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# International Journal of Water Resources and Environmental Engineering

Table of Contents: Volume 6 Number 6 June 2014

## ARTICLES

### Research Articles

**The use of high resolution monitoring in the management of water quality failures caused by discolouration** 144

Anonye, D. and Nwachukwu, A. N.

**Application of System Dynamics model in the determination of the unit cost of production of drinking water** 155

Adelere Ezekiel Adeniran

*Full Length Research Paper*

# 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  $1.04 \text{ gm}^{-1}\text{y}^{-1}$ . 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.

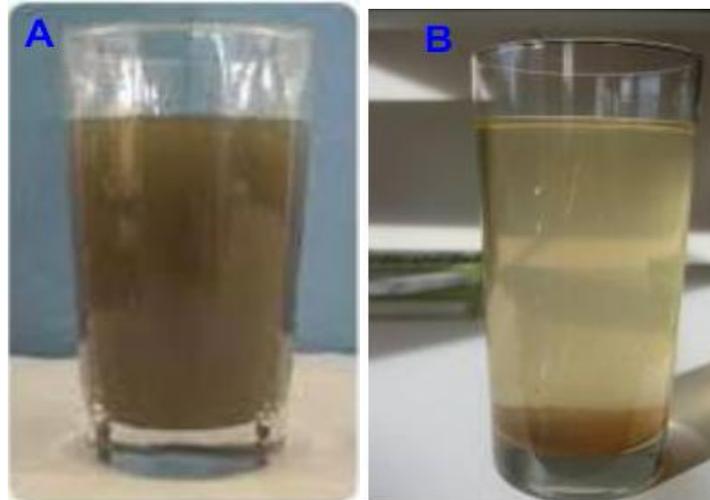
**Key words:** Water quality, turbidity, sediment movement, discolouration, hydraulic disturbance.

## 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.

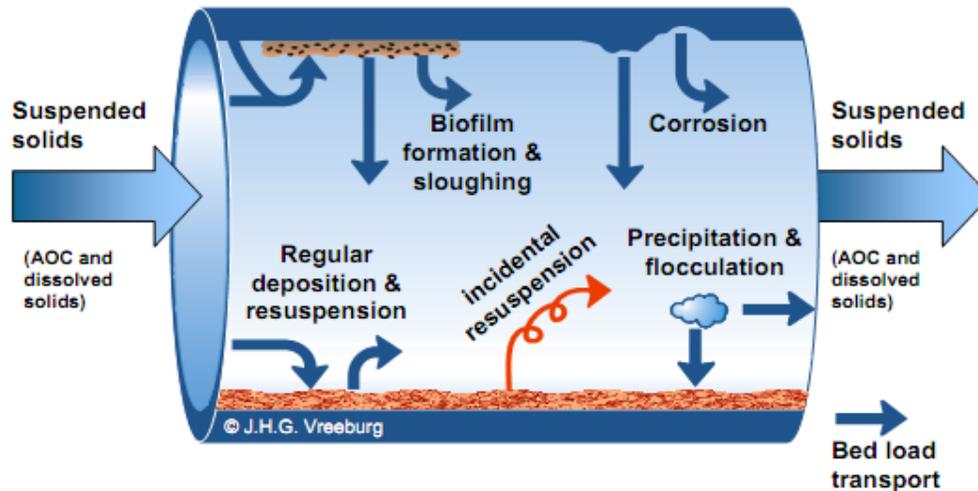
most cases, highest on the list of reoccurring issues. This is because many of such water quality failures, for example discolouration and chlorine-induced odour are largely unpredictable and measures to manage them are only carried out after it has been called for by several complaints from customers. 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; Paphitis, 2001).

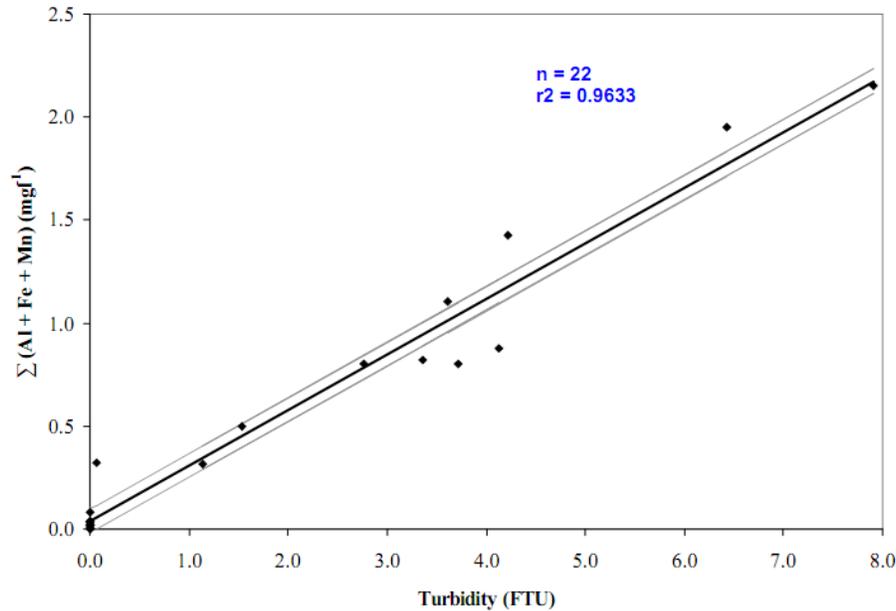
However, it is also likely that hydraulic disturbance alone may not give a consistently accurate prediction of discoloration. For example, when there is a hydraulic disturbance but insufficient sediments in the resulting suspension to cause discoloration. It therefore follows that the knowledge of sediment availability within a distribution network would be required in order to better understand and predict the likelihood and size of discoloration events after a hydraulic disturbance. However, the current method of managing discoloration falls short of this critical requirement. Currently, the process of managing discoloration 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 discoloration. This is because discoloration 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 discoloration 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 discoloration. 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 discoloration 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 Boulton, 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 Boulton, 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 Boulton (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 Boulton (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 order 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™ 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.

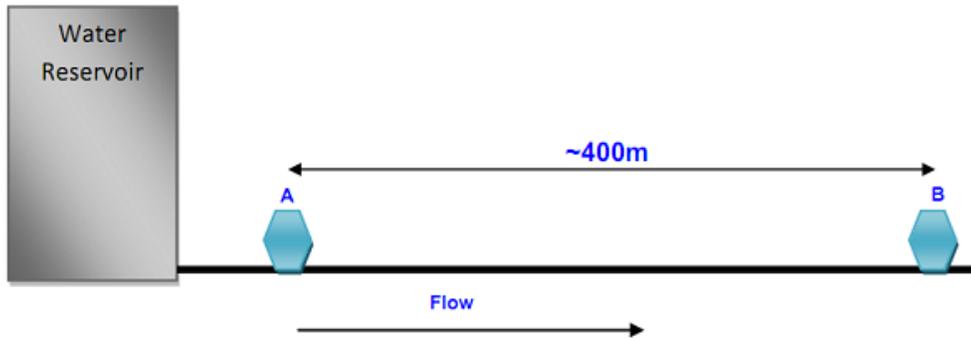
In calculating the sediment flux, discharge data was collected at 15 min interval using a hydraulic model (SynerGEE, GL Water) and this was multiplied by the corresponding turbidity data after appropriate conversion to sediments in mg/l using the calibrated curve. The SynerGEE hydraulic model uses an 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<sub>3</sub> (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.

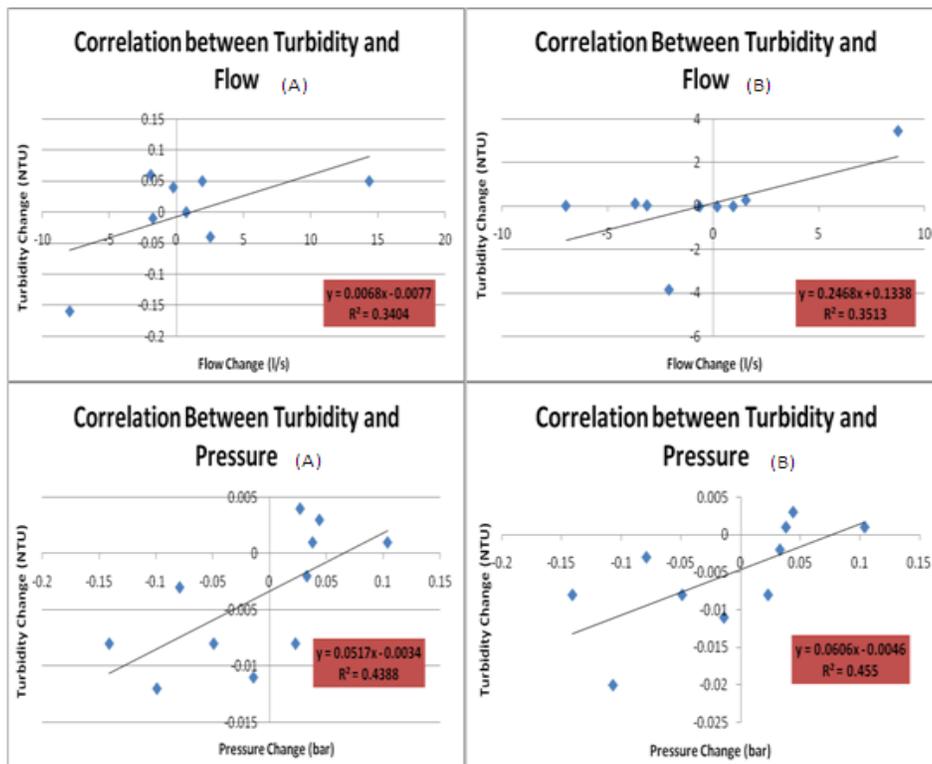
Each turbidity event was counted and categorised by size of event in each location. Hourly hydraulic changes prior to each turbidity event were observed to check if it was causal or acausal to subsequent discolouration event. Hydraulic changes analysed and compared with turbidity was that of pressure 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

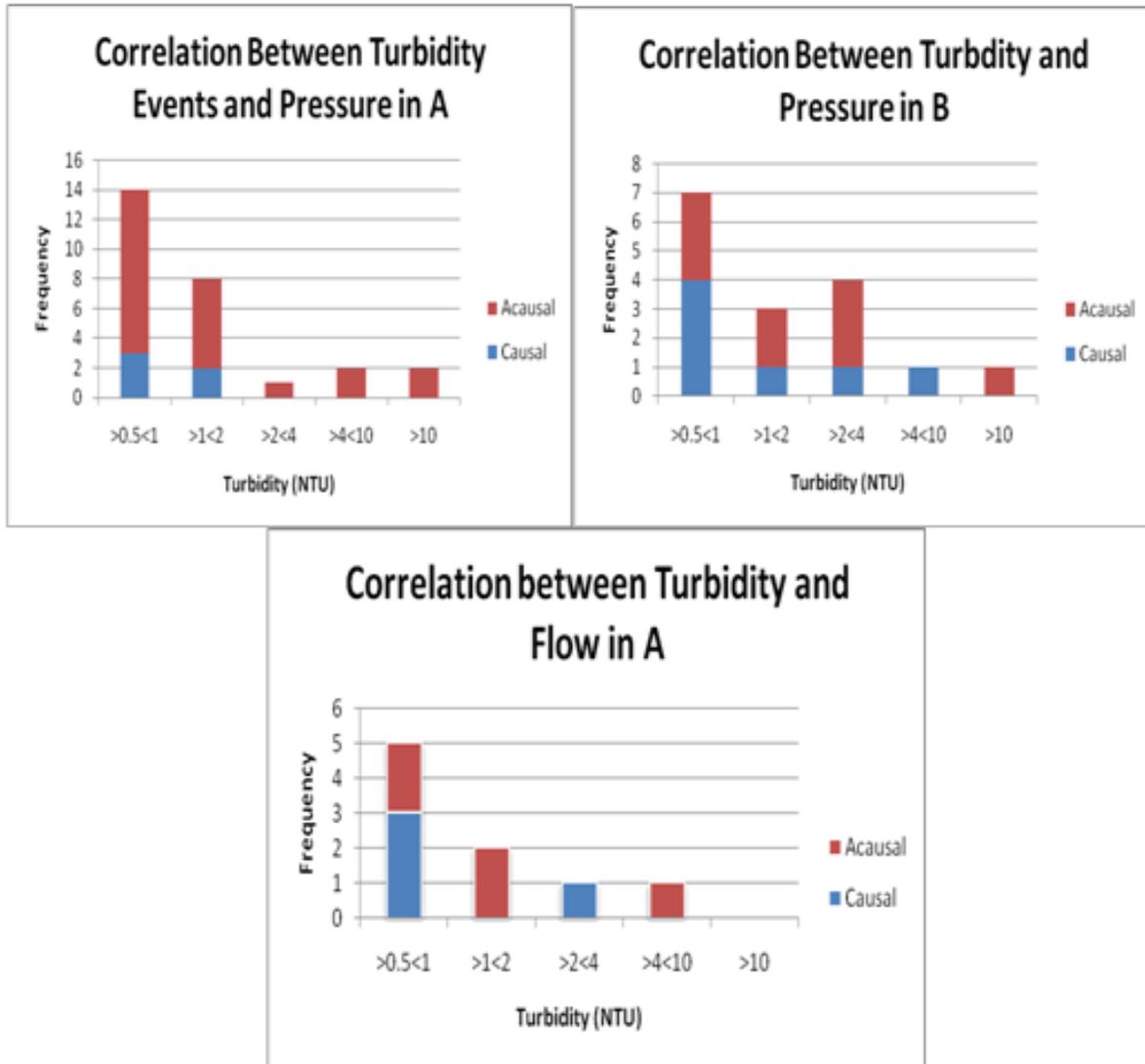


Figure 6. Causal and non-causal turbidity events occurring in the distribution networks.

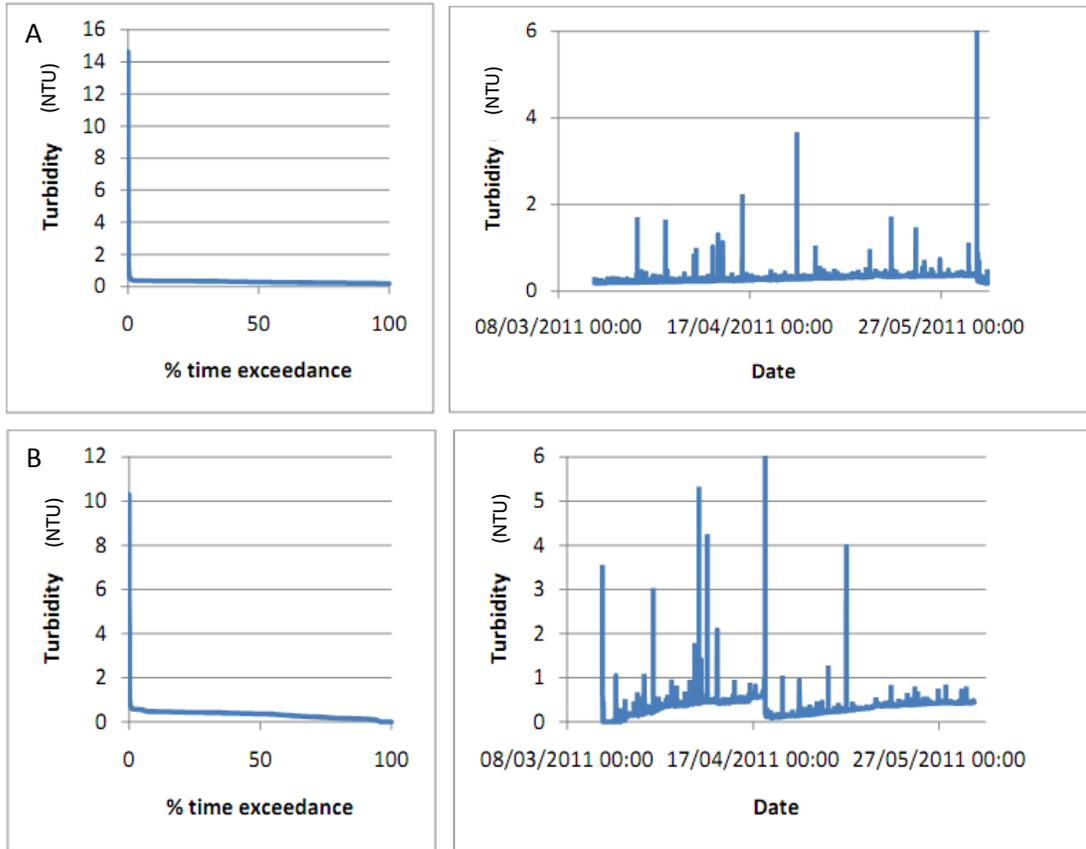
collected across all sites showed that only 14% of the entire sediment movement was greater than the regulatory standard of 4 NTU (representing just 2% of the whole turbidity events of interest in this research) was actually caused by a hydraulic disturbance.

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.

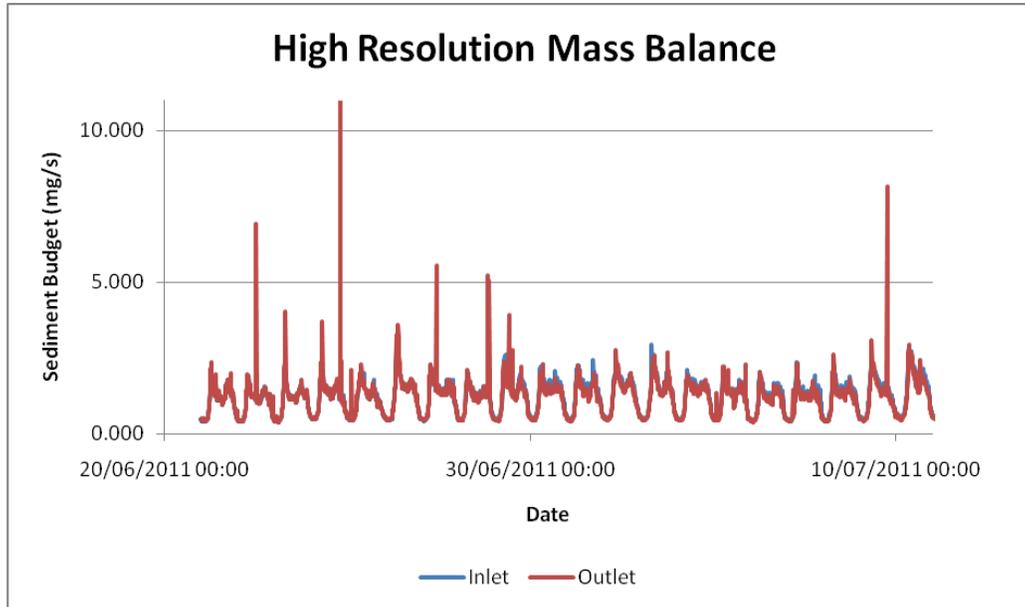
Sediment input		Sediment output		Balance		gm <sup>-1</sup> y <sup>-1</sup>
Mass (kg)	Error (kg)	Mass (kg)	Error (kg)	Mass (kg)	Error (kg)	
2.660	3.0 x 10 <sup>-5</sup>	2.628	3.0 x 10 <sup>-5</sup>	0.032	4.24 x 10 <sup>-5</sup>	1.04

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<sup>-5</sup> 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

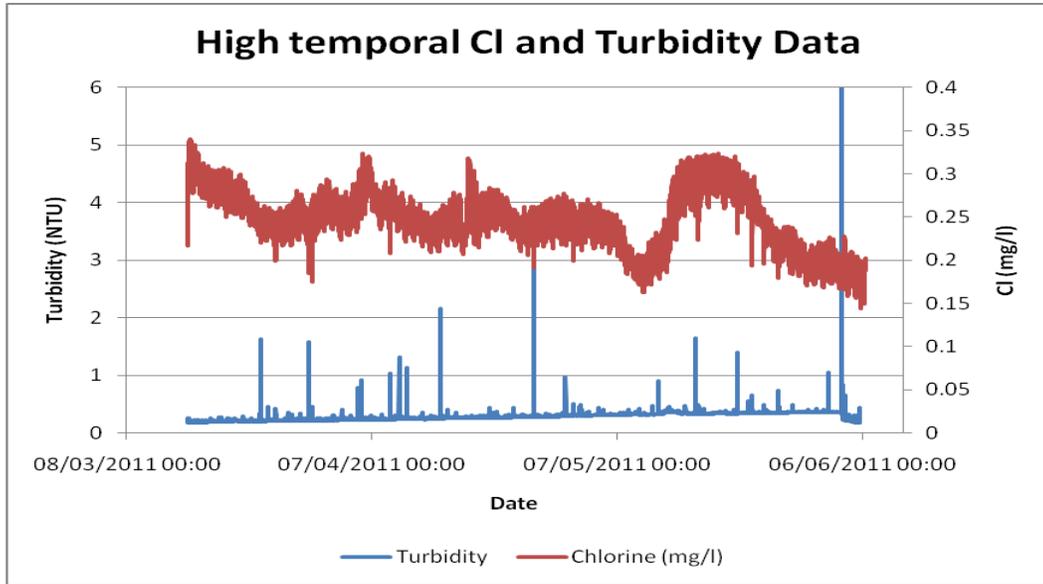


Figure 9. Showing high temporal changes in turbidity and residual chlorine concentration.

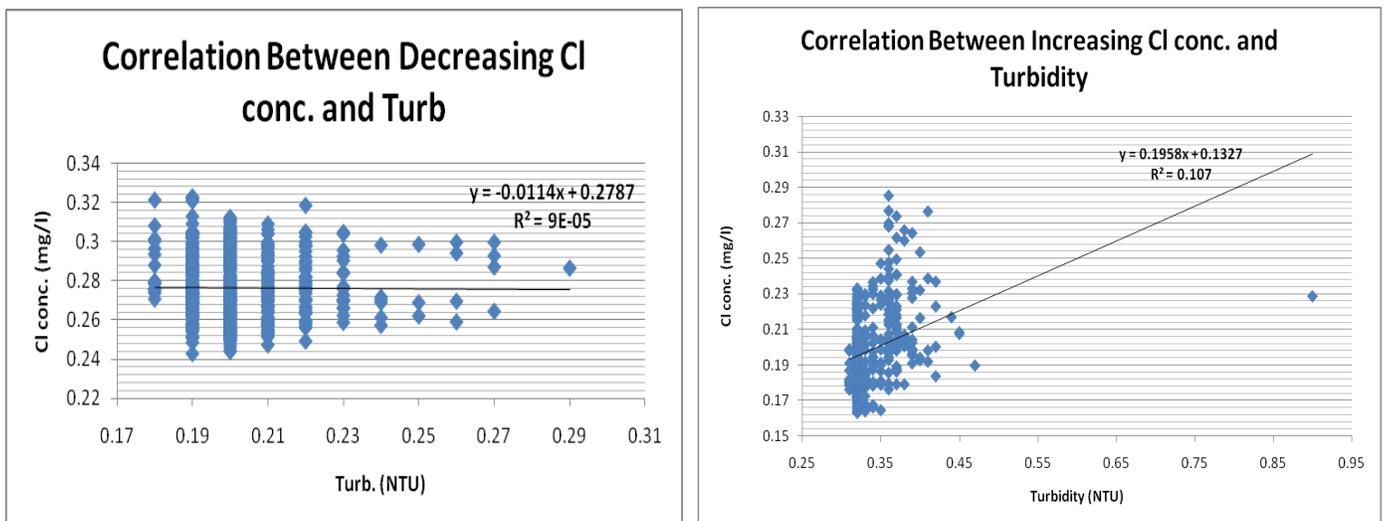


Figure 10. Showing the correlation between turbidity and changing pattern (that is, instances of decreasing and increasing) of residual chlorine concentration.

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 Boulton, 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 exist (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 suggested 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 datasets to fully explain this behaviour. However, the query by Gaffney and Boulton (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  $1.040 \text{ gm}^{-1}\text{y}^{-1}$ , 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  $0.112 \text{ gm}^{-1}\text{y}^{-1}$  and  $5.212 \text{ gm}^{-1}\text{y}^{-1}$  from the work done by Gaffney and Boulton (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  $1.071 \text{ gm}^{-1}\text{y}^{-1}$ .

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  $1.047 \text{ gm}^{-1}\text{y}^{-1}$ ). 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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Full Length Research Paper

# Application of System Dynamics model in the determination of the unit cost of production of drinking water

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Establishment of tariff structures and economic pricing regimes are contemporary issues in the water supply sector. The need to determine the economic price for water production has taken the centre stage in the face of dwindling world water resources. This paper reports the development of a System Dynamics (SD) model for the determination of the unit cost of domestic water production schemes in a developing economy. The dynamics and interconnectivities of the production factors of water production are considered. The model was applied to the University of Ibadan, Nigeria domestic water supply scheme for which extensive and historical data are available. The capability of SD Vensim software was used to examine some critical scenarios. The unit cost of production obtained using field data compares well with unit costs already established for some countries. The results of the scenarios investigation, confirm the model developed, can handle the various dynamics of water supply production and thus assist water utilities to determine appropriate tariffs to be charged on their consumers. Also, the unit rate of N107/m<sup>3</sup> compare very well with the Lagos state water tariff of N100/m<sup>3</sup>.

**Key words:** domestic water supply, production factors, unit cost, scenario investigations.

## INTRODUCTION

Until recently, municipal water supply was maintained with few difficulties for the consumers and at relatively low cost. That happy state is changing rapidly. The industry's management for efficient service delivery, its relationship with the environment and its costs are coming under increasing pressure. At an International Symposium held between 8-10 June, 1999 at Kobe, Japan on "Effective Water Use in Urban Areas", all practitioners in the water industry the world over were

called upon to "find urgent solutions to the multi-faceted problems of water planning and management" (UNEP-IETC, 1999). This declaration underscores the need for research works to contribute to finding solutions to the problem of water management and planning. Why should the 'water model' not be 'the brain' or the 'oracle' of the water supply system; a template against which the real system could be constantly monitored for effective control of operations and for strategic planning? These requirements

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have made the application of mathematical modelling techniques, in general, and System Dynamics modelling, in particular, very vital to the water industry (Adeniran, 2007).

There is no doubt that water is the most important resource in the world. Until recently, water supply management has been taken for granted. In most countries, water is regarded as social good rather than economic good. As water becomes scarcer and its quality continues to deteriorate, policy makers have been compelled to explore new approaches to improve the management of water resources. Water pricing reforms are among various measures designed to encourage the efficient use of water resources (Danar, 2000).

In 1990, the World Bank reported that the depletion of freshwater resources for domestic, industrial and agricultural purposes is likely to become the single most important environmental issues facing the Mediterranean countries and, in particular, their coastal areas. Even countries not yet facing water crises are likely to experience large increases in the cost of providing water to meet growing demand. Improving the planning, management and conservation of water will be critical for economic development. Failure to protect freshwater resources will render existing water-based patterns of development unsustainable in a number of countries by significantly increasing the cost of water over time (World Bank/EIB, 1990).

Winpenny (1994) argued that, in the water supply industry, there have been institutional, policy and market failures on a universal scale. He highlighted three underlying causes of the problem:

- (1) the fact that water is underpriced compared to its real cost of provision,
- (2) the fact that water is often a public good which makes it difficult to extract an economic price from users, and
- (3) the existence of environmental 'externalities' in the use of water which are not reflected in its price.

In 2004, the Norwegian Agency for Development Co-operation published the Water Supply Authority Tariff Determination Guidelines Edition 6. In the guidelines, the unit cost determination was based on operating costs, depreciation cost, profit and interest. From the foregoing, there is the need for evolving a tool that can capture the complexity of water production and variables in order to facilitate appropriate pricing and the establishment of reasonable tariff structures. The principles of SD are well suited for handling the dynamics of water resources and environmental problems. Yang et al. (2008) applied the principles of System Dynamics (SD) to carry out the impact analysis of (1) the severity of the water shortage and (2) total financial cost in central Taiwan. Adeniran (2007), Adeniran and Bamiro (2010) reported the development of a SD model for the strategic planning of a water supply system. In order to sustain the continuous availability of drinking water to a community, the need to price water appropriately and recover some, if not all, of the

cost of production and investments for future developments has become urgent.

The objective of this paper is to develop a model to determine the unit cost of water production using the System Dynamics method. The capabilities of Vensim Software were explored in achieving the objective. The developed model takes input from Excel Data sheet and it is therefore easy for the model inputs to be varied as economic and environmental factors may demand.

## MATERIALS AND METHOD

### Study Area

Ibadan is located in southwestern Nigeria in the southeastern part of Oyo State. The city's total area is 1,190 sq mi (3,080 km<sup>2</sup>). The mean total rainfall for Ibadan is 1420.06 mm, falling in approximately 109 days. There are two peaks for rainfall, June and September. The mean maximum temperature is 26.46 °C, minimum 21.42 °C and the relative humidity is 74.55%. The University of Ibadan is the oldest and one of the most prestigious Nigerian universities and is located 5 miles (8 km) from the centre of the major city of Ibadan, Figure 1.

### The Water Supply System and the University of Ibadan Water Scheme

"In order to undertake the modelling of any system, all the processes that work together to constitute the system must be well understood" Forrester (2000). The processes involved in the production and supply of water in order to (1) make it suitable for human consumption and (2) make it available at the various end users; include a complex of physical, chemical, biological and mechanical methods (Twort et al., 1994). Water processing involves not only purification and removal of various unwanted and harmful impurities, but also transportation with the aid of prime movers through conduits as well as storage in specially designed pressure vessels and tanks.

The methods adopted in processing water include:

- (a) Those aimed at improving organoleptic properties of water (clarification, decoloration, and deodorization),
- (b) Those which ensure epidemiological safety (chlorination, ozonization, Ultraviolet, and irradiation) and (c) Those by which the mineral composition of water is conditioned (fluorination and defluorination, deionization, demagnetization, softening, and desalination).

A particular method of water processing is chosen upon preliminary examination of the composition and properties of the water source to be used and comparison of these data with the standard specification expected of the final processed water. A Section through the University of Ibadan water production and supply system is as shown in Figure 2.

### System Dynamics Modeling

System dynamics models are causal mathematical models (Barlas, 1996). In system dynamics modelling (SDM) the underlying premise is that the structure of a system gives rise to its observable and thus predictable behaviour (Forrester, 1968; 1987). The first step in any system dynamics modelling project is to determine the system structure consisting of positive and negative relationships between variables, feedback loops, system archetypes, and delays (Stermann, 2000; Wolstenholme, 2004). This understanding of system structure requires a focus on the system as a whole. Holistic

**MAP OF UNIVERSITY OF IBADAN SHOWING WATER FACILITIES**

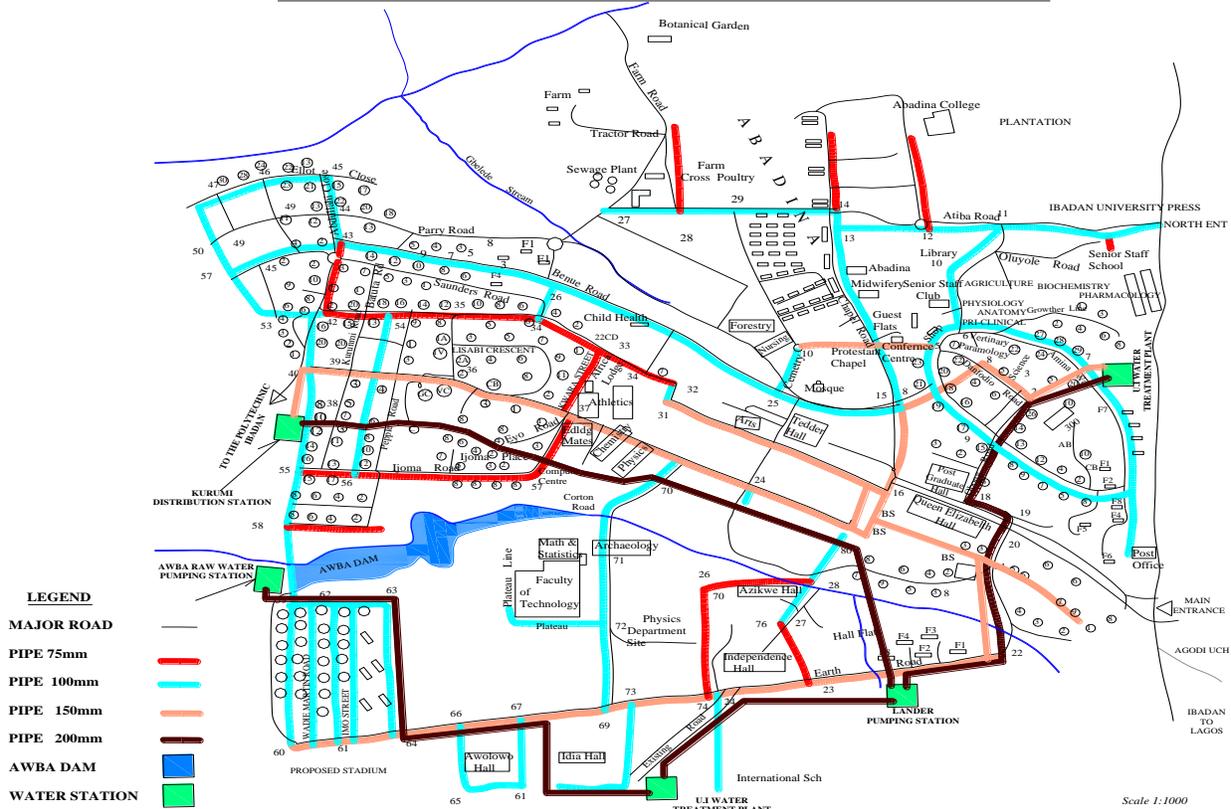


Figure 1. Map showing water supply facilities of the university of ibadan.

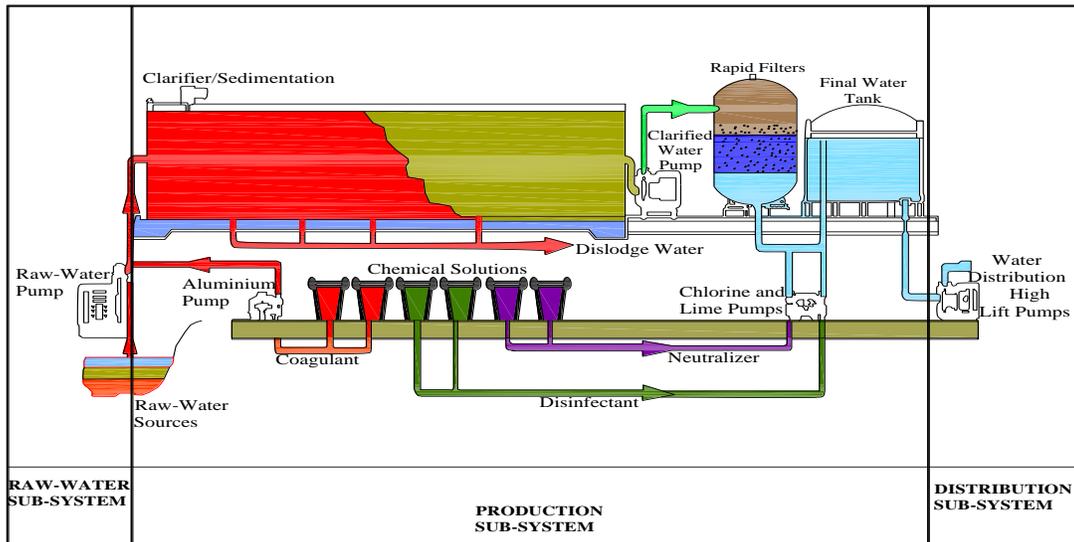


Figure 2. Section through the University of Ibadan Water Supply System.

system understanding is a necessary condition for effective learning and management of complex systems as well as consensus building. These are important goals in their own right. Additionally, systems modelling and simulation supports policy analysis and evaluation (Morecroft, 1992). System dynamics allows simple ideas

to be combined into models of complex systems and processes; it makes the integration of modeling and experimentation a simple matter (Adeniran, 2013). In particular, SDM involves:

- (1) Defining problems dynamically, in terms of graphs over time;

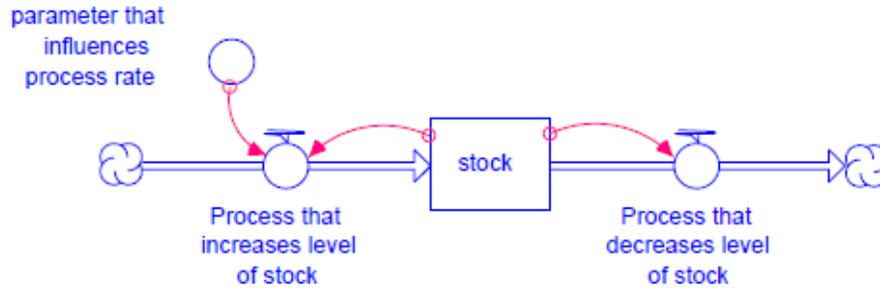


Figure 3. System Dynamics Stock-Flow Diagram.

- (2) Striving for an endogenous, behavioral view of the significant dynamics of a system, a focus inward on the characteristics of a system that themselves generate or exacerbate the perceived problem;
- (3) Thinking of all concepts in the real system as continuous quantities interconnected in loops of information feedback and circular causality;
- (4) Stocks or accumulations (levels) in the system and their inflows and outflows (rates);
- (5) Formulating a behavioral model capable of reproducing, by itself, the dynamic problems of concern. The model is usually a computer simulation model expressed in nonlinear equations, but is occasionally left un-quantified as a diagram capturing the stock-and-flow/causal feedback structure of the system; deriving understandings and applicable policy insights from the resulting model; and
- (6) Implementing changes resulting from model-based understandings and insights (Richardson and Andersen, 2010).

Mathematically, the basic structure of a formal system dynamics computer simulation model is a system of coupled, nonlinear, first-order differential (or integral) equations:

$$\frac{dx(t)}{dt} = f(x, p) \tag{1}$$

where:  $x$  = vector of levels (stocks or state variables),  
 $p$  = a set of parameters, and  $f$  is a nonlinear vector-valued function.

Simulation of such systems is easily accomplished by partitioning simulated time into discrete intervals of length  $dt$  and stepping the system through time one  $dt$  at a time. Each state variable is computed from its previous value and its net rate of change.

$$x'(t) : x(t) = x(t - dt) + dt * x'(t - dt) \tag{2}$$

In the earliest simulation language in the field (DYNAMO) this equation was written with time scripts K (the current moment), J (the previous moment), and JK (the interval between time J and K):

$$X.K = X.J + DT * XRATE.JK \tag{3}$$

The computation interval  $dt$  is selected small enough to have no discernible effect on the patterns of dynamic behavior exhibited by the model (Richardson and Pugh, 1981).

In more recent simulation environments, more sophisticated integration schemes are available. The current simulation

environments include VENSIM, STELLA, PowerSim, and AnyLogic. The conceptual tools and concepts of the field include stocks and flow diagrams. These are called the Building Block. The amount of material or other quantity accumulated in a stock is referred to as the 'level' of the stock (corresponding to the 'value' of a state variable). The cloud symbols represent sources and sinks with unlimited capacity. The circles represent parameters and auxiliary variables. The rectilinear double-line arrows represent 'flows' (processes) that can change the levels of the stocks. Inward arrows indicate processes that can increase the level of a stock and outward arrows indicate processes that can decrease the level of a stock. The tap symbols associated with each arrow represent the 'flow rates' of the processes-that is, the rates at which the processes change the levels of the stocks.

In a model, these 'valves' can be considered to 'contain' the process-rate equations. The curved single-line arrows represent influence or 'information' links- the small circles at the tail of these influence arrows serve as a reminder that an influence is exerted via a 'measurement' that does not change the levels of the variables and stocks that exert the influence, Figure 3. The net flow is therefore the derivative of the total stock with respect to time, Equation 4. Stock-and-flow diagram do not only show the structure's components and their relationships, it also draws more attention to accumulation and flow processes (Sterman, 2000).

$$\frac{d(Stock)}{dt} = Inflow(t) - Outflow(t) \tag{4}$$

**Model concept and development**

The development of the model targets the determination of the unit cost of production of water from a domestic water supply scheme. The model was developed using the SD and captures a number of factors contributing to the total production cost.

The University of Ibadan Water Supply scheme that was used for the development of this SD model has all the characteristics of a modern water treatment scheme comprising the raw water, production and distribution sub-systems as shown in Figure 4.

The production cost variable factors include chemical costs (cost of the coagulants, the cost on neutralizers to normalize the pH of the water and the cost of disinfectants); energy costs (costs of public energy usage and cost of fuel used to generate energy where necessary); cost of transportation; cost of spare parts; salary and wages; equipment depreciation; general expenses and cost of purchase/movement of raw water. The water production variables include hours of operation, plant capacity, and number of days of operation in a period. A period is a calendar month in a planning horizon of 1 year or 12 periods. The monthly volume of water production and the total monthly cost are calculated by the model.

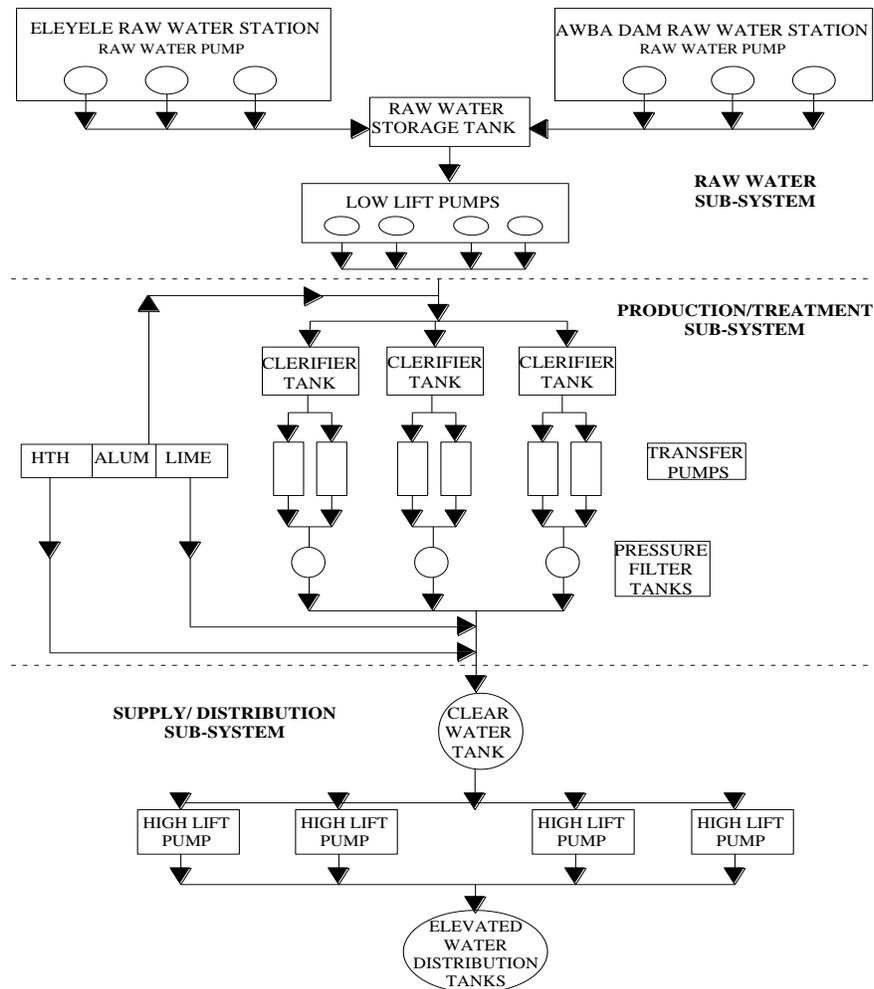


Figure 4. Schematic diagram of University of Ibadan water scheme.

The periodic volume, as well as the periodic cost is accumulated by SD level equations. The cumulated volume is divided by the cumulated total cost to determine the unit cost. The concept of the model is as shown in Figure 5.

The Vensim DSS™ System Dynamic Modeling platform was the adopted model system while the input variables were entered from an Excel worksheet. The Vensim Stock and Flow diagram describing the model is presented in Figure 6.

## RESULTS AND DISCUSSION

### Model Application

The model was applied to the University of Ibadan Water supply scheme for which extensive operation and maintenance data, spanning over 15 years, are available. The input data, which are averages of actual field data, are stored in an Excel file “unitcost.xls”. The Vensim Model, using the “GET XLS DATA” command obtains the data for the simulation run from the Excel file “unitcost.xls”. The field data used for the initial simulation run is shown

in Table 1.

Simulating with actual field data returns a unit cost of production ranging from N160.63 (\$1.07) to N169.70 (\$1.13) per  $m^3$ . This result is shown in Figure 7. This result obtained is reasonable and is comparable to field results and other tariff structures obtainable in other parts of the world. The result obtained compares favourably well with data for unit cost of water from other countries as shown in Figure 8 below.

### Scenario Investigations

System dynamics is a method for understanding the dynamic behavior of complex systems. In particular, System Dynamics models have the capability of scenario investigation to consider the effect of changes in any or all of the input variables of the model. In this case, two scenarios are considered:

(1) The effect of the change in the source of raw water on the unit cost

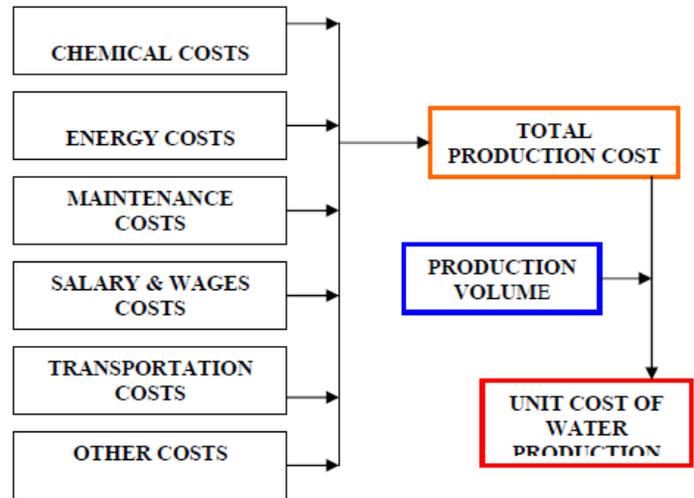


Figure 5. The concept of the unit cost of production model.

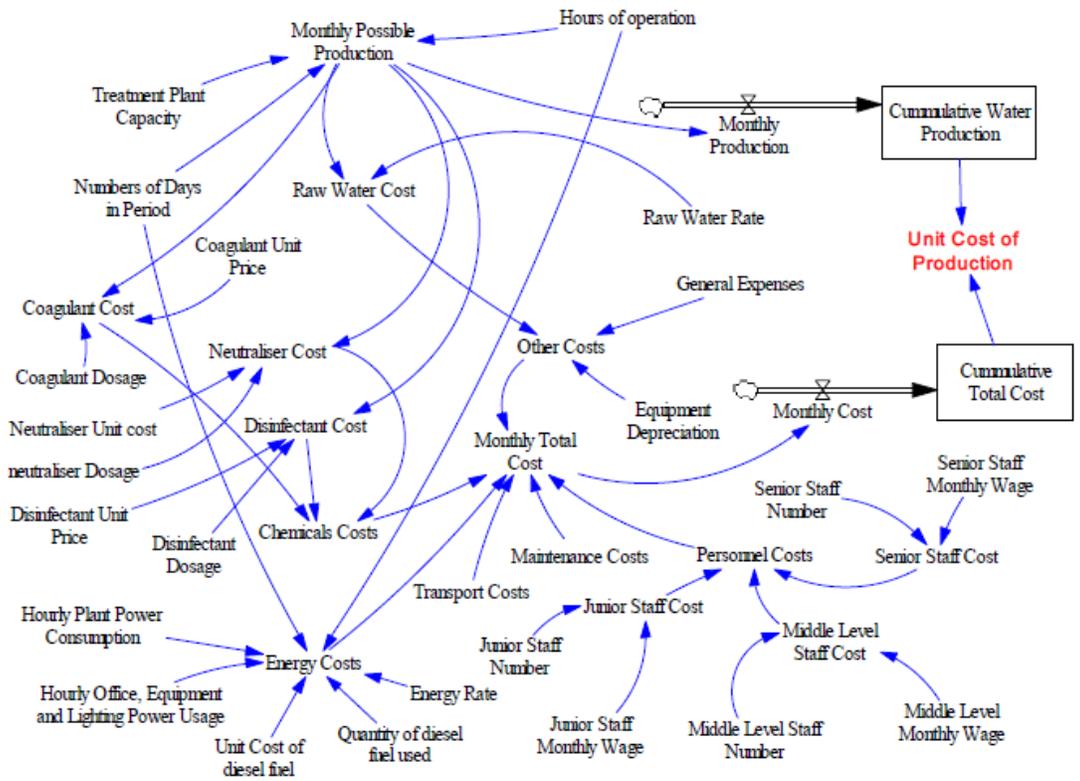


Figure 6. SD model for unit cost of water production system.

(2) The effect of improved power supply on the unit cost.

**Change of the source of raw water from surface water to deep boreholes**

The raw water used in the mode is imported surface

water that requires a coagulant in order to achieve WHO standard, payment is also made to the Water Supply Agency that owns the dam from where the raw water is abstracted. This scenario investigates a situation where the water scheme is located in a place where the source of raw water is boreholes. In the investigation of this scenario, the University of Lagos water scheme that uses

**Table 1.** Field data used for unit cost of water model

Time	1	2	3	4	5	6	7	8	9	10	11	12
Days	31	28	31	30	31	30	31	31	30	31	30	31
Hours	18	20	20	20	20	20	12	12	20	20	20	18
Plant Capacity (cu.m/hr)	250	250	250	250	250	250	250	250	250	250	250	250
Raw Water Rate (N/cu.m)	10	10	10	10	10	10	10	10	10	10	10	10
Alum Unit Price (N/kg)	450	450	450	450	450	450	450	450	450	450	450	450
Alum Dosage (ppm)	80	90	90	90	110	120	120	90	120	120	80	80
Lime Unit Price (N/kg)	150	150	150	150	150	150	150	150	150	150	150	150
Lime Dosage (ppm)	35	35	35	35	35	35	35	35	35	35	35	35
Chlorine Unit Price (N/kg)	750	750	750	750	750	750	750	750	750	750	750	750
Chlorine Dosage (ppm)	20	20	20	20	20	20	20	20	20	20	20	20
Plant Power Usage (Kw/hr)	600	600	600	600	600	600	450	450	600	600	600	600
Office/Equip Power Usage (Kw/hr)	35	35	35	35	35	35	35	35	35	35	35	35
Unit Cost of AGO (N/l)	65	65	65	65	65	65	65	65	65	65	65	65
Quantity of AGO used	2000	2000	2000	2000	2000	2000	1500	1500	2000	2000	2000	2000
Current Energy Rate (N/Kwh)	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Junior Staff Number	32	32	32	32	32	32	32	32	32	32	32	32
Junior Staff Ave Wage (N/month)	25000	25000	25000	25000	25000	25000	25000	25000	25000	25000	25000	25000
Middle Level Staff Number	12	12	12	12	12	12	12	12	12	12	12	12
Mid Level Staff Ave Wage(N/month)	90000	90000	90000	90000	90000	90000	90000	90000	90000	90000	90000	90000
Snr Staff Number	5	5	5	5	5	5	5	5	5	5	5	5
Snr Staff Ave Wage (N/month)	250000	250000	250000	250000	250000	250000	250000	250000	250000	250000	250000	250000
Equipment Depreciation (N/month)	1200000	1200000	1200000	1200000	1200000	1200000	1200000	1200000	1200000	1200000	1200000	1200000
Maintenance Cost (N/month)	750000	600000	600000	600000	750000	750000	750000	600000	600000	750000	750000	750000
Transport Cost (N/month)	450000	450000	450000	450000	450000	450000	450000	450000	450000	450000	450000	450000

boreholes as source of raw water was adopted. In that case, the cost of the coagulants can be set at zero but disinfectants and neutralizers would still be required. The result obtained is shown in Figure 9. It is observed that the price reduced to between N107.00 (\$0.71) to N112.00 (\$0.75).

### Improved Power Supply

This scenario investigates the same water supply scheme with surface raw water source but here with improvement from the public power supply. Improved public power supply would lead to

elimination of running of standby power generators and accordingly for the reductions on the diesel fuel consumption and its maintenance cost. The result of this scenario is presented in Figure 10. The unit cost of production for this scenario now ranges from N154.00 (\$1.023) to N163.00

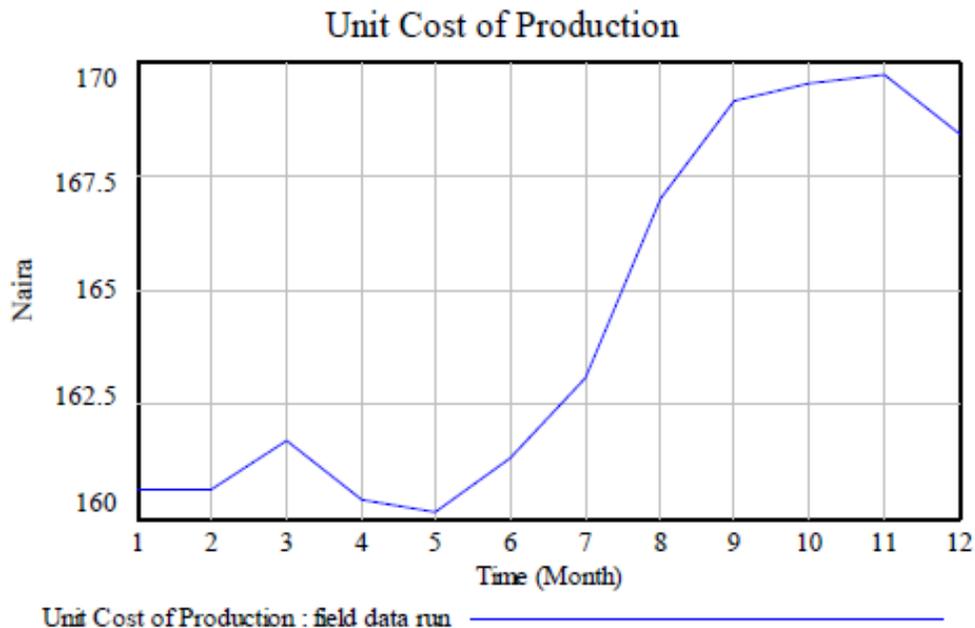


Figure 7. Unit cost of production using field data.

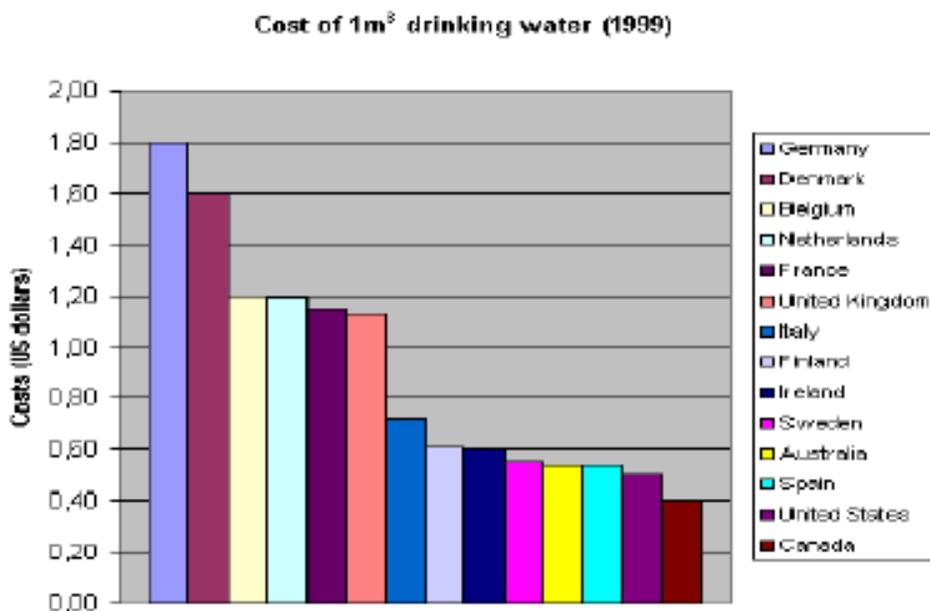


Figure 8. International comparison of unit cost of water production.  
 \*Source : [www.lenntech.com/specific-questions-water-quantities.htm](http://www.lenntech.com/specific-questions-water-quantities.htm)

(\$1.09). It is noted that the unit cost of production will reduce, even with importation of surface raw water, if there is steady public power supply. The results for the three scenarios are presented together in Figure 11. The results obtained show that the unit cost of water from borehole is cheaper than the surface water raw water. This is expected because of the saving in the cost of coagulation which is, usually, not necessary for borehole

raw water.

**Conclusions**

A System Dynamics model using Vensim platform to capture the operation, maintenance and production variables with the objectives of determining the unit cost

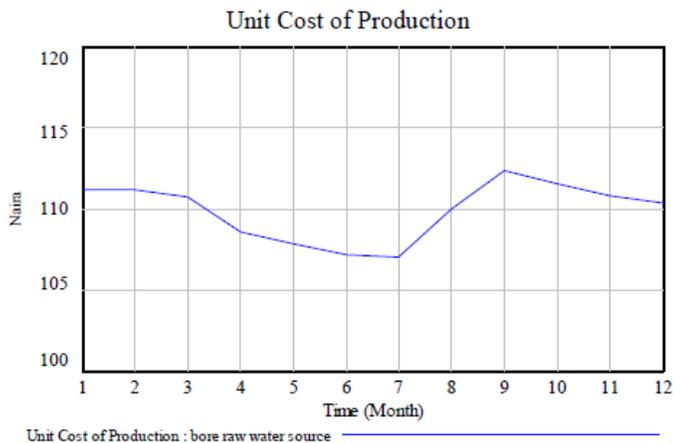


Figure 9. Unit Cost of Production with Borehole Raw Water Source.

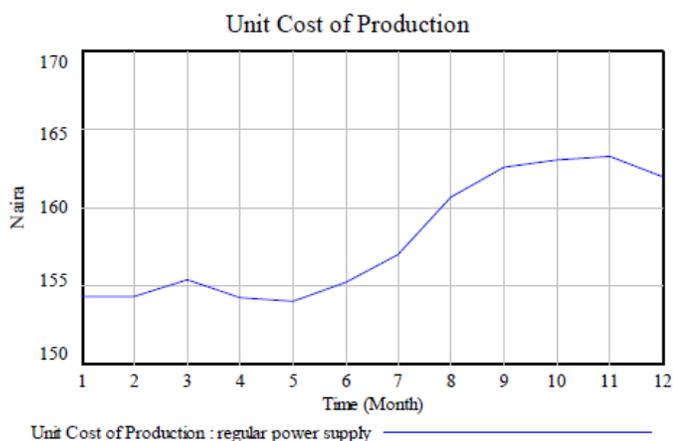


Figure 10. Unit cost of production with regular power Supply.

of domestic water supply production has been developed and reported here. The data input was from an Excel file to facilitate and enhance easy changes to be made to the variables using real life data. The model was applied the University of Ibadan Water Supply Scheme for which extensive field data spanning over fifteen (15) years are available. The model was then used to carry out scenario experimentations for strategic planning. The results obtained for the unit cost of production with the field data are reasonable and compare well with unit cost of production from other countries which were obtained through other techniques. It is concluded that the SD model can be successfully deployed for the establishment of reasonable and realistic water tariffs, which is currently on the front burners of industry, organizations and academic debates.

### Conflict of Interest

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

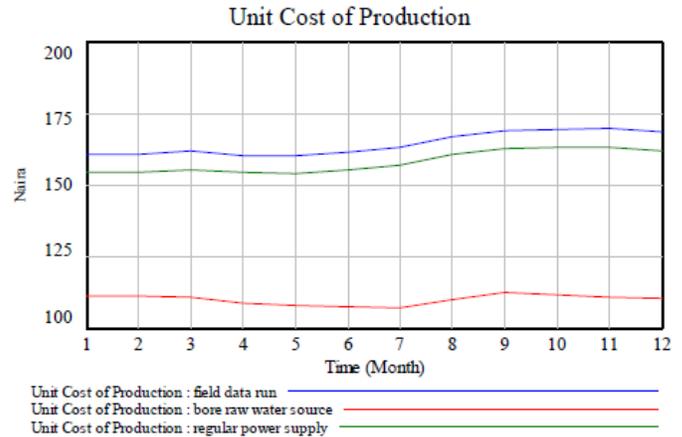


Figure 11. Comparison of unit costs of production under three scenarios.

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