and turbidity, it would then explain why discolouration risk tends to be less predictable, as desired, since the risk of quality failures still lingers even after "maintenance" by flushing or pigging as observed by previous studies (Gaffney and Boult, 2011; Barbeau et al., 2005; Carriere et al., 2005).

This then suggests that bulk sediments within the pipes may withstand external hydraulic disturbance as well as internal pressure during normal operations until they build-up to a size that they can no longer continue growing and are therefore mobilised. For example, at one of the sites studied, a continuous period of low sediment movement was observed, which was immediately followed by a sudden water quality failure (high turbidity) without any prior hydraulic disturbance. Although, such possibilities are likely to occur in areas where sediment layers exists (Husband and Boxall, 2011) or conditions where the hydraulic status are relatively quiescent (Boxall and Saul, 2005; Prince et al., 2003) even during flushing, like dead-ends within the networks. It therefore follows that during normal operations significant mobilisation of sediments occurs only when sufficient amount has been accumulated. But this likely condition could change quickly, say, during a turbulent flow as obtainable in flushing, when mobilisation then takes preference over accumulation, which is also supported by previous studies (Blokker et al., 2010).

From the analysis of the results, it can be suggests that under “normal operations”, as obtained during the period of the research, the role of hydraulic disturbances may be passive and only becomes strong when sufficient amount of shear is induced on the system, such as obtainable during “flushing”. Whether sediment mobilisation would result in a water quality failure would only depend on the amount of material accumulated and mobilised at any point in time. This result also suggests that a high hydraulic disturbance would be important but not necessary for sediment mobilisation to result in a quality failure. It therefore follows that reducing or eliminating the risk of discolouration would require knowledge of areas where sediments are or could possibly be and an estimation of the quantity present at that period. This would then require a system of sediment mapping to ascertain the locations of highest risks within a DMA. The calculation of a section of the DMA would be discussed later.

An interesting finding from the results analysed was the strong correlation between increasing and decreasing baseline turbidity and corresponding risk of water quality failures. The baseline turbidity datasets were low enough not to be detectable by customers and drops sharply immediately after a significant turbidity event, that they are not likely to be observable by low temporal sampling. However, the possibility of incorporating the pattern of increase and decrease of these low turbidity data (or baseline turbidity) in risk models could provide a promising alternative in predicting discolouration risk. For example, in all the turbidity events that resulted in a water quality failure, an increase of the baseline turbidity by 37 to 50% was observed. This failure occurred without any observable hydraulic disturbance. Also in one of the sites analysed, the baseline turbidity drop by 30% immediately after a turbidity event that resulted in water quality failure, still suggesting the possibility of a self-cleaning process as earlier explained.

Whether this observed behaviour is a “rule” or just an exception cannot be established by the data from this study. It would therefore require a more analysis that would contain both high temporal and high spatial data-sets to fully explain this behaviour. However, the query by Gaffney and Boult (2011) of whether a self-cleaning process (which this observation proposes), could result in a compliance failure could now be clearly seen as a likely possibility as 17% of all the events considered as self-cleaning actually resulted in a quality failure.

In the 28 days of continuous monitoring of a section of the DMA, it was demonstrated that data from high resolution monitoring can be used to calculate the sediment budget of a section in a DMA. The sediment budget calculated by adopting the concept of material balance into and out of the selected section of DMA was 0.032 kg, which is equivalent to 1.040 $gm^{-1}y^{-1}$, estimated as metal oxides from the calibration curve of Figure 5. This result was within the range of previous studies as it can be compared with 0.112 $gm^{-1}y^{-1}$ and 5.212 $gm^{-1}y^{-1}$ from the work done by Gaffney and Boult (2011) using a similar method, and that carried out by Vreeburg et al. (2008) which estimated the weight of sediments from a flushed section of a DMA to be 1.071 $gm^{-1}y^{-1}$.

It is however important to note the variability that could occur in such mapping exercise. For example, during the first 10 days of the mapping study, data collected showed that the system was not net accumulating but rather “erosional” (a term used by hydrologists to describe a river system that dislodges more material than it takes). During those first 10 days the sediment deficit was roughly about the same figure it turns out to have accumulated by the end of the 28 days of monitoring (that is 1.047 $gm^{-1}y^{-1}$). The reason for the “reversal” in the character of this section of the DMA could be attributed to a likely event of sediment mobilisation, as supported by the results which showed that the highest sediment output from the system also occurred within this period. It however suggests that for any sediment mapping result to provide an accurate picture of the character of any section of a DMA, that is either net accumulating or sediment source, an extensive study would be required for that section of the DMA.

From the results, the chlorine concentration was also variable just like the turbidity data with a maximum measurement of 0.33 mg/l and a minimum of 0.14 mg/l. The correlation with turbidity was generally weak. However, a careful observation of the pattern of scatter on both graphs reveals that the density of the data was within the area of low turbidity and at high turbidity there was little or no residual chlorine. This therefore suggests that high turbidity is likely to affect residual chlorine across distribution networks, although this may not be instantaneous possibly because of time required for any chlorine-demanding reaction to occur. For example, on day 15 of the first stage of the study, an increase in turbidity from 0.22 NTU to 1.06 NTU (380% increase), resulted in a drop of residual chlorine by 17%, thirty minutes after the turbidity event. Also on day 30, an increase of turbidity from 0.24 NTU to 2.16 NTU (800% increase) resulted in a drop of residual chlorine by 12%, also thirty minutes after the turbidity event. Such drops were not however observed at other times, even with similar increase in turbidity, which suggests the complexity of the controls and the need for more studies.

It was also interesting to note that residual chlorine concentration could display a sinusoidal pattern within the network, since it is only possible to add chlorine in treatment plant. However, a recent laboratory simulation study done by Ryan and Jayaratne (2003) suggested that such changes in concentration as observed in this study could be as a result of the age or transient time of the water and/or the pipe material used in its distribution.

The huge difference in the r^2 values of the results of increasing and decreasing residual chlorine with respect to turbidity is suggestive of the possibility that high chlorine concentration could also possibly play a role in particulates generation. Earlier studies have also suggested this, with respect to wall reactions and reactions with other organic compounds (Zhang et al., 2011; Castro and Neves, 2003). However, the data from the study is insufficient to make certain any such claim, but further investigation could help to shed more light on this finding.

Another potential use of high temporal data of residual chlorine concentration would be the prospects of tracking odour complaint, which would be indicated by an unusually high chlorine concentration. This has never been previously observed and could only be made possible by high temporal measurements.

Conclusion

The monitoring of water quality at high temporal resolution has given tangible proof of high magnitude but short period changes that occurs in water quality as it travels through distribution networks. The results from high temporal measurements also confirm, with greater confidence, the following:

i. The bulk of sediment movement occurs at low concentration,
ii. Under normal operating conditions, the hydraulic control on the risk of discolouration is low and sediment mobilisation would depend more on availability. The implication of this is that more resource would be required for the collection of data about sediment availability so as to ensure a more accurate prediction of discolouration,
iii. Distribution networks are likely to be self cleaning with regards to discolouration. However, it is recommended that the density per DMA of such continuous monitoring devices like those used in this study be increased so as to determine the sinks or fate of the sediments from the section that seem to be self cleaning,
iv. Mapping of sediments within a DMA is possible and can become useful in predicting areas of high risk, by conducting a more extensive mapping exercise with the method used in this study.

Further recommendations

Another usefulness of high temporal monitoring is the ability for it to track the baseline turbidity within a DMA. As shown in this study, this could be an alternative method in predicting discolouration risks under normal operating conditions, and can be monitored only with high temporal measurements. Hence, further study on this is recommended. It is also recommended that sediment mapping, as demonstrated in this study be extended to other sections of the DMA or distribution networks in general. This would help in the development of sediment sinks that would aid proactive management and reduce the uncertainties of general periodic flushing.

It is important for any proactive approach to managing water quality failures to adopt continuous monitoring across the networks as more extensive data from such monitoring would be useful for further research towards understanding the behaviour of sediments in distribution networks.

Conflict of interests

The author(s) have not declared any conflict of interests.

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