School of Civil and Mechanical Engineering
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Evaluating and Improving the Tools for Predicting Discolouration Events in Potable Water Supply System

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature: ……………….

Date:

ACKNOWLEDGMENTS

Praise be to **"ALLAH"** and to his prophet **"Mohammed".** This research has been completed under his benediction.

It has been a long journey to come to the end of this research project. In retrospect, it is always easier to reflect on a few exciting moments when encouraging findings were achieved, rather than the countless days when one was toiling away on hundreds of failures. In a long expedition, those people who light up the torch when one is exploring in the dark, and those who lend their helping hands when one is struggling in difficulties, will never be forgotten and always be appreciated.

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TO

MY GRANDFATHER
AL-HUSSEIN "ABU EBD ALLAH"
(PEACE BE UPON HIM)
MY FAITHFUL FAMILY
WHO BURN THE CANDLE AT
BOTH ENDS FOR MY AMBITION
THE EYES THAT OBSERVE
CLOSELY
THE HEARTS THAT SUPPLICATE
FOR SUCCESS

AFRAH

January- 2013

EXTENDED ABSTRACT

One of the key performance and compliance indicators for the water industry is customer complaints about discoloured water. Such discolouration is frequently caused by particulates from reticulation systems appearing at the customer's tap. Little is understood of the origins of such material, yet it may cause from 60% to 80% of water quality related customer complaints. It is generally believed that the accumulation of sediment in the water pipes is main reason for complaints. Hence, to avoid these kinds of problems, water utilities regularly clean the drinking water network, using enormous amounts of resources and money. In many distribution systems, cleaning frequency is determined based on the number of complaints received. However, it is not clear how effective this cleaning may be in preventing discolouration events and whether or not it is the cleaning that may actually be one of the main causes of discolouration events.

Various tools have been proposed to determine the degree of water fouling so that cleaning frequency might be estimated before complaints are made. Out of all methods and models, the Resuspension Potential Method (RPM) and the Particle Suspension Model (PSM) were chosen for use by the Water Corporation and Curtin University. The RPM can be used to evaluate a pipe for its cleanliness. The PSM tracks the sediment transport using a background hydraulic model by implementing additional algorithms for sediment settlement, resuspension etc.

Despite the availability of many different models and tools, water utilities are still struggling to predict discolouration events, to know when cleaning has to be undertaken and whether the cleaning is effective. The general aim of this research is firstly to critically evaluate the existing knowledge, practice and tools, and then to improve the predictive capability of the available tools so that better management of discolouration can be undertaken in the future.

Out of all complaints registered with a water utility, discoloured water complaints account for the majority. For discoloured events to occur, suspended particles should be present in the system and they should be carried to the customer. Despite an obviously logical relationship, no studies have proven the strong relationship of hydraulic events to complaints. In order to understand the usefulness and effectiveness of complaints data analysis, a desktop study was conducted in water supply Zone M in Perth, Western Australia. To neutralise the unreliability of discoloured water complaints, they were divided into batch and isolated complaints. Batch complaints are defined as more than two complaints occurring from different addresses in a locality on a single day. The evaluated parameters, covering ten suburbs, were population distribution, seasonal variation and effects of burst pipe events over the period 2003 to 2009. Of all complaints received, 63.8% were batch complaints. Seasonal variation did not show a definitive relationship.

The results indicated that burst pipe events are the major causes of discolouration complaints although the presence of material causing discolouration is a prerequisite. Approximately 53% and 66% of total and batch discoloured water complaints can be attributed to burst pipe events. This activity was recorded in all suburbs over the seven year case study period. This result was reached in all years, although other factors also appear to influence the likelihood of dirty water complaints, such as the extent of hydraulic events caused by burst pipe events or fire fighting. The analysis of isolated complaints assisted in ascertaining the fact that complaints were located in places where water use patterns were heavily affected by changes in land use patterns, i.e., increases in population/housing density. This significant finding should assist water utilities to effectively target and minimise discolouration events.

To evaluate the dirtiness of pipes, 25 sites were tested by applying the RPM. Interestingly, the results showed that pipes in suburbs recording a higher number of complaints (or that had more burst pipes) resulted in a lower RPM ranking, i.e. pipes were found to be clean. In contrast, the pipes in suburbs registering fewer complaints showed a higher RPM ranking. To deal with discoloured water events, the Water Corporation of Western Australia (WCWA) adopts the protocol of flushing the nearest appropriate hydrant for a short period of time at a high flow rate until the water becomes clear. It is likely that the burst pipe events and the above protocol adopted by the Water Corporation of Western Australia (WCWA) could have cleaned the pipes in areas where more complaints were reported.

It is clear therefore, that the current approach to cleaning pipes in an area where more complaints are made needs careful evaluation. This finding is expected to change how a water utility makes a decision about the area to be cleaned.

The current RPM method evaluates the turbidity profile, giving weight to the time taken to reach base level turbidity. If the base level turbidity is below the turbidity level of concern then it is unreasonable to say that one has to wait until base level turbidity is reached, as these turbidities will not cause any concern to exposed customers or to the water utility. To improve the interpretation of field data obtained with RPM measurements, two new methods of evaluation were proposed. These methods consider initial turbidity and the turbidity after the disturbance has ceased or been stopped (TADS). A comparison between these three evaluations; i.e., the two new methods with that of Vreeburg et al., 2004a; has indicated the benefit of utilising new methods.

Detailed evaluation in the field indicated that the resuspension velocity could be as low as 0.2 m/s as opposed to the 0.6 m/s suggested in the available literature. It is also noted that the resuspension velocity could actually vary depending on the previous hydraulic history and type of sediment in the pipe. It was also found that a dirty pipe could be cleaned if a flushing velocity of around 0.4 m/s were adopted in a directed manner through a unidirectional length of pipe. A new understanding of real suspension behaviour on networks was used to devise a new pipe cleaning strategy. This is expected to guide the water authorities in implementing orderly hydrant flushing programs or other pipe cleaning methods which will not only save money, labour and water but also reduce the number of complaints.

This research also analysed the usefulness of the PSM to predict discoloured water events. It was found that the PSM had many issues that required attention. The PSM was calibrated, tested as a prediction tool and improved upon by proposing a new resuspension velocity, depending on fieldwork results. One example includes difficulty in assigning sediment concentrations at the beginning of a run.

Overall, the results that question current cleaning strategies prove that it is often the case that pipes are already clean in an area where a high number of complaints are received. A new method is proposed to decide upon which areas and pipes to clean and how. This, along with the identification of issues in the PSM is expected to change the way water utilities manage distribution systems to counter a high number of complaints. Proposed methods are expected to be both economical and practicable.

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CHAPTER 1 INTRODUCTION

1.1 Introduction

The majority of customer complaints received by water utilities in Australia and many parts of the world are due to discoloured water. These usually constitute from 60% to 80% of water quality related customer complaints. The problem is amplified by the fact that these complaints are simply incorporated into key performance and compliance indicators in the water industry. Current customer complaints in Australia average between 1.1 and 17.9 per 1000 properties, per year. However, Australian Drinking Water Guidelines (ADWG) specify that complaints should be kept below 4 per 1000 customers per year; by and after 2013 that recommendation will be reduced to 3 per 1000 customers per year. In 2005-2006, water quality complaints regarding the Perth metropolitan water supply system were 11.3 per 1000 properties (WSAA Facts 2005). From the figures above, it can be seen that water discolouration is one of the most important issues that the water utility is facing.

Apparent colour is caused by suspended material (usually very small particulate or colloidal in size) in water that absorbs and scatters visible light. Coagulation and gravity sand filtration will eliminate apparent colour. True colour is caused by dissolved organic matter that usually includes aromatic chemicals such lignin. Coagulation and sand filtration will not remove all true colour of this type from water, but coagulation and flocculation with hydrolyzing metals such as aluminum in alum, will allow some of this true colour to be removed by sand filtration. However, oxidation, activated carbon adsorption and membrane filtration technologies like ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) are considered the most efficient methods to remove most of the soluble organic-related color from water supplies. Discolouration, the visual effect observed by customers, is rarely 'colour' in a strict water quality sense. It is defined as contaminants absorbed into the chemical composition of the water. Typically, if a 'discoloured' water sample is left to stand for a prolonged period (overnight) it will clear as the material deposits. It can therefore be concluded that it is this particulate matter that customers experience as 'discolouration'. The measurable parameter requiring investigation is therefore turbidity. However, different particles have significantly different effects on perceived turbidity, or discolouration. Similarly, they are likely to have different characteristics that govern sediment transport such as sediment settlement, resuspension, and attachment to the pipe wall. Furthermore, the turbidity level which triggers a customer to complain is different for different utilities and this generally depends on the normal turbidity the customer is exposed to. For example, Netherlands customers regularly exposed to riverbank filtered water may complain when the turbidity level is as small as 3 NTU. On the other hand, a customer in Melbourne, Victoria, exposed to unfiltered water may not complain until the turbidity reaches 5 NTU (Kjellberg, 2007). All Australian water utilities follow the Australian Drinking Water Guidelines (NRMMC 2004). The guidelines state 5 NTU as being the maximum acceptable turbidity measurement, which is consistent with Western Australian legislation.

Most researchers agree that discolouration is most likely to occur in unlined mains pipes with a low water velocity and high particle loading, since these conditions provide sections acting as sediment reservoirs. These sediments stay as loose deposits in networks which can originate from different sources. The processes that determine water deterioration in distribution systems are known, but they are complex and relatively poorly understood. The understanding of the fundamental process causing discolouration is limited when compared with knowledge of water quality processes in treatment plants. In both treatment and distribution there are chemical, physical, biological and hydraulic processes that all influence the generation of discoloured water, but exactly when or where discolouration occurs, it is not yet possible to determine.

At present, water complaints are dealt with in a reactive manner by regularly cleaning the drinking water network. Determining when and how to clean is a challenge, and in many distribution systems the cleaning frequency is determined based on the number of complaints received. The Water Corporation in Perth, Western Australia also adopts a similar approach. By the time the water utility decides to clean the system, many complaints have already been made and this seriously affects customer relationships. Water companies are therefore under pressure to implement planned activities to control discolouration prior to customer contact. As cleaning programs are pragmatically analysed in how they positively affect the number of complaints, it is advisable to investigate these programs more systematically.

Cleaning programs would be effective if the cleaned pipes could remain so for longer, despite hydraulic disturbances. In the available literature, the cleanliness of pipes has been studied using the Resuspension Potential Method (RPM). Various researchers have noted the time it takes for sediment to reach a steady state. In the Netherlands, it has been found that this takes approximately five to ten years whereas in Melbourne it was found to be between two and four weeks (Kjellberg, 2007).

The RPM is based on creating an additional velocity in order to resuspend deposited material. The RPM is not a quantitative method, but it provides information on the cleanliness of a pipe after processes such as cleaning or the changing of influent water quality by treatment processes or the water source. It is however, yet to be understood how the RPM tool could be applied in directing limited resources to effectively prioritise the particular pipe or pipes that need cleaning.

Many commercial and non-commercial models/tools are available to predict sediment transport and simplify complex systems. These include the Discolouration Risk Management (DRM) tool, the Prediction of Discolouration Events in Distribution Systems Model (PODDS), the Resuspension Potential Method (RPM) and the Particle Suspension Model (PSM). The DRM tool is based on a risk assessment of which pipes are likely to fail. This is assessed by an expert panel and it is deemed to be a pragmatic approach.

The other two programs are based on EPAnet, a free dynamic water distribution system simulation model; with the addition models used to track transport of contaminants. For example, an extension to this program named EPAnet-MSX has recently been introduced the transport of contaminants can be tracked. EPAnet-MSX has specially built functions readily available for the user to define and track through the system the various contaminant species with different characteristics, and it is a more effective and flexible method for the testing of process models (Wricke et al, 2007). Similarly, PSM and PODDS use the hydraulic capability of EPAnet. However, PODDS is not available for evaluation. The details are given in the literature review.

PSM was developed by the Cooperative Research Centre for Water Quality and Treatment (CRCWQT), Australia. For the first time, this software took into account the factors of sediment transport, settlement, attachment to the pipe wall and resuspension. Despite the detailed incorporation of these processes into the model, very few utilities have actually used it to track sediment transport or predict discolouration risks. As its usefulness to the Australian water industry is yet to be charted, it will be evaluated in this thesis.

Very few studies have attempted to assess the above tools in relation to complaints – the ultimate aim. Therefore there is an urgent need to critically evaluate these existing tools and procedures in terms of controlling the occurrence of discoloured water more systematically. This thesis analyses the issues from their original starting point, i.e., the complaints. The order of progression is complaints to data to programs and models.

1.2 Aims of the Study

The general aim of the research is to firstly critically evaluate the existing knowledge, practice and tools. Secondly, the purpose is to improve the predictive capability of the available tools in order to better manage discolouration in the future. It is hoped that this will guide the water authorities in the management of discolouration events and/or customer complaints effectively.

This research focused on a water supply sub-system supplying about 33,000 properties and it had the following specific objectives:

1. To thoroughly analyse complaints data. The link between hydraulic disturbances, population distribution, seasonal variation and cleaning by air-scouring was established using data obtained from 2003 to 2009.
2. To critically evaluate the usefulness of RPM by RPM measurement of targeted sites and establish the link between dirtiness and complaints.
3. To propose improvements to the RPM.
4. To critically evaluate the PSM for its ability to predict discolouration events through modelling and field trials. This should lead to identification of the advantages and disadvantages of the PSM tool.
5. To critically evaluate local mains cleaning strategies adopted by water utilities, particularly the flushing of local pipes following complaints.

6. To propose an effective discolouration water management strategy and to recommend future research directions.

1.3 Thesis Structure

In order to fulfil the objectives of this research, both desktop and field studies were undertaken. To supplement hydraulic and sediment transport modelling, research was undertaken by applying and interpreting the capabilities of existing tools, in particular the RPM (to examine dirtiness) and the PSM (to examine prediction capability).

- ❖ Thoroughly analyse complaints data: The water supply, Zone M in Perth, Western Australia was used as a case study (see Chapter 3). The study area was divided into ten sub-zones according to the number of suburbs. The desktop study evaluated a range of parameters and their association with customer complaints of dirty water over a seven year period between 2003 and 2009. Parameters evaluated included population distribution, annual seasons, events such as burst pipes and fire-fighting, and the effects of pre-cleaning by air-scouring.

- ❖ Evaluation of RPM: When applying the RPM method, visually noticeable turbidity (NTU) levels are created and measured, then translated to a numerical ranking of the discolouration risk, between 0 (no risk) and 15 (highest risk). The evaluation of RPM tools was carried out as follows:

1. The RPM tests were conducted at twenty-five sites. The sites represented a variety of complaints (number of complaints/population) and various flow conditions. The idea was to connect the dirtiness of pipes in a particular area to complaints from that area. This also allowed an evaluation of the RPM method as to its suitability to Australian conditions (see Chapter 5).
2. Based on the evaluation, improvements to the analysis of RPM results were proposed. Results of the proposed methods were compared with that of current method and these are discussed in Chapter 6.

- ❖ Applying and understanding capabilities of PSM when applied to previous events: Since about 53% of all complaints were identified as being due to burst pipes events or fire hydrant activities, these were considered to be the principal causes of dirty water incidents. The PSM was used to predict discolouration complaints using the same input conditions; burst pipes or fire-fighting. These events were drawn from an initial analysis of customer complaints conducted in Phase 1. This type of analysis helped in examining the predictive capability of the program before it could be improved further (see Chapters 7 and 8). This also assisted in understanding the problems associated with PSM in the prediction of discoloured water complaints.

- ❖ Fieldwork part 2 "Evaluation of PSM under known conditions for controlled event": One of the aims of this project was to validate a computer model (Particle Sediment Model-PSM) designed to predict sedimentation patterns in the pipes of drinking water distribution and reticulation networks. To improve the PSM, especially in terms of its capability to predict discoloured water events, a controlled event was manually created and the resultant turbidity and customer complaints closely monitored. This allowed calibration of the PSM and the formulation of questions around some of the assumptions made in the PSM. The results are discussed in Chapter 9.

- Fieldwork part 3 “Find the real resuspension velocity”: Previous theories have assumed that sediment moves at a velocity of 0.6 m/s (PSM program) but the majority of these theories were based on laboratory experiments. In contrast, the fieldwork conducted in Phase 4 showed that even a velocity of between 0.1- 0.2 m/s was enough to mobilise the sediment in some pipes. Therefore, a fieldwork study was conducted to understand sediment resuspension velocity and the type of sediment resuspended, by manually increasing the velocity gradually from 0.1 to 0.7m/s in five different types of sites (two with dead-ends, loop, and flow-through pipes). The results were used to propose improvements to the PSM program and develop a new cleaning strategy. The results are presented in Chapter 10.

- A new cleaning strategy for distribution systems: The final results of Phase 4 and 5, which provide a new understanding of resuspension behaviour in networks, can guide water authorities in hydrant flushing programs or other pipe cleaning methods and further refine cleaning strategies for distribution system pipes. A new cleaning strategy is proposed at the end of Chapter 11.

This project provides a demonstration of improvements to existing models (tools) in the prediction of discolouration events before they occur, as well as proposing a well-defined cleaning strategy. The entire project is designed to analyse complaints and to draw links with burst pipe events. The application of predictive tools such as the PSM model to link and predict complaints should allow the early prediction of discolouration events.

The results of this research can now guide water authorities in deciding in advance when and where to conduct hydrant flushing programs or utilise other pipe-cleaning methods, before complaints become significantly high.

Previous studies in Australia showed the number of complaints to average 6 per 1000 customers. It should be noted that there was a large variation in this range from 1.1 to 17.9 complaints per 1000 customers. Australian Drinking Water Guidelines recommend an acceptable level of customer complaints to be 4 per 1000 customers. By, and after 2013 this recommendation is expected to drop to 3 per 1000 customers. The rate per 1000 customers is seen as one of the key performance and compliance indicators for the water industry. Little is understood regarding the origins of discolouration events, yet they appear to be responsible for 60% to 80% of water quality customer complaints. The intention of this project is to solve these water quality problems by predicting discolouration in advance. The project is backed by the Water Corporation which has undertaken to implement planned activities to control discolouration prior to complaints occurring.

This research is significant for Australia due to the high levels of customer complaints relating to discoloured water. The project intends to improve our understanding of both the dominant processes and the predictive and management tools that will further our knowledge in this field.

The current efforts of water utilities in cleaning water mains are either reactive or rely on indirect measures of the degree of sediment in a water mains. An understanding of the location and deposition patterns of discoloured water in drinking water networks would improve the ability to target preventative maintenance. Such improvements would lead to cost savings in a more targeted proactive cleaning of water mains. Additionally, customer satisfaction would increase and water utilities would be more in compliance with the turbidity standards in Perth Water Guidelines.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

All drinking water supply systems suffer from discolouration from time to time. This is an issue that has affected global water supplies since public drinking water supplies were first introduced. Until a few years ago, this phenomenon received relatively little attention. However, with improvements in the supply of drinking water, discolouration is now the single most common reason for customer contact with water authorities. For example, Prince et al. (2001) and Polychronopolous et al. (2003) reported that discolouration is likely to be the instigator of between 60% and 80% of all water-quality related customer complaints.

A discolouration event requires five factors to be registered as such: sediment or particles should be present in the pipe; they should be sufficiently disturbed to resuspend the sediment; they should be carried to the customer; and the customer should notice it, and at least one customer register a complaint.

The presence of sediment and particles in pipe water result from a combination of factors, for instance, active corrosion of cast iron pipes, valves and fire hydrants (ferrous material) in combination with a large mains or the presence of sediment in pipes (Slaats et al., 2003; Vreeburg et al., 2004b). In addition, particles and sediment can enter into the distribution system from treatment processes, source water, or during maintenance works.

In disturbing and carrying the sediment to customers, hydraulic disturbances are widely recognised to play a prominent role. However, the likelihood of complaining to the water utility is affected by the magnitude of turbidity, its relative value compared to the quality customers are used to and the time it happens (weekend and daytime variations are usually noticed by customers).

Various actions have been taken in the past to control the number of complaints. These include cleaning and research/field trial/modelling to understand the problem. Historically, cleaning methods have usually been adopted by water utilities. These include preventative cleaning and flushing, emergency cleaning at the time of incident, and cleaning undertaken as a result of widespread complaints in a particular area.

In the recent past, research has been carried out with a view to improving the understanding of discolouration and controlling it more effectively. Research in the Netherlands has assisted in developing a theoretical tool called the Resuspension Potential Method (RPM), which effectively measures the cleanliness of a pipe by inducing a controlled hydraulic disturbance and observing the profile of turbidity. Research in England has contributed to the development of a model known as Prediction of Discolouration events in Distribution Systems (PODDS) which, as the name implies, claims to predict discolouration events, but this approach is data driven as the model needs calibration for each pipe. Research in Australia has resulted in the development of a Particle Suspension Model (PSM) which aims to predict the mobility of sediment by using well established EPAnet software (Vos et al., 2005).

Despite all these developments, water utilities continue to spend millions of dollars attempting to reduce complaints regarding discoloured water (Perth Water Corporation, 2007). A thorough evaluation of all these tools will be conducted, in terms of the ability of the tools to predict discoloured water complaints, and the evaluation will determine how effective these tools are. The following sections critically review the literature, providing a detailed background and critical analysis that should highlight gaps in current knowledge around discoloured water complaints.

2.2 Customer Complaints and Discoloured Water Events

Despite continual improvements to problems within the water supply that affect customers, water authorities still find that customer complaints arising from discoloured water events contribute to more than 50% of total complaints.

Customer complaints of discoloured water vary greatly around the world. In the Netherlands, the annual average figure is 0.5 complaints per 1000 customers, in the UK, 4 complaints per 1000 properties, and the average in Australia is 6 complaints per 1000 customers. Within Australia however, there is a large variation ranging from 1.1 to 17.9 complaints per 1000 customers (Vreeburg and Boxall, 2007; Kjellberg, 2007; Prince et al., 2003). Australian Drinking Water Guidelines (ADWG) recommend that customer complaints should average less than 4/1000 customers, demonstrating that further work is needed to reduce customer complaints. By, and after 2013, it is estimated that the recommended level will be adjusted to 3 complaints/1000 customers. In 2005-2006, Perth water quality complaints were 11.3 per 1000 properties (WSAA Facts 2005).

The use of customer complaints to identify discolouration risks is important, but as a quantification tool, customer complaints are not particularly effective. For example, Kjellberg, 2007 reported that complaints are neither reproducible nor reliable. For example, with regard to water facilities in the home, customers with bathtubs might have a higher complaint rate than customers with showers, possibly due to ease of observation of discolouration. The longer the discolouration lasts, the higher the risk of customer complaints. In some cases, it has been reported that the number of complaints decreases if discolouration events become too frequent. Kjellberg, 2007 reported that customers may actually become used to a certain level of discoloured water and eventually stop reporting to the water utility.

Several reported factors appeared to affect the likelihood of a customer complaining about dirty water. These were: the size and nature of the incident particles; the complexity of the associated reticulation network; the presence of an undulating topography in the street of concern; and whether or not the street had a dead-end (Polychronopolous et al., 2003). Based on their desktop study for South East Water in Melbourne, the authors found an apparent contribution from topography (streets with an undulation) and street location to the incidence of customer complaints. For example, dead-end streets had a disproportionate number of dirty water customer complaints (relative to through streets), comprising some 10% of the streets in the zone, but accounting for almost 50% of the customer complaints. In Melbourne, operational maintenance for the control of discolouration events costs hundreds of thousands of dollars a year, yet customer complaints persist. There is the potential for large savings and reduced complaints if the risk, location, severity and timing of discoloured water could be predicted, modelled, and managed (Boxall and Prince, 2006).

Polychronopolous et al., 2003 further reported that there was an absence of correlation between customer complaints and water velocity. This is in contrast to what has been written by others (Vreeburg, 2000; Prince et al., 2001). Based on the data of Polychronopolous et al., 2003, a positive correlation has been found in this research between the number of complaints and peak turbidity, and the historical velocity of water ($velocity_{normal}$ /$velocity_{maximum\ turbidity}$).

In most countries, the number of customer complaints determines the cleaning frequency. Traditionally, this is done by cleaning the pipes either regularly or in places where most complaints are received. The Water Corporation in Perth, Western Australia adopts a similar approach. By the time a water utility decides to clean a system, many complaints have already been made and this seriously affects good customer relations. Control measures, including cleaning, are dealt with separately in Section 2.6. However, from the perspective of the water utility there is no easy way to determine the dirtiness of a pipe before it affects customers. Although cleaning the pipe is one solution it does not stop the problem occurring in the first place. Without a deeper understanding of the issue, cleaning may be an overreaction and/or result in unnecessary spending of resources.

In this research, over the period 2003 to 2009, an extensive complaints analysis was conducted. Evaluated parameters were: population distribution, seasonal variation, effects of air-scouring, and effects of burst pipe events.

2.3 Role of Hydraulic Events in Causing Discolouration Events

For a customer complaint to occur, hydraulic events such as the movement of particles are required. Yarra Valley Water, 2006 reported that the increases in flows and disturbances caused by events such as increased demand from customers, burst pipes, leakage, the use of fire hydrants, construction activities drawing large amounts of water and operational changes can unsettle the sediment and cause dirty water in localised areas. Of all major hydraulic events, burst pipes events are the most significant contributors. In Melbourne, burst pipes account for around 9 events per 100 kilometres per year. Roughly 50% are caused by third party interference; the remainder being due to the wearing of the material, or for unknown reasons. The frequency of burst pipes in Melbourne itself is small compared to nearby water utilities in Victoria such as South East Water (SEW) and Yarra Valley Water (YVW). The SEW had 18.4 burst pipes per 100km, with YVW having 22.6; a significantly higher proportion of burst pipes and consequent disturbances to their systems. The main factors affecting these events were climate and soil conditions. The SEW and YVW sites consisted of clay soil and this type of soil can lead to pipe breakage, especially during the wetting and drying out of soils (Clark, 1971, Yarra Valley Water, 2006).

Despite previous investigations and studies, results have been inconclusive regarding the contribution of burst pipe events to dirty water complaints. For example, two separate studies concluded that the events that trigger these complaints are largely unknown (83%), with 17% attributable to system management and operation (Prince et al., 2001; Polychronopolous et al., 2003). These conclusions were possibly reached due to difficulties in accounting for all operational changes in a real distribution system, or difficulty in analysing spatial customer complaints.

Although hydraulic events are thought to be the major reason for discoloured events, conclusive proof has not been found in the literature. In this research, an extensive complaints and burst pipes data analysis was conducted within the area supplied by sub-system M in Perth, Western Australia. A positive correlation between hydraulic events and discoloured water complaints was established through this analysis.

2.4 Particles in the Distribution System

Generally, for a discolouration event to occur, sediment or particles must be present in the pipe. The origins of accumulated sediment are multiple and often demonstrated by following the mass balance model illustrated below Figure (2-1) (Vreeburg and Boxall, 2007, Vreeburg and Boxall, 2008). Vreeburg and Boxall (2007) have reviewed this subject well, and an abstract of the review is presented below the Figure.

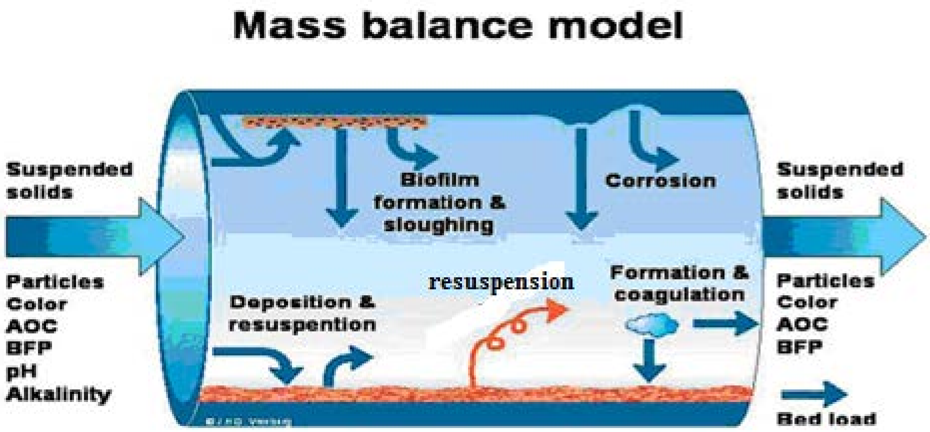

Figure 2.1: Schematic mass balance model of sediment going in, retained, and leaving the system (Technical University of Delft- Vreeburg, 2007).

Sediments in the system may have a variety of causes and sources. There is, therefore, the possibility of the sediment itself being made up of particles of different sizes and densities, and these may come from external sources or from the actual changes and operations taking place within the system. Organic and inorganic concentrate from the actual water source may be drawn into the distribution system in the form of particles (Lin and Coller 1997; South East Water, 1998; Kirmeyer et al., 2000; Slaats et al., 2002; Ellison, 2003). This may be due to the unsatisfactory filtering of suspended solids at the treatment plant (Gauthier et al., 2001; Vreeburg et al., 2004b). It may also be the case that these particles come into the water from the treatment plant itself in the case of such additives as carbon and sand particles, alum or iron flocs and bio-particles originating from bio-filters. The distribution system may also spread corroded particles emanating from pipes and linings (Stephenson, 1989; Ruta, 1999; Gauthier et al., 2001; Clement et al., 2002; Slaats et al., 2002; Boxall et al., 2003), biological growth (Le Chevallier et al., 1987; Stephenson, 1989; Clark et al., 1993; Meches, 2001) and chemical reactions (Stephenson, 1989; Sly et al., 1990;

Walski, 1991; Lin and Coller, 1997; Kirmeyer et al., 2000). Other causes may be due to contamination from pipe repairs (Gauthier et al., 1996; Slaats et al., 2002) and even backflow. One of the most critical occurrences in the system is the creation of bio-film, where assimilable organic carbon is found in the water or the pipe wall (van der Kooij, 2002). The resultant undesirable colour may be created by tannins or lignins from decaying plant material (Polychronopolous et al., 2003). As is widely known, turbidity in water causes the fine particles present to agitate and release contaminants; hence the phenomenon of dirty water. The Australian Drinking Water Guidelines (1996) indicate that a turbidity level of 5 NTU may be observed on very close inspection of a glass of water.

The above effects may be further complicated by various physical and chemical conditions occurring as the water passes through the various distribution systems and encounters old and new pipe materials of differing ages and hydraulic conditions. From the account above, it can be seen that the creation and presence of particles in a system is due to many reasons, many of which still require further investigation and validation. (Vreeburg and Boxall, 2007).

Factors such as contact times, contact surface and hydraulic condition are likely to play an important role in controlling these processes. These sources, external and internal, rarely contribute directly to discolouration events but facilitate the gradual accumulation of material within the distribution system (Vreeburg and Boxall, 2007).

Destabilisation of suspended matter can lead to the creation of extra particles, and smaller particles can also coagulate to form larger particles and settle. The variation of flow over time influences the shear stress in the pipes leading to the resuspension and settling of particles. The suspended solids leaving the system will either be transported to the customer or removed by cleaning the pipes (Vreeburg et al., 2004a).

Along with the sources and growth of particles, it is important to understand their hydraulic behaviour in order to determine the fate of the particles in the network. Boxall et al., 2001 presented results for the distribution of particle sizes found in discoloured water samples, suggesting a repeatable distribution of particle sizes irrespective of factors such as network conditions and source water. They suggested that the size range of the particles was predominantly less than 0.050mm, with an average size of around 0.010mm along with a significant number of particles in the sub-0.005mm range. Boxall et al., 2001 went on to show that it is unlikely that gravitational settling alone is a sufficient force for the accumulation of such particles, as turbulent forces generated by even the lowest flows within a distribution system are likely to be sufficient to overcome gravity settling forces. This is particularly so for the smaller sized particles which are predominant within the discolouration samples due to their light-scattering properties. This phenomenon can be explained by turbophoresis (Young and Leeming, 1997).

Turbophoresis is a process that describes the turbulent transportation of particles from more turbid regions to less turbid regions in a flow pattern. The turbophoretic force is dependent upon the gradient of turbulence over the flow profile. In pipe flow this means that particles are transported from the bulk fluid to less turbid regions near the pipe wall, where they can be trapped in cohesive layers. With higher velocities, the gradient is greater, as the turbulence at the pipe wall must always be zero, resulting in a larger force which drives particles from the centre to the wall of the pipe. In light of this theory, Vreeburg and Boxall, 2007 suggested that at a flow rate of 0.14 m/s the turbophoretic force exceeds the gravitational force, resulting in a uniform supply of material at the pipe surface, while at 0.06 m/s the gravity and turbophoretic forces were nearer to equilibrium (Vreeburg and Boxall, 2007).

Overall, Vreeburg and Boxall, 2007, concluded that the mechanisms leading to discolouration events are complex, poorly understood and interactive. However, the processes may be understood through a relatively easy concept. Discolouration is caused by particles attaching themselves by some means to the pipe wall. In normal flow, the particles remain in place and do not affect the aesthetic quality of the water. If flows are increased above the normal rate, scouring forces and shear stresses increase consequently; particles may then be mobilised which sometimes leads to customer complaints, Figure 2.2.

In this research, attempts were made to study the effect of water velocity on sediment mobility in pipes. A new theory was confirmed about the required mobilisation velocity of accumulated particles within distribution networks, depending on the original velocity in the pipe itself as well as the history and type of the sediment and pipe. The effect of the pipe’s history on the turbidity values was confirmed by fieldwork results.

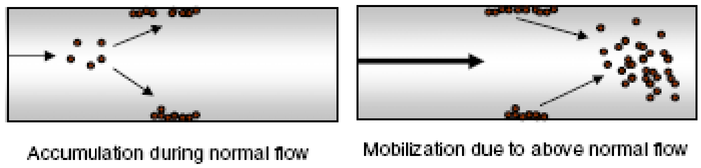

Figure 2.2: Conceptual model of the fundamental processes leading to the occurrence of discolouration within potable water distribution systems (Vreeburg and Boxall, 2007).

It is hypothesised that sediment accumulates in drinking water pipes over time, before reaching a steady state where the thickness of the sediment layer is governed by the sheer stress at the sediment water interface and the sediment then ceases to increase over time, see Figure 2.3 (Cromwell and Ryan., 2007).

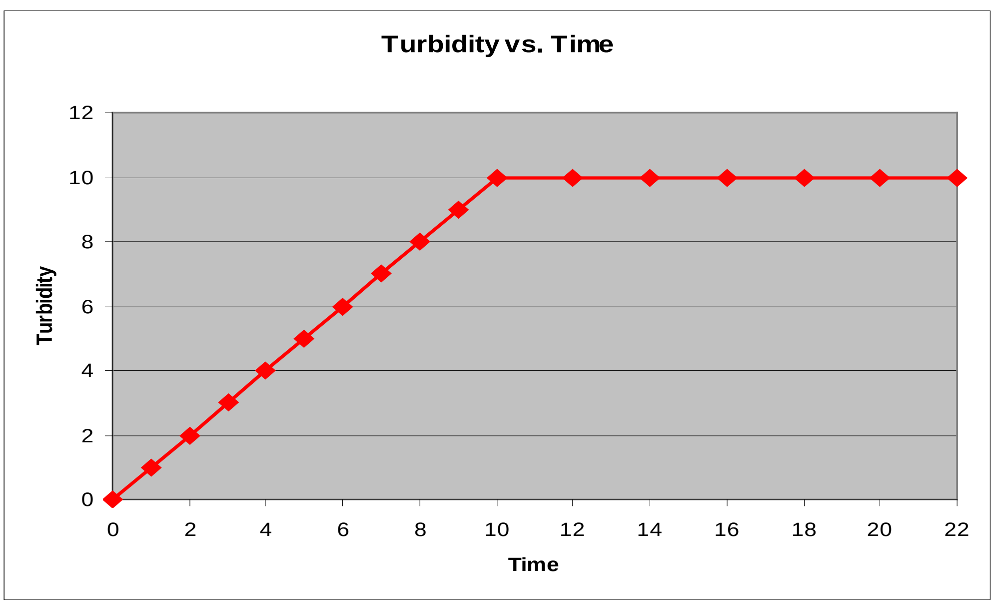

Figure 2.3: Hypothetical figure of how sediment is thought to accumulate in drinking water networks (turbidity (NTU) and time (min) are arbitrary values), after Cromwell and Ryan, 2007.

Kiwa Water Research (Netherlands) identified that their well-filtered drinking water networks displayed a constant accumulation of sediment over time for a number of years (5-10yrs). While Melbourne networks rapidly move to a steady state (within 2-4 weeks); the Croydon network operates at a steady state after less than 2 weeks, (Cromwell and Ryan, 2007, Cromwell et al.,2007).

It is possible that the Netherlands experiences a constant accumulation of sediment over time due to having a highly filtered drinking water network, and that perhaps it takes five years or more to reach the steady state. In Melbourne, it is possible that a steady state is reached within a matter of days, due to having a primarily unfiltered network (Cromwell et al., 2007).

One of the ultimate aims of this research is to understand sediment accumulation by analysing complaints about the area to be cleaned, both before and after cleaning. This will enable a thorough evaluation of cleaning effectiveness.

2.5 Measurement Techniques

Various measurement techniques have been developed in the past to track the fate of particles or the potential of particles and sediment in a pipe to cause discolouration events. A primary and widely measured parameter is turbidity, which has led to the development of the RPM. This method is essential to an understanding of the potential of sediment and particles to cause discolouration events.

2.5.1 Turbidity

Turbidity meters have been available for some time as proven and reliable instruments. The need to optimise treatment has driven the development of continuous, low-range instruments. More robust instrumentation, with greater dynamic range and improved logging and communications technology is now available and suitable for deployment in distribution systems. Such equipment allows continuous monitoring at several locations at the same time, making it possible to record the changes in turbidity and hence identify causal factors (Slaats et al., 2002; Van den Hoven and Vreeburg, 1992; Vreeburg and Boxall, 2007).

Data obtained from turbidity meters such as these has been used to develop techniques to aid water companies in identifying and quantifying discolouration risks within distribution networks (Vreeburg and Boxall, 2007).

2.5.2 Resuspension Potential Method (RPM)

The RPM was developed to directly measure the discolouration resulting from a controlled change in hydraulic conditions, providing a direct assessment of discolouration risk, although intrinsically requiring the limited generation of discoloured water within a live network. The RPM was developed within the joint research program of the Dutch water companies (Bedrijfstakonderzoek BTO) and has been applied by Dutch water companies for more than a decade. The method is used to evaluate the need for cleaning, and through application following maintenance, to evaluate the effectiveness of cleaning regimes. Regular assessment with the RPM in the network can provide information on the necessary frequency of cleaning.

The RPM consists of a controlled and reproducible increase of the water velocity by 0.35 m/s in a pipe on top of the actual velocity. The hydraulic shear stress as a result of the increased velocity causes particles to mobilise, affecting the turbidity of the water. The method is mainly applied to 100mm –150mm pipes; hence the absolute difference in shear stress caused by the uniform velocity increase is not very large. The velocity of 0.35 m/s was empirically determined (Vreeburg et al., 2004a, b). When applying this method, visually noticeable turbidity (NTU) levels are created and measured. The turbidity effect is translated into a ranking of the discolouration risk.

The RPM method flushes a 100mm diameter pipe at a velocity of 0.35m/s. Kiwa water (the water research institute in the Netherlands), adjusts the RPM conditions for alternative pipe diameters by converting the velocity in a 100mm pipe into a shear stress at the wall (i.e., 0.527Pa using the Moody Chart), and amending the RPM flow rate for different diameter pipes while holding this shear stress constant; for different diameters the same velocity results in different shear stresses. However, this is also dependent on the roughness of the material in the pipe, the roughness of the sediment and how it is distributed over the complete wall i.e., taking the shear stress for a 100mm diameter pipe and applying this to a 150mm pipe, and then comparing them using the same velocity (different shear stresses) for the 100mm and 150mm pipe. It is worth noting that Jasper and Jan, 2008 said that the RPM is mostly used within distribution systems with smaller diameters, up to a maximum of 250 mm. For simplicity, in the field application, the variables were limited as much as possible and thus used a uniform velocity. The velocity is however, always the driver for a discolouration event and in that way, the best parameter to use when assessing the discolouration risk. Most of the time, in large mains, the velocity is high so there is not much accumulation, nor is there a great deal of possibility for a large variation in the velocity, which is typically responsible for discolouration events, and finally, it is difficult to clean such large pipes.

The RPM in general is primarily developed as an empirical tool to assess the actual discolouration risk in a pipe. The basic assumption is that the discolouration event is caused only when there is resuspendable sediment in the pipe in combination with a hydraulic disturbance. So it is possible that there are areas with a high discolouration risk but no discolouration events (i.e., much resuspendable sediment but no hydraulic disturbances) and areas with discolouration complaints but a low discolouration risk (little sediment, but many disturbances and complaints from customers concerned about the possibility of discoloured fittings).

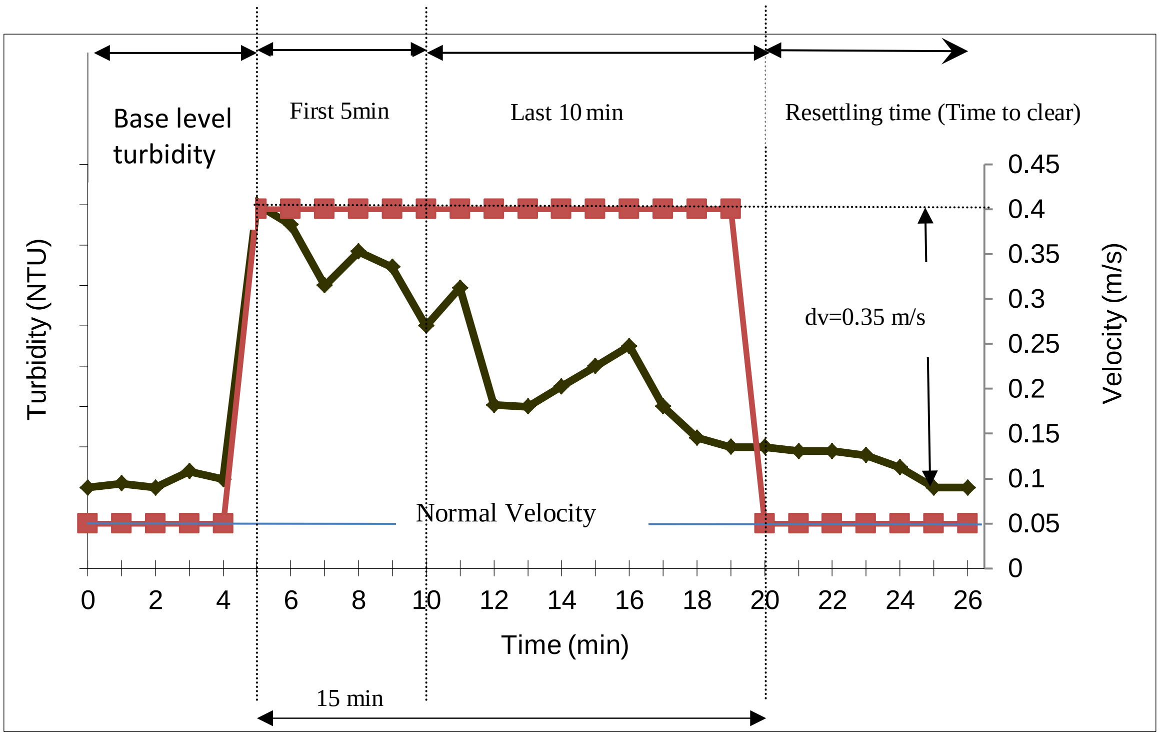

Figure 2.4: Typical turbidity trace resulting from an RPM test, showing four regions used to rate the discolouration risk.

The result obtained from an RPM test is the turbidity response of a pipe. A typical example is shown in Figure 2.4, highlighting a four region trace that is utilised to rank discolouration risk.

When evaluating the RPM results, five aspects are considered and rated equally, each weighing 20%. These aspects are: the maximum and average turbidity in the first 5 minutes and the last 10 minutes of the disturbance and the time taken to clear the disturbance (time to clear). Each of these aspects can be rated on a scale from 0 to 3 and summarised, resulting in a single figure on a scale of 0–15.

The ranking tables can be adjusted, based on the results obtained and instrumentation used (i.e., average turbidity levels) to obtain a spread of risk scores, providing the flexibility to tailor the method to different networks (Vreeburg et al. 2004a, b). In the Netherlands, the maximum allowed turbidity level in distributed water is set at 1 NTU. Therefore, the Dutch ranking table used the RPM limit as (< 0.3 NTU, 0.3-1 NTU, 1-2.4 NTU, and > 2.4) for the first four aspects, and (< 5, 5-15, 15-60, and > 60 minutes) for the time to clear aspect. The values were selected depending on the maximum allowable turbidity level in distributed water and the results from the RPM (Vreeburg et al., 2004 b).

Since July 2005, Yarra Valley Water, Melbourne's largest retail water company have applied the Resuspension Potential Method with the goal of optimising their mains cleaning program. The method was first applied to unfiltered source water by Kjellberg, 2007. Work at Yarra Valley Water started in September 2006 and an analysis of the RPM data which had been collected since 2005, was undertaken. Kjellberg et al., 2007 developed a ranking for Yarra Valley Water with the RPM limits as (<10 NTU, 10-50 NTU, 50-100 NTU, and >100 NTU). Kjellberg et al., 2007 used the same values as the Dutch ranking scale for the time to clear aspect.

2.6 Models

Many commercial and non-commercial models are available to predict sediment transport and to simplify complex systems. They all contain advantages and disadvantages. The models are mainly used for hydraulic calculations; however additional modules are added to track the transport of contaminants.

2.6.1 EPAnet Model

The EPAnet is a dynamic water distribution system simulation model released by the United States Environmental Protection Agency for both utilities and consultants. It uses the standard node-link relationship common throughout most engineering programs. EPAnet was very well received in the market as it was distributed freely, and even today it is considered to be the industry standard computational engine. It removed the cumbersome Hardy-Cross procedure from models and introduced what is termed "The Hybrid-Gradient Algorithm" that takes the network and writes it into a series of linear equations. EPAnet can be used for all kinds of drinking water modelling: flows in pipes, pressures at junctions, propagation of a contaminant, chlorine concentration, water age, and even alternative scenario analyses. It can also simulate spatially and temporally varying water demand. Recently an extension to this program named Multi-Species Extended EPAnet (EPAnet-MSX) was introduced. It has specially built functions readily available for the user to define various species with different characteristics and allows the user to track contaminant species through the system (Wricke et al., 2007).

The EPAnet-MSX is a new extension to the EPAnet 2.0 programmable toolkit. It is essentially a new set of water quality modelling routines that extends on those previously available, namely allowing for multi-species, that is, the consideration of an array of concentrations, instead of the concentration on a single parameter (or travel time or source contribution). It keeps all the existing capabilities of EPAnet, namely for extended-period hydraulic and water quality simulation (Wricke et al., 2007), while introducing additional capabilities to track various reactive and non-reactive agents in a complicated environment such as a water supply system.

2.6.2 Infoworks (Watsed) Model

Infoworks (Watsed) is a hydraulic modelling software package developed by Wallingford Software Ltd. (UK). The package consists of three different modelling parts: RS: modelling of rivers and estuaries, CS: modelling of sewer systems and WS: modelling of closed water pipe systems. Within Infoworks WS a sediment model called Watsed has been implemented to predict sedimentation in drinking water networks. This sediment module is based on the distribution of sediment according to the Ackers-White formulae; this formula can only be used for sand or gravel. Because sediment in drinking water networks is (mostly) not of this origin, the formula is actually not suitable for this particular research. The sediment measure that can be entered into the model has to lie in the range of 45 µm to 200 µm. The specific weight (SW) of the particles that can be entered is between 2000 kg/m3 and 4000 kg/m3 (Vos, 2005). This model was not suitable for application to Dutch sediment which has a particle size range of 1 µm to 100 µm with a density of 1280 kg/m3 (Vos et al., 2005). The same situation applies in Australia where normal sediment in drinking water networks lies between 1 and 130 microns, as reported by Grainger, 2003, and the density is 1640 kg/m^3 on average for particle sediment, which tends to be lighter than the given values for the SW of particles used in the Ackers-White formulae.

2.6.3 Aquis Model

Aquis is a hydraulic modelling package developed by Seven Technologies in Denmark. Aquis specialises in the calculation of the age of water in drinking water networks; age being the time that water remains in the pipes until it is consumed. Sediment types in Aquis can be determined by the size and the rate at which they suspend and resuspend. Aquis deposition and/or resuspension is based on May's equations, these equations are developed from experimental data and describe the relationship between volumetric sediment concentrations and the flow velocity at the limit of deposition, and they are mainly used for calculating the maximum bed-load transport. The size of the sediment that can be entered can be chosen to be sufficiently low, with 1μm being possible. The same applies for specific gravity; this is the comparison of the density of the particle to the density of water. The fall velocity of the sediment in Aquis is determined with the help of Equation (2.1). However the origin of this equation is not very clear and no references to it can be found in the existing literature (Vos et al., 2005).

$$W_s = \frac{\sqrt{9v^2 + d^2 g * 10^{-9}(s-1)(0.03869 + 0.0248d)} - 3v}{(0.11607 + 0.074405d) * 10^{-3}} \quad \text{..........................(2.1)}$$

W_s = fall velocity [m/s]
υ = kinematic viscosity [m2/s]
d = particle grain size [μm]
g = gravitational acceleration [m/s2]
s = specific gravity [-]

Vos et al., 2005 compared the results of this equation with Stokes' settling equation and reported that the settling velocities calculated by Aquis were much larger than the Stokes' settling velocities.

2.6.4 Transport Model (PODDS model)

The PODDS (prediction of discolouration events in distribution systems) model was developed by the Pennine Water Group at the University of Sheffield (UK) to predict levels of turbidity as a result of changes in hydraulic conditions, but the model is semi-empirical and requires calibration. Apart from the amount of sediment in the pipes, the mobility of the sediment is also important when determining the discolouration risk. Relatively heavy particles such as sand grains will settle quickly. Lighter particles are easier to resuspend, they are mostly of organic origin and take a longer time to deposit. Gauthier et al., 2001 found that organic matter represents the most significant fraction of suspended solids (from 40% to 76%) in treated and distributed water. Another factor that influences the mobility of sediment is the roughness of the pipe wall (Vos et al., 2005).

Boxall et al., 2001 carried out a theoretical analysis of the interaction between particles of the sizes predominantly found in discoloured water samples, with respect to the hydraulic forces generated within distribution networks. They concluded that forces and mechanisms above and beyond gravity settling forces must be in effect to inhibit particle movement. They suggested a semi-empirical model that could be used to account for the effects of any such processes. The model they proposed was based on the theory developed to describe the erosion of estuarine mud by Parchure and Mehta, 1985, and as applied to in-sewer deposits by Skipworth et al., 1999.

The model is based on the concept that the discolouration material is held in stable cohesive layers attached to the pipe walls of distribution systems, and that these layers are conditioned by the usual daily hydraulic regime within the system. Within the model the material layers are described by a profile of discolouration potential versus layer strength, with an increase in potential corresponding to a decrease in strength. This strength, hence layer state, is dictated by the shear stresses imposed by hydraulic conditions. Hence areas with low daily maximum hydraulic forces, such as dead-end pipes, redundant loops, oversized pipes, zone boundaries, extremities of loops etc. will have low strength and high discolouration potential, as has been noted in practice. Hydraulic conditions that are in disequilibrium (burst pipes, re-zoning, increased demand etc.) may expose the layers to shear stress in excess of their conditioned cohesive strength and lead to a mobilisation of the cohesive layers, resulting in a discolouration event.

PODDS has been coded into EPAnet (Rossman, 2000) and runs as a water quality element that utilises the EPAnet hydraulic solution, substance tracking and transport algorithms. The incorporation of such a modelling approach into a calibrated hydraulic model allows the simulation of the discolouration risk (potential and impact) posed by different network areas and hydraulic scenarios. Once calibrated, the model may be used to plan proactive management strategies such as the flushing of systems to reduce the risk of discolouration events.

The model has been validated for data collected from flushing operations in the UK (Boxall and Saul, 2005). It has also been used by Boxall and Prince, 2006 to simulate the low turbidity response measured as a result of ‘naturally’ occurring hydraulic disequilibria in relatively large diameter transfer pipes. For the clay dominated discolouration problems in Melbourne, the Wantirna Water Quality Zone (WQZ), managed by the

South East Water in Melbourne was selected. To reduce model simulation times and to simplify the calibration procedure, the hydraulic model was simplified to include only the monitored pipeline. The WQZ network was simplified to one modelled pipeline from the reservoir to the final monitoring point; a total length of 5.5 km, with a diameter of around mostly 470mm and a Hazen-Williams roughness of 110. The PODDS model efficiently predicts the short-term turbidity response to hydraulic disturbances which do not allow any accumulation of clay particles, but it does not predict the loss of material from the bulk flow during prolonged transport in the pipeline downstream of the hydraulic disturbance. This is because the PODDS model assumes that material remains as a permanent suspension once mobilised. This assumption has been appropriate for both data collection and events modelling in the UK to date, but appears inappropriate for the long residence time and the clay driven processes of the Wantirna WQZ, as some accumulation, flocculation, or other process appears to occur within the pipeline (Boxall and Prince, 2006).

2.6.5 Particle Sediment Model (PSM)

The Particle Sediment Model (PSM) has been developed by the Cooperative Research Centre for Water Quality and Treatment (CRCWQT) Australia, for the purpose of tracking the transport, settling and resuspension of (cohesive) particles in drinking water distribution systems. PSM is a software which can be added onto the hydraulic model software packages used by water authorities (EPAnet) .The model assumes that all particles entering the network come from the treatment plant and that no other processes contribute, there is no sediment accumulation in pipes and no other processes occur inside the network (Van et al., 2005; Kjellberg, 2007).

It is assumed that the particles will settle under the influence of gravity and/or that they will resuspend when the flow velocity is above a certain level. The sediment would then be slowly distributed over a network, with the model calculating how much and where the sediment settles for the whole network. The result of PSM is a graphical visualisation of the network with coloured pipes, meaning pipes with different amounts of sediment deposited or suspended inside of that pipe. In the approach of the model, bed-load transport is not implemented. Bed-load transport is the (slow) movement of sediment at the bottom of the pipe. More details about this model theory and calculation may be found in Van et al., 2005.

The two mechanisms observed in the modelling of sediment in drinking water networks are gravity settling and wall attraction (Wu et al., 2003).

Mechanism 1: Gravity settling is the settling of particles under gravity; this mechanism is shown in a simplified model in Figure 2.5. The velocity at which the water flows is u, the velocity at which it resuspends is notated as u_{rs} and the velocity at which all particles will suspend is u_d.

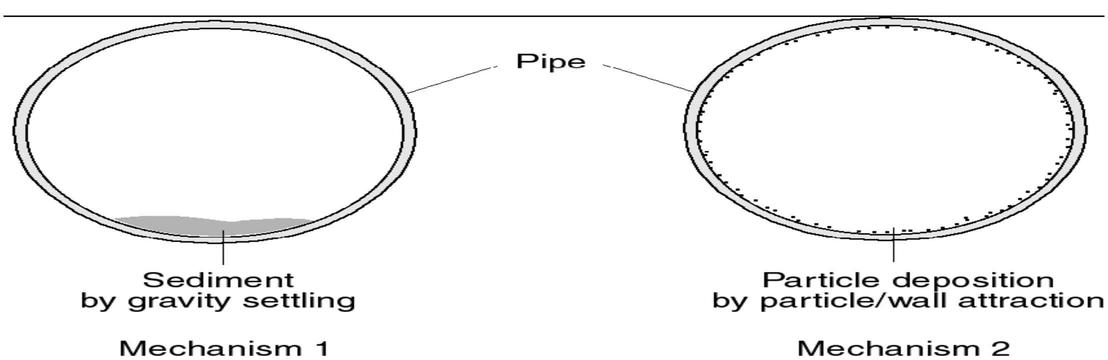

Figure 2.5: Mechanisms of sedimentation in drinking water pipes, after (Wu et al., 2003).

There are three situations that can occur, depending on the flow velocity u:

A. $u > u_{rs}$:

The flow velocity is more than just the resuspension velocity that allows resuspension of all sediment. u_{rs} is the critical velocity beyond which particles are resuspended, u_{rs} is a function of particle diameter, density and packing of sediment.

B. $u_d \leq u \leq u_{rs}$:

The particle mass is transported through the pipe with no settling/resuspension, due to the flow velocity u being between the velocity at which the sediment suspends (u_{rs}) and the velocity at which it settles (u_d).

C. $u < u_d$:

All particles will settle, due to the velocity of the water being so low that all sediment will suspend.

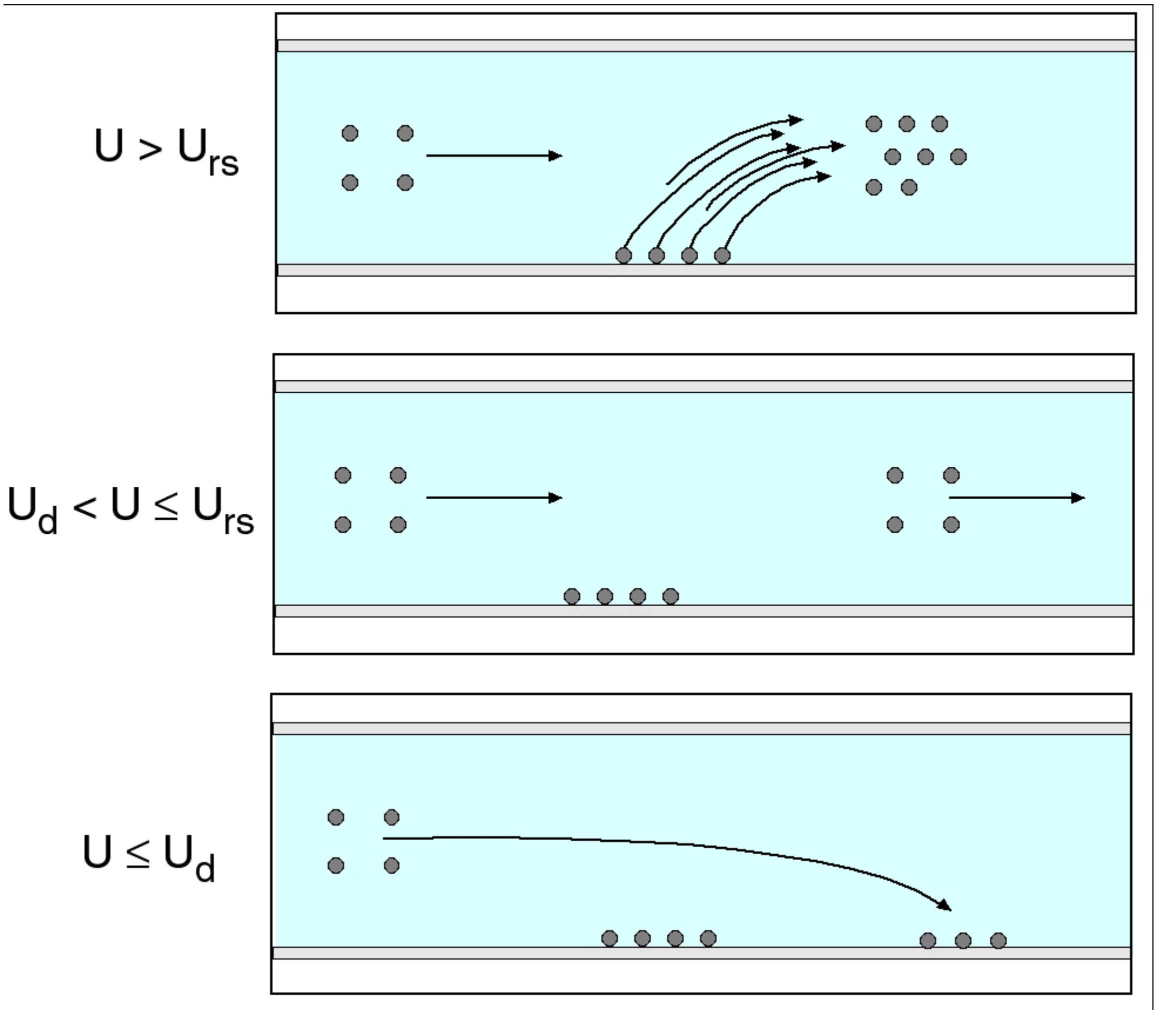

Figure 2.6: Model gravitational settling, after (Wu et al., 2003).

Data required to be able to run the model is listed below:

1. Model of a network:

- hydraulic data of network
- x, y and z coordinates of all nodes
- length, diameter and roughness of all pipes.

2. Water quality parameters have to be determined i.e., the concentration of particles from the treatment plant and the different characterisation velocities for the sediment. These velocities are the settling velocity of the sediment and velocities for which the sediment will settle or resuspend.

In April 2003 the CRC for Water Quality and Treatment conducted research in collaboration with Yarra Valley Water to validate the PSM as a case study; PSM was found to predict particle concentration within ± 50% of field measurements. The 5th report of the CRCWQT research was carried out by the project team at CSIRO Manufacturing and Infrastructure Technology (CMIT) to understand the "dirty water" problem and predict the movement of particles in water distribution systems. This followed on from the 4th report (October 2002) and the earlier literature review reports of June 2002 (2nd, 3rd progress reports) which documented relevant literature data and theory. The 5th report presented an analysis of published data to establish a basic theoretical framework for the settling, resuspension and transport of particles (Grainger et al, 2003).

The first step in the practical research involved the obtaining of samples of particulates from the water distribution systems (WDS) of Melbourne, Adelaide, Sydney and Brisbane. Initial samples were used at CMIT to investigate the settling, transport and resuspension behaviour of typical water distribution system sediment samples in a physical model called the Particle Sediment Test Loop (PSTL). This used a pipe test-loop and a water tunnel, the test being conducted at CMIT (CSIRO Manufacturing & Infrastructure Technology). The rig consisted of a pipe with a diameter of 100mm; a schematic drawing of the test pipe is shown in Figure 2.7.

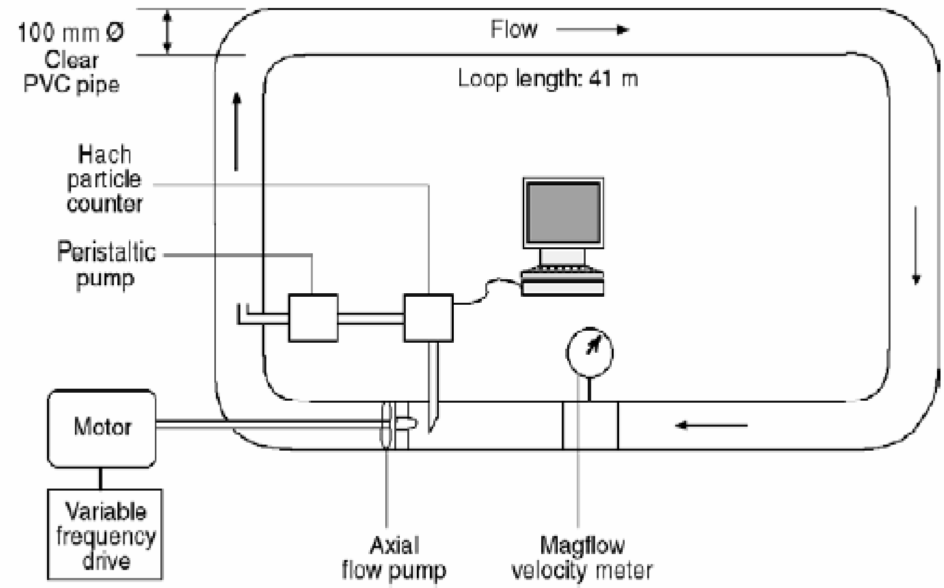

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Figure 2.7: Schematic drawing of pipe test loop (Grainger et al, 2003).

The second step in the practical research was the establishment of field measurements of mass concentrations of particles in the YVW and WDS at various sites in the zone of Doncaster. The second-step data, together with the flow data collected for the hydraulic modelling program at YVW was used to validate the PSM software by simulations of the particle movements and mass concentrations in this zone.

The third step of the practical research focused on measurements of the suspension, settling, transport and resuspension of the particulate samples. Further characteristics of the samples were also investigated as particulate samples in sample bottles which were observed to exhibit a gel-like behaviour, possibly inhibiting the resuspension of the sediment. Samples were subjected to autoclaving, gamma rays and immersion in chlorine to kill off bacteria and thus to determine if the gel effect was caused by biological bonding. However, it has been found that thick sediment samples which settle for a day or more exhibit a gel-like cohesion. This phenomenon probably arises from Van de Waals forces of attraction between the particles, but it is very unlikely to arise from biological effects. The gel-like phenomenon requires further investigation (Grainger et al, 2003).

To be able to use the program in other countries (i.e., the Netherlands) the different velocities for resuspension and settling of sediment in drinking water networks have to be determined. Some types of sediment have been investigated at Delft University (Lut et al, 2005). These sediments were Kaolinite, FeCl3 and sediment from a flushing operation in the Netherlands (Van et al., 2005). In Australia, Jayaratne et al., 2004 demonstrated that after tests on a clear PVC pipe Figure 2.7, the particles will settle with gravity if velocities are less than 0.07 m/s. when the velocity is between 0.07- 0.25 m/s the sediment will start to resuspend, and when the velocity is between 0.25-0.6 m/s the particles will be moving completely. If the particles do not start to move until velocity is above 0.6 m/s it is probable that there is manganese in the water supply. By determining the velocities for typical sediment found in Australian networks, the problems with the theory of settling (Stokes) and resuspension (Shields) can be avoided. This simplification was made to profile the sediment characteristics and use them in the PSM (computer) model. Figure 2.8 shows the possible behaviour of the sediment and the corresponding velocities.

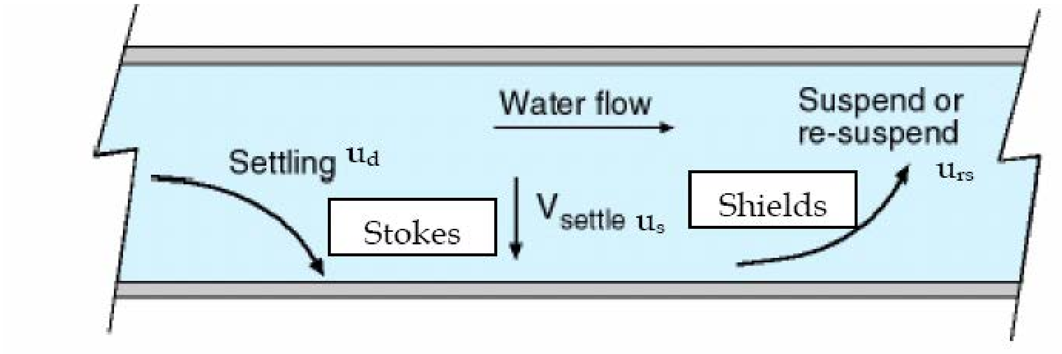


Figure 2.8: Cross section of pipe illustrating suspension, resuspension and settling, after Grainger et al, 2003.

This model was trialled by Yarra Valley Water to support the RPM and determine when mains cleaning is required. Although Grainger et.al; 2003 reported that the PSM model could be used by water companies as a guide for pipe cleaning with the above velocity values, another resuspension velocity value was established in this research. The PSM model was applied to selected water systems in Perth with the purpose of evaluating the PSM for its ability to predict discolouration events through modelling and field trials. The advantages and disadvantages of the PSM tool have been identified and the resuspension velocity value was tested and through fieldwork connected with PSM runs. The PSM was also used in this research to evaluate local mains cleaning strategies. PSM software requires further improvement before it can be used as a working tool by water authorities.

2.7 Control Strategies

Discoloured water, caused by long-term accumulation and formation of sediment in drinking water networks can basically be prevented in three stages: sufficient water treatment at the plant, removing sediment adequately through pipe flushing and creating hydraulic conditions which prevent long-term settling of sediment (Van et al., 2004). A great deal of research has been conducted internationally on the first two measures to prevent discoloured water (sufficient water treatment at the plant and removing sediment adequately through pipe flushing) (Van den Hoven and Vreeburg 1992; Van den Hoven et al., 1994). In 1990, about 1,200 water quality complaints were registered in a year by a representative Dutch water utility which serves approximately 530,000 connections. By 2004, this number had decreased to approximately 250 per year. The decrease in complaints was ascribed to improved water quality management and the results of 10 years of joint research on the nature and causes of discoloured water. Van den Hoven et al., 2004 conducted research concentrating on creating hydraulic conditions which prevented long-term settling of sediment and they introduced the concept of the self-cleaning distribution system.

It has been suggested that material will tend to accumulate in areas with low velocities, such as dead-ends, oversized pipes and redundant loops. The velocities in such systems are low and the loops will probably experience flow reversals and tidal points, leading to long residence times and the risk of discolouration. A velocity of at least 0.4 m/s is stipulated as being sufficient to prevent accumulation of material.

Past studies of Western Australian 'dirty' water events and incidents, and reviews of available literature indicate that these sediment usually contain relatively high amounts of Manganese (Mn) and Iron (Fe) as well as other metals. The load of microorganisms associated with dirty water events can be high (Sly et al., 1990). However, an elucidation of the microbiological quality of drinking water during a dirty water event has not yet been fully documented.

Two types of cleaning are usually adopted by utilities: firstly there is the emergency response, and secondly, the planned cleaning. In the emergency response, upon receiving a complaint, personnel are sent out to the location and the nearest hydrant is flushed for a short period of time, usually about five minutes. During this time, personnel keep in contact with the resident(s) to ensure that their water eventually runs clear. If the water has not cleared, the hydrant is flushed until it the water runs clear.

In the planned cleaning approach, an area where most complaints are received and targeted, all pipes in the area are cleaned, irrespective of whether they are clean or dirty. In Western Australian, the Perth Water Corporation uses air-scouring as its most preferred cleaning activity and this costs approximately $1000/km.

2.7.1 Flushing

Flushing is one of the most powerful tools available to water utilities for maintaining the water quality of the distribution system. It is important however, to put flushing into perspective and to recognise that by itself, it will not correct other deficiencies or problems in the system. A flushing program must be part of a comprehensive approach to preserving and improving water quality within the distribution system. In 1999, Antoun et al. cited a number of important aspects to consider in any flushing program. One of those points was that flushing velocities should be at least 1.8 m/s whenever possible. However, in this research a new velocity value was established as an adequate velocity value for the purposes of unidirectional flushing.

2.7.1.1 Shear Stress Criteria for Flushing

Boxall et al., 2001 suggested that traditional sediment transport theory is not appropriate for describing the generation of discolouration within distribution systems. In their opinion, the processes are better described through consideration of the interaction of hydraulic shear stresses and the pipe wall/water interface with material layers. Similarly, Ackers et al., 2001 recognised the importance of shear stress for the mobilisation of material and recommended a value of $2.5 N/m^2$ to be achieved by flushing. However, this value is based on previous research and design principles for sewer systems and may not be appropriate for distribution systems.

2.7.1.2 Flushing Approaches Summarised

There are four flushing approaches. The four basic flushing approaches are conventional, continuous blow-off, unidirectional, and pulse flushing. Each approach can be implemented on a comprehensive system-wide basis or on a narrower spot basis (Friedman et al., 2002).

- **Conventional Flushing:** Conventional flushing is defined as the opening of hydrants in a specific area of the distribution system until preselected water quality criteria are met. These criteria could include such changes as a detectable disinfectant residual, a reduction in, or elimination of colour, or reduction in turbidity. Conventional flushing is the approach currently used by most water utilities (Friedman et al., 2002), with the Perth Water Corporation adopting this method.

In conventional flushing, the process of opening hydrants may or may not be sequential, i.e., working from the water treatment plant or other source out towards the periphery of the distribution system. However, valve isolation is not part of conventional flushing. Without valve isolation, water to the hydrant may flow from several mains in the vicinity of the open hydrant. As a result, the velocity in each individual main may remain lower than if valve isolation is used (Oberoi, 1995). Furthermore, if valves are not isolated and conventional flushing is not performed sequentially, the water used to flush a particular main may not originate from a segment that has already been flushed. When this occurs, the water flowing to the hydrant may actually bring dirty water into the area being flushed (Friedman et al., 2002).

- **Continuous Blow-off:** For dead-ends or oversized water mains, continuous blow-off or bleeding of water may be conducted to force a low velocity flow through a small portion of the system. Blow-offs can help restore disinfectant residuals and reduce water age. However, a typical velocity is < 1 fps (0.3 m/s), which is not sufficient to remove sediment or provide any scouring action, and this practice can use large quantities of water. Use of blow-offs is generally not considered a permanent solution (Friedman et al., 2002).

- **Unidirectional Flushing (UDF):** UDF, a refinement of conventional flushing, was first developed for the city of Edmonton. Alta., in the early 1990s (Oberoi, 1994). UDF is designed to bring the water through the system in a controlled fashion at velocities sufficient to provide a scouring action within the distribution piping. The technique consists of isolating a particular pipe section or loop (typically through closing appropriate valves) and exercising the hydrants in an organised, sequential manner, generally progressing from the treatment plant or source to the periphery of the system, from large-diameter pipes to smaller-diameter pipes, and always from cleaned sections to dirty ones.

UDF is most often associated with establishing velocities of approximately 6 fps (1.8 m/s) within each pipe segment being flushed (Brashear ,1998). This velocity promotes a scouring action within the pipe that helps remove sediment, bio-films, and loose deposits. UDF of the distribution system in a sequential manner at scouring velocity helps ensure that pipe sections are completely flushed (with the dirty water being expelled from the system) and avoids simply moving debris from one part of the system to another. As with conventional flushing, UDF can be implemented on a spot basis or as a comprehensive system-wide effort.

- **Pulse Flushing:** The results of the theoretical research on the dynamics of flow have already been applied to the concept of pulse flushing. The same principle for removing daily drinking water sediment from the network is valid for removing accumulated sediment. From practical experience, satisfactory cleaning results are obtained with unidirectional flushing and a steady flushing velocity of 1.5 m s^{-1}. The calculated shear stress at a flow velocity of 1.5 m s^{-1} forms the starting point for the calculation of pulse patterns with steady final velocities of less than 1.5 m s^{-1} (Van den Hoven et al., 2004).

Generating a pulse pattern in the field allows water companies to flush pipes using a lower final velocity than the conventional flushing velocity practice. The technique of pulse flushing is applicable in those areas where the conventional flushing velocity cannot be met. The first test results were very promising and the technique should become more common in practice in the future (Van den Hoven et al., 2004).

2.7.2 Air-scouring

Water and/or air-scouring was developed in part because of the seemingly insufficient results of the conventional flushing programs. The method is based on injecting pressurised air into the water flow to create more turbulence and scouring stresses to resuspend the sediment, as illustrated in Figure 2.9. Another reason for developing this method was that more aggressive cleaning would not only remove mobile sediment, but also remove the more firmly attached and numerous corrosion products. The two-tiered goal in that case is not only the removal of loose deposits, but also the reinstatement of the hydraulic capacity. The claimed extra benefits of water/air-scouring compared to conventional flushing are that it would take less water and the efficiency of sediment removal would be better (Vreeburg, 2007). The cost of air-scouring is too high, for example, the cost of air-scouring pipes in the Perth network system is around $1000 per km which is made up of $680 for preparation and $320 for the scouring of approximately 1km (Perth Water Corporation).

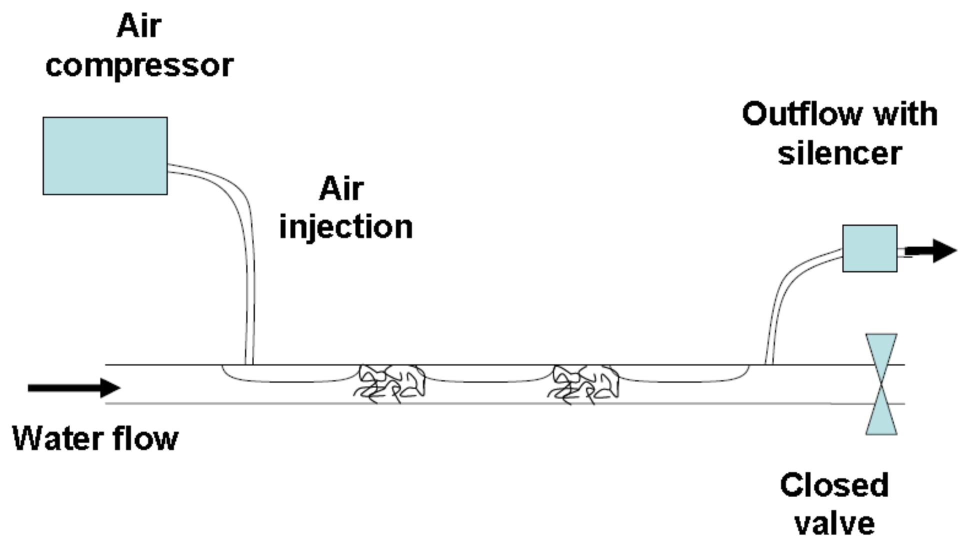


Figure 2.9: Principle of water/air-scouring after Vreeburg, 2007.

2.7.3 Self Cleaning Velocity

The concept of a self-cleaning threshold is defined as a shear stress (which a pipe experiences regularly due to normal daily demand), that prohibits the accumulation of sufficient material within the pipe, posing no discolouration risk. This was investigated by Boxall and Prince, 2006.

One sustainable measure to prevent reaccumulation of material is the adoption of a self-cleaning threshold, and a hydraulic force which a pipe experiences on a regular basis, that effectively prevents the accumulation of material. This concept has been effectively employed for the design of new networks in the Netherlands. The basic difference compared with the traditional way of designing distribution networks is that the self-cleaning networks are designed as branched systems instead of looped systems (Figure 2.10). In addition, the diameters of the self-cleaning networks are designed on a once a day flow velocity of 0.4 m s^{-1} based on household peak demand (Van den Boomen et al., 2004).

The advantages of self-cleaning distribution networks are:

- no stagnant water
- short residence times
- improved water quality
- a proven reduction of up to 30% on material costs.

Although some results indicate that a flow velocity of 0.3 m s^{-1} could be sufficient for self-cleaning of works (Van den Boomen et al., 2004), the value of 0.4 m s^{-1} is recommended at this time. The reason for this recommendation is based on the observation that the sediment will be transported mainly along the bottom half of the pipes.

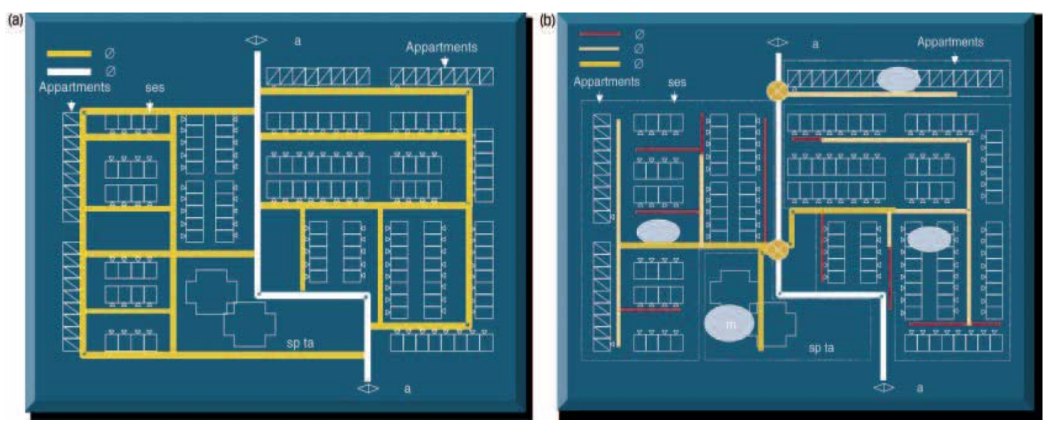


Figure 2.10: Concepts of distribution networks (a) looped system; (b) self-cleaning system (Van den Boomen et al., 2004).

2.8 Cleaning Frequency

The RPM is not a quantitative method, but gives a value for the discolouration risk and can be used to see how the discolouration risk develops after any action like cleaning or change of treatment (Vreeburg et al., 2004 b; Kjellberg, 2007).

By performing several RPMs over time and after plotting the overall RPM score as a function of the time period between successive mains cleaning, objective and proactive cleaning action can be taken.

In Figure 2.11 the general principle to determine this time period is given. Over time several RPM measurements are taken and by assuming a constant water quality, the overall RPM score can be calculated. This score is plotted against time and when a water main fouls, an increase in the overall RPM score in time is observed. When the overall RPM score exceeds the threshold level for cleaning, the mains should be cleaned. From just a few overall RPM scores, the time period can be extrapolated when the supply zone is fed with a constant particle loading.

The time between successive RPM measurements at each site is different. Kiwa recommended a frequency of 12 months. In applying the method to Melbourne's unfiltered system, RPM measurements were taken one week prior to cleaning, immediately after cleaning, and subsequently at the following intervals (after cleaning): one week, one month, two months, three months, six months, nine months and twelve months. The networks rapidly moved to a steady state within four weeks; one month after a mains cleaning the rate was already at 5 (of a maximum of 12) points. The result in most locations showed an increase in sediment loading after between six and eight months. A cleaning would be required in less than a year for many of the mains since they would pass the threshold level for cleaning; the threshold level is set at 10 points in this evaluation of Melbourne (Kjellberg, 2007).

In many distribution systems, cleaning frequency is determined based on the number of complaints received. However, it is not clear how effective the cleaning is in preventing discolouration events or whether it is the cleaning itself that mainly causes the discolouration events. It is therefore crucial to calculate the effective period for cleaning either by RPM or by complaints analysis. This research has concluded that the efficiency of cleaning, as it applies to the drinking water network, costs enormous amounts in terms of resources and money.

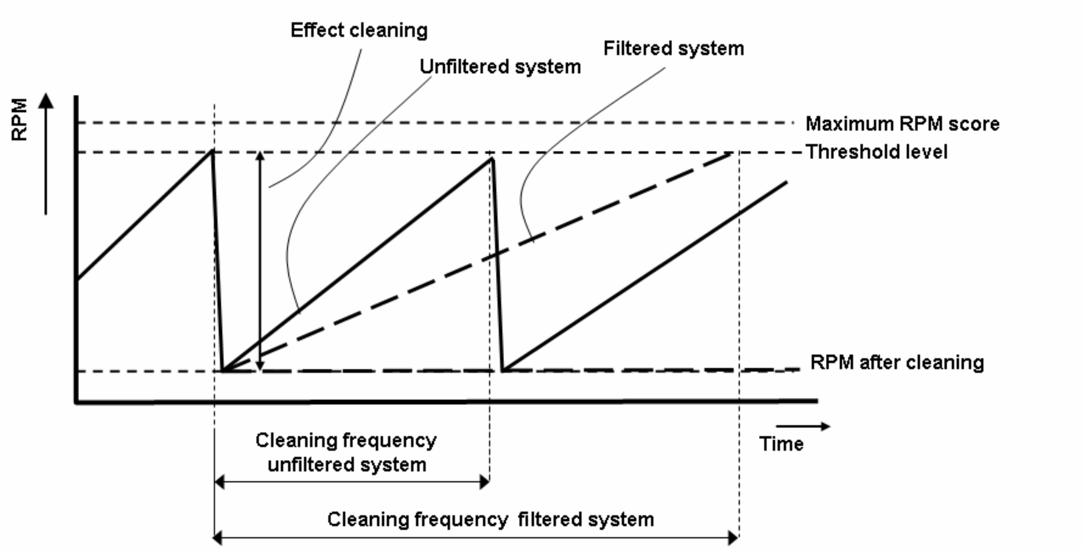


Figure 2.11: Principle of using RPM measurement to determine cleaning frequency.

CHAPTER 3 DESCRIPTION OF THE STUDY AREA

3.1 Introduction

In order to critically evaluate the existing tools and approaches in terms of minimising customer complaints, a potable water supply sub-system named Zone M in Perth, Western Australia was selected. The zone is controlled by the Water Corporation of Western Australia. The site was selected in consultation with the Water Corporation, as it exhibited high and varying levels of customer complaints, had experienced a particular cleaning history and a number of hydraulic disturbances such as burst pipe events and other activities. The zone was also of an appropriate size for hydraulically modelling the system and tracking the sediment, as the majority of the suburbs were supplied by a single water source. Above all, it was selected for its results reliability, with over nine years of data on complaints and hydraulic disturbance being available.

3.2 Location Details

The water supply, Zone M is located in the city of Perth, Western Australia and is situated north of the Swan River. It supplies water to about 33,000 properties subdivided into ten suburbs termed A-J; for the purposes of the thesis.

Zone M contains three tanks which receive water from two reservoirs. Both reservoirs receive treated water from the same source, but the treated water is separated into two reservoirs due to the topographical conditions of the area. The two reservoirs are named Reservoir 1 and 2 for the purposes of the thesis. Reservoir 2 sources its water from Reservoir 1, but it also contains chlorinated borehole water (Perth Water, 2007).

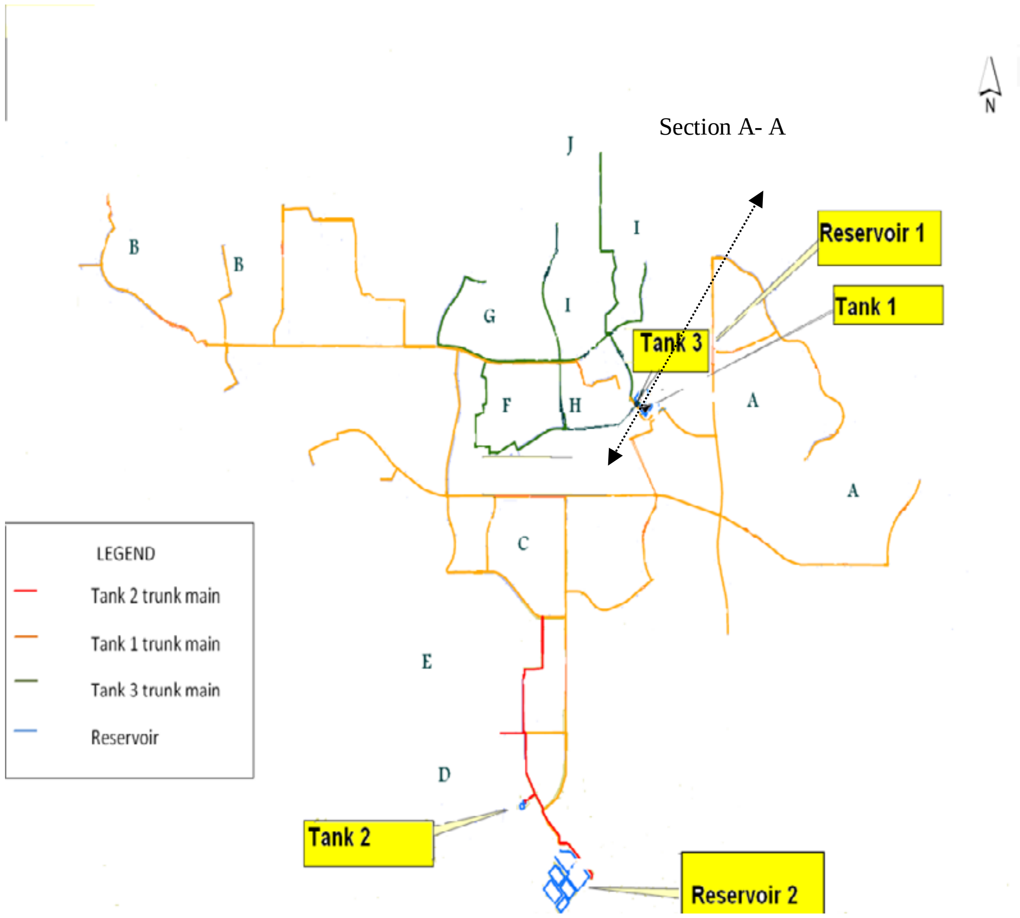


Figure 3.1: Schematic diagram of tanks and main trunk of the studied water supply Zone M.

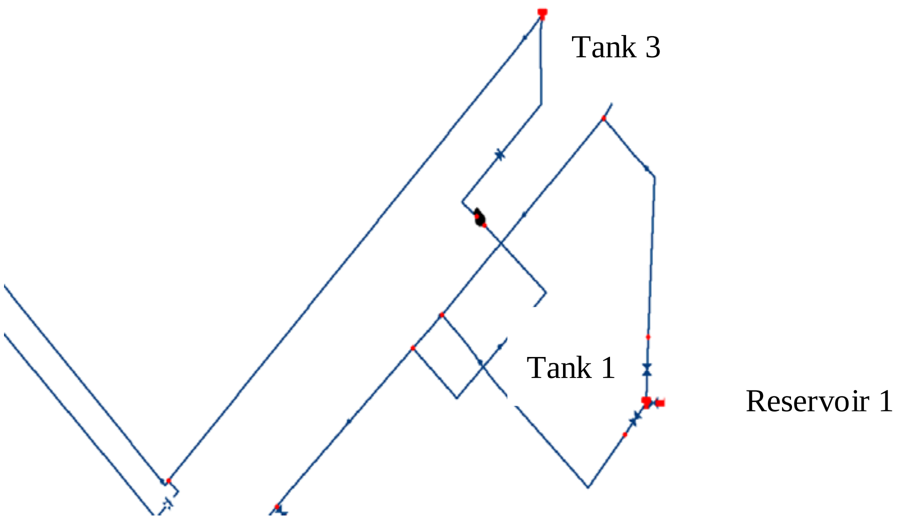


Figure 3.2: Details of Reservoir 1 connectivity.

Table 3.1: Details of sources and tanks for each suburb with sub-system "M".

Suburb	Supply Tanks	Supply Reservoir	Cleaning history[4]	Populations	sub-systems supplier
A	Tank 1	Reservoir 1	Not air-scoured	19234	M
B	Tank 1	Reservoir 1	Not air-scoured	9542	M
C	Tank 1	Reservoir 1	Not air-scoured	8493	M +H
D	Tank 2	Reservoir 2[1]	Not air-scoured	7560	M+H +Y
E	Tank 2	Reservoir 2[1]	Not air-scoured	4068	M+H
F[2]	Tanks 1 & 3	Reservoir 1	Tank 3 air-scoured: 09/10 – 11/11-2003	7992	M
G[2]	Tanks 1 & 3	Reservoir 1	Tank 3 air-scoured: 09/10 – 11/11-2003	10321	M
H[2]	Tanks 1 & 3	Reservoir 1	Tank 3 air-scoured: 09/10 – 11/11-2003	3688	M

I[3]	Tanks 1 & 3	Reservoir 1	Tank 3 air-scoured: 09/10 – 11/11-2003	7834	M
J	Tank 3	Reservoir 1	Air-scoured : 09/10 – 11/11-2003	3178	M +W

[1]Water in Reservoir 2 is a mixture of water from Reservoir 1 and chlorinated borehole water.
[2] Some pipes in these suburbs are served by Tank 1 and the others by Tank 3.

[3] Suburb I receives a small amount of water from Tank 1, but water is mostly supplied by Tank 3

[4] In all suburbs customer complaints trigger hydrant flushing, which is undertaken by completely opening a hydrant closest to the home of the complainant(s), to achieve a flow of about 10 L/s until the water is clear, (Perth Water Corporation).

Details of all tanks and main trunks are shown in Figure 3.1. This also gives a pictorial representation of each suburb's location within Zone M. Figure 3.2 illustrates the details of the connectivity of the Reservoir 1. Zone M was divided into three sub-zones according to the tank which supplied the water to customers: Tanks 1, 2 and 3. All tanks received treated water from the same source through Reservoir 1. The source water itself was made up of both treated ground water and chlorinated artesian borehole water. Due to the topographical conditions of the area, three tanks were used to store the water before supplying it to consumers. Reservoir 1 supplied water to two tanks: Tanks 1 (capacity is 136090 m^3) and Tank 3 (capacity 2270 m^3). Tank 1 (Gravity Tank) was gravity fed from Reservoir 1 with the water then supplied to households by means of gravity. Tank 3 also sourced its water from Reservoir 1 through two pumps, as shown in Figure 3.2, to overcome topographical issues. The water in Tank 3 was distributed to households by gravity. Tank 2 (capacity 6735 m^3) sourced its water from Reservoir 2 through three pumps; Tank 2 also used gravity to supply water to households, (Perth Water, 2007).

As has been mentioned, the two supply reservoirs mostly serviced different suburbs within Zone M. However, some parts of some suburbs within the ten suburbs received water from multiple sources i.e., from other sub-systems: H, Y, or W. The different suburbs serviced by each reservoir are detailed in Table 3.1.

Pipes in suburbs receiving water from Tank 3 had been air-scoured between 9/10/2003 and 11/11/2003 making the pipes in those suburbs clean at the end of air-scouring. The pipes in suburbs supplied from Tanks 1 and 2 were not air-scoured within the data analysis period. However, when complaints were received, the Water Corporation adopted a protocol to clean the pipes. This was achieved by opening a nearby hydrant to achieve the highest possible flow rate (≈10 L/s), until the water became clean. Such activity can affect the cleanliness of the pipe in the vicinity of the hydrant operation (Perth Water Corporation).

Currently, the water treatment method at Zone M involves chlorination with chlorine gas followed by conventional anthracite filtration as the preferred method of Mn and Fe removal prior to the water entering the distribution system, (Perth Water Corporation).

The majority of the pipes in the study were made of reinforced concrete, although other materials such as asbestos-containing, medium density polyethylene, high density polyethylene, steel, ductile iron, mild steel cement lined and cast iron were also used (Perth Water Corporation).

3.3 Topography of Zone M

A ridge of relatively high land runs north/south through the centre of the zone. Reservoir 1 is located at the highest point of this ridge, with a Top Water Level (TWL) of 92.8 m AHD, AHD is Australian Height Datum which is equivalent to Mean Sea Level. Tank 2 is located on a local high spot near the southern part of the zone and has the same TWL of 92.8 m AHD.

3.4 Distribution System

A brief overview of the Zone M distribution system was given in the section above to show the relationship of the suburb location to the water supply point. It is also important to have a reasonably detailed view of the distribution network in order to understand the water supply boundaries and the general layout of the distribution system. Figure 3.3 represents this information.

Figure 3.3: Layout and distribution network boundaries of Zone M, (Perth Water, 2007).

It is important to note that in general, potable water pipelines are situated along road networks. This is reflected by the fact that the overall arrangement of the distribution network is similar to the road network shown in the earlier figures. The general arrangement of the supply network shown above also reflects that of the literature review, i.e., Perth distribution networks are looped systems in comparison to the branch systems used in the Netherlands to achieve the concept of a self-cleaning threshold velocity.

CHAPTER 4 Novel Complaints Analysis

4.1 Introduction

The occurrence of discoloured water within potable water distribution systems is a major source of customer complaints worldwide. Although hydraulic events are thought to be the major cause of discolouration, conclusive proof has not been found in the literature. Customer complaints are not always seen to be reliable, and this is further complicated by hydraulic events generally being poorly recorded. In order to understand the usefulness and effectiveness of complaints data analysis, the extensive data analysis in this chapter was conducted within the area supplied by sub-system M in Perth, Western Australia. Despite the obviously logical relationship between hydraulic events and complaints, no studies have proven this relationship. The current way of dealing with this issue is that utilities prioritise the areas that receive the highest number of complaints and follow up by spending vast amounts on cleaning the systems. In this study covering ten suburbs, the evaluated parameters were population distribution, seasonal variation, effect of air-scouring, and effects of burst pipes over the period 2003 to 2009.

4.2 Data and Method of Analysis

Nine years of accumulated complaints regarding discoloured water, and six years of burst pipe data were analysed for all associated suburbs. The complaints data ranged from 01 January 2001 to 31 December 2009.

However, the data used was taken from the seven years 2003-2009, and the data from 2001-2002 was used to validate conclusions drawn from the analysis of the seven years of data. The burst pipe data ranged from 01 July 2003 to 31 December 2008. The data provides an extensive detail of complaints trends for the sub-system.

Complaints were separated into two categories. The first was the batch of complaints (batch complaints) where more than two complaints occurred on a single day in one locality at different addresses. The second (isolated complaints) was where isolated complaints occurred sparsely. Dates and suburb of distribution system events were matched with complaints. While matching, efforts were made to consider the flow direction of water.

The number of customer complaints due to discoloured water varied greatly over the suburbs but they were normalised to complaints per 1000 persons to nullify the effect of population on the complaints. In order to conduct this analysis, population data was obtained from the Australian Bureau of Statistics (ABS).

4.3 Raw Complaints Data

In order to understand the trends resulting from customer complaints, the data required presentation in such a manner that it produced information that was appropriate for use in figures and charts. Prior to this, the raw complaints data required analysis to provide a basic understanding of the trends that were obtained, and these are reflected in the resultant graphs.

Table 4.1: August 2003 data for complaints and burst pipes as an example of raw data trends.

date	Complaints										Total comp.	Burst pipe location
	A	B	C	D	E	F	G	H	I	J		
1/08/2003											2	
2/08/2003											1	
3/08/2003					1						1	
4/08/2003											0	
5/08/2003											0	
6/08/2003											0	
7/08/2003											0	
8/08/2003											0	
9/08/2003											0	
10/08/2003											0	
11/08/2003											0	D
12/08/2003											0	
13/08/2003					2						2	
14/08/2003											0	D

15/08/2003											0	
16/08/2003											0	Fire Hydrant Replace
17/08/2003				1							1	
18/08/2003		1		1							2	
19/08/2003	2	13	4			5	2	1	4		31	A
20/08/2003	9	1		1			2		2		15	D, D
21/08/2003	2										2	
22/08/2003											0	G
23/08/2003				1							1	
24/08/2003											0	
25/08/2003			3								3	C
26/08/2003			1								1	
27/08/2003			1	2							3	
28/08/2003											0	
29/08/2003											0	
30/08/2003											0	
31/08/2003											0	F

It can be immediately deduced from the raw complaints data that a significant number of events occurred where numerous complaints were recorded across a short period of time, and these complaints extended across different suburbs. It was also observed that days recording only single or double complaints occurred randomly and there was no specific trend behind such recordings i.e., the complaints may have lacked detail or the dirty water may have been related to an issue in a particular household, or to a localised effect. Table 4.1 gives an example of these trends. All the raw data on complaints and burst pipe events is illustrated in Tables A.1 and A.2 in Appendix A.

In conjunction with high level complaint periods and random single/double complaint days, it was noted that there was an extremely high number of days throughout the seven year period where no complaints were recorded. This fact greatly emphasises that when complaints were recorded they were due to a dirty water event of some kind, which led to a number of households complaining across a number of suburbs in the distribution network.

The raw complaints data provided extremely useful information on data trends. However, in order to gain an even better understanding of such information, a visual representation of the raw complaints data was created.

4.4 Data Visual Representations

To gain a clear visual understanding of the complaints trends over nine years, Figure 4.1 was produced. Figure 4.1 shows how the number of complaints varied across 10 suburbs with a total population of 81,910 and it provides a detailed view of how the complaints are distributed between the suburbs. It can be seen that complaints from certain suburbs showed drastic annual variation. For example, suburbs E and F registered larger annual fluctuations. It is noteworthy that suburb D registered the largest number of complaints, and that most complaints occurred in 2004. For additional details, see Figures A.1 and A.2 in Appendix A. Suburbs I, J and H registered a lower number of complaints with the exception of suburb J, in 2004. These results reinforce the view that complaints happen arbitrarily and that it is very difficult to pinpoint the reasons for such complaints. Logically however, one would conclude that customer complaints are the result of the following: presence of sediment, hydraulic events strong enough to carry sediment to the customer, customers identifying the issue and lodging a complaint. While the first two processes are prerequisites, the last two are associated with probability. To make sense of the data, a systematic analysis is presented below.

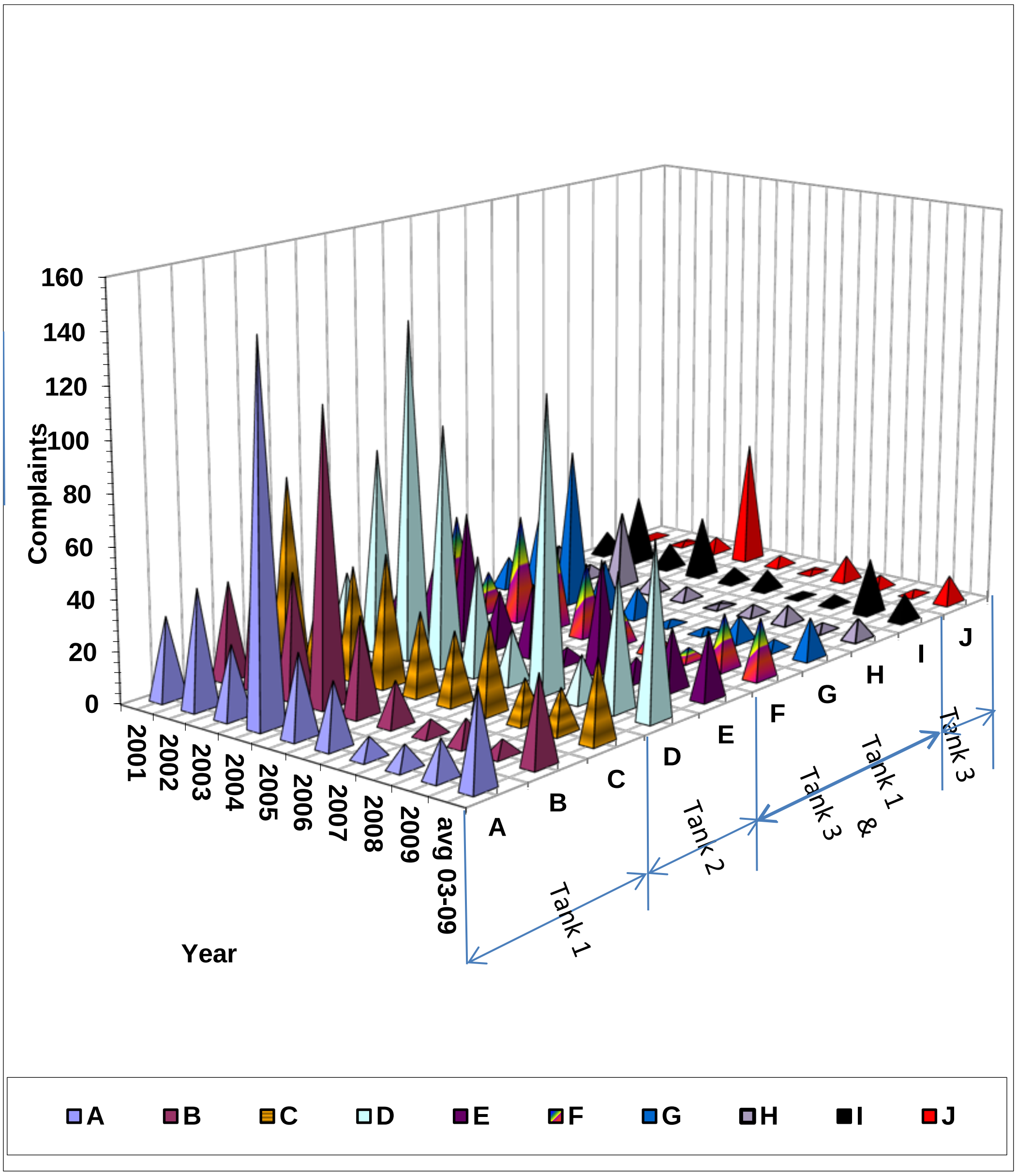


Figure 4.1: Total complaints analysis for all suburbs, over nine years.

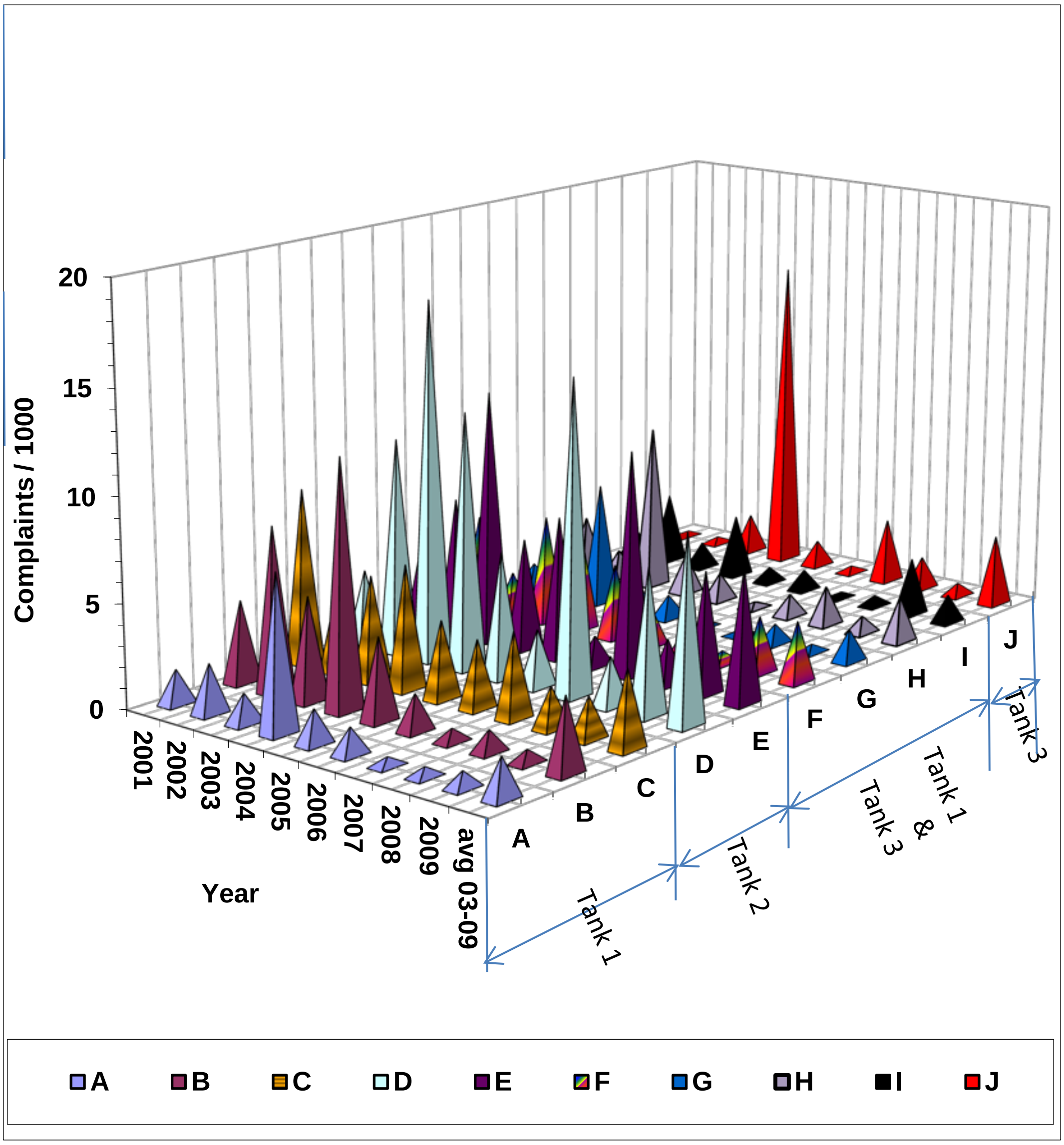
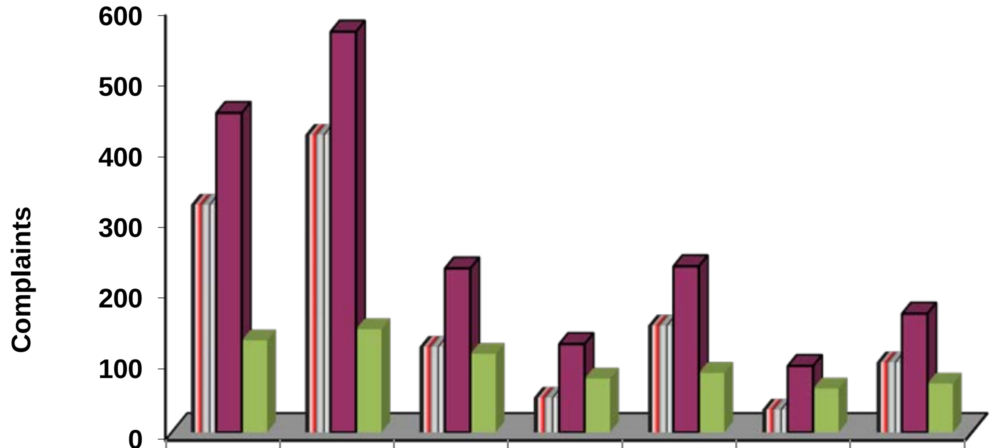


Figure 4.2: Complaints/1000 persons for all suburbs, analysis for all suburbs, over nine years.

Initially, the complaints were analysed by normalising the data per 1000 persons (Figure 4.2), followed by a more detailed analysis. The results show that complaints varied between 0 and 17.52 per 1000 persons per year and that there was still a substantial variation across suburbs and over time. Almost all suburbs registered on average, more complaints than the ADWG accepted guideline values of 4 per 1000 customers. Suburbs B, C, D and E were the top four suburbs registering the highest average of complaints. In order to effectively manage the complaints, investigation into the reasons behind them was conducted. It is worthy to note that the higher number of complaints from suburb A was due purely to the number of customers served (19,735 person), with the exception of 2004. The reasons behind these complaints are analysed in greater detail in the following sections.

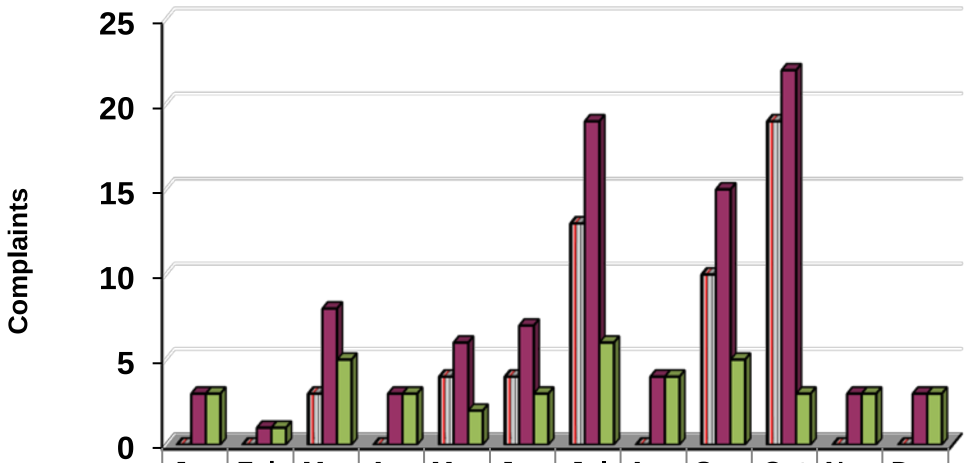
4.5 Separation and General Aspects of Isolated and Batch Complaints

To identify and analyse the complaints accurately, and to attribute them to hydraulic events, complaints over the last seven-year period are graphically represented in Figure 4.3. From this figure, it is clear that the number of complaints was mainly controlled by the actual batch complaints, and that there was a significant variation in batch complaints compared with isolated ones. For example, batch complaints varied from 34% (32/94*100) in 2008 to 74% (420/566*100) in 2004, with an average of 63.8% over seven years. These complaints could have been related to major hydraulic events and hence further analysis is taken up in the next section (Section 4.7). Close inspection of Figure 4.3 indicated that isolated complaints per year varied between 62 and 146. These complaints were found to generally decrease along with a decrease in batch complaints, but the decrease was not as significant as that found in the batch complaints. For example, between 2004 and 2005, batch complaints varied between 121 and 420 but isolated complaints only varied between 111 and 146. Similarly between 2007 and 2008, batch complaints varied between 32 and 151, but isolated complaints varied between 62 and 84. These steady isolated complaints may not have been due to major system failures or events, however, batch complaints can be expected to have a strong correlation to hydraulic events. Therefore, further analysis was conducted and the results are reported in Section 4.7.



	2003	2004	2005	2006	2007	2008	2009
complaints>2	321	420	121	49	151	32	99
Total complaints	451	566	232	125	235	94	168
Isolated complaints	130	146	111	76	84	62	69

Figure 4.3: Total, isolated and batch complaints variation over a seven year period of analysis. Batch complaints refer to more than two complaints registered in a single day in a single suburb or adjacent suburbs, whereas the isolated complaints refer to a lesser number of complaints than the batches.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Complaints > 2	0	0	3	0	4	4	13	0	10	19	0	0
Total complaints	3	1	8	3	6	7	19	4	15	22	3	3
Isolated complaints	3	1	5	3	2	3	6	4	5	3	3	3

Figure 4.4: Total, isolated and batch complaints, for suburb D over 2004.

In earlier Figures 4.1 and 4.2, it can be seen that suburb D recorded a maximum number of complaints in this period. Therefore, total, isolated and batch complaints, for suburb D over the year of 2004 are shown in Figure 4.4. Again, in Figure 4.4, one can note that the variation is highlighted more in the batch complaints than the isolated ones. For example, batch complaints varied between 0 and 19, but isolated complaints varied between 1 and 6. More interestingly, there was a six month period without any batch complaints, even in the year with high complaints (2004), but there were no months without isolated complaints. These results again confirm that isolated complaints were steadier across the year although batch complaints varied markedly.

4.6 Relating Discolouration Periods to Recorded Activities/Faults

Water reticulation pipe failures are undesirably common. For example, one major Australian water utility reported a failure rate of 85.7 failures/100 km/year in 2006–2007 (National Water Commission & WSAA 2008) or around 9.7 failures per day; as cited in Gould et al., 2011.

In the previous section, it was shown that out of all complaints, 63.8% were batch complaints. Most of the batch complaints occurred within a narrow time period across a single suburb or different suburbs. These times can be easily isolated from the database, and are referred to as discolouration events. Batch complaints can be expected to have a strong relationship with hydraulic events. Hydraulic events are burst mains events (burst pipes), fire hydrant operations, or other operational changes that affect the hydraulics of the flow. The Water Corporation records the first two, but not the last. Although the data is not complete in this respect, an analysis of the existing data may reveal an important correlation that will be useful for operational control of discolouration events. As with the earlier section, the data was analysed for the whole study period and microanalysis was then conducted for the year 2004, as this year was the most prolific for complaints (Figures 4.3 and 4.4).

Table 4.2 provides details on the number of complaints recorded over 2004 and the associated activities/faults that were recorded by the Water Corporation during those periods. From an initial inspection of all cases, where an associated activity could be identified, either a burst water main or the replacement of fire hydrants was the cause for the discolouration. Fire hydrant operations occurred only once and there was one instance of a mains break (burst pipe). Therefore, it is hard to attribute the complaints to fire hydrant operations. Similarly, in other years, it was found that fire hydrant operations did not affect the number of complaints. Therefore, the effect of fire hydrant operations was excluded from further analysis. For almost all cases except for one or two isolated discolouration events which had no obvious cause, the complaints occurred on a single day, or were low and spread across a number of days. These events can therefore be considered as minor discolouration events and their respective causes were most likely localised and not usually associated with major discolouration events, indicating that the major reasons for the high level of complaints in 2004 were burst mains events.

Although the majority of complaints could be attributed to burst water mains, there were still significant discolouration events which had no obvious cause, such as events number 2 and 4 in Table 4.2. In addition to the possible causes previously mentioned, another reason for the complaints could have been pipes which burst some time before or after the dates of high complaints, and these were therefore not recorded as associated activities/faults or hydraulic events. However, the discolouration may have also been due to other reasons which are unknown. Similarly, there is a possibility for a no discoloured water event even when a burst main occurred, such as the 12th of October 2011 in event number 5 (Table 4.2). This could be due to the size of the burst mains events (i.e., if it was only small and could be fixed rapidly), the duration of the pipe leak prior to repair, and the location of the pipe.

Table 4.2: Discolouration Events and Corresponding Faults/Activities for 2004.

DISCOLOURATION EVENT					CORRESPONDING ACTIVITIES/FAULTS				
Event	Date	Suburbs	Number of Complaints		Activity	Primary fault	Diameter mm	Date of Activity	Suburbs of Fault/Activity
			Total	Batch					
1	10-Jan to 18 May	G, D, E, A, F, H	14	14	11 Burst Water Main	broken 2 leak 2 wear, roots, broken, leak, unknown broken broken	1*40 2*50 6*100 1*150 1*220	10-Jan to 18 May	G,D,E,A,F,H
2	22 Jun	B, D	8	8	No Obvious Cause	-	-	-	-
	24 Jun	B	14	14	No Obvious Cause	-	-	-	-
3	16 Jul to 3 Sept	A, B, C, D, E, F, G, H, I, J	33	33	Burst Water Main	wear	220	16 Jul	G,D
			9	8	Burst Water Main	leak	500	19 Jul	I
			1	0	Burst Water Main	leak	200	24 Jul	I
			8	8	Burst Water Main	leak	150	27 Jul	A
			196	195	Burst Water Main	broken	150	29 Jul	B
			37	37	Burst Water Main	leak	100	2 Aug	B
			1	0	Burst Water Main	broken	100	16 Aug	D
			5	5	Burst Water Main	broken	100	18 Aug	C
			3	3	Burst Water Main	leak	***[1]	31 Aug	D

			1	0	**Burst Water Main**	**unknown**	**100**	**03 Sep**	**F**
4	**25 Sep to** **07 Oct**	**B, D, G**	**17**	**17**	**No Obvious Cause**			**-**	**-**
5	**12 Oct to** **06 Dec**	**A, B,C, D, E, F, J**	**8** **0** **9** **33** **0** **1** **3** **1**	**8** **0** **9** **32** **0** **0** **0** **0**	**Burst Water Main** **Burst Water Main** **Burst Main+ F H R**[2] **Burst Water Main** **Burst Water Main** **Burst Water Main** **Burst Water Main** **Burst Water Main**	**unknown** **broken** **leak** **leak** **broken** **unknown** **unknown** **leak**	*******[1] **100** **100** **215** **100** **100** **200** **100**	**12 Oct** **16 Oct** **20 Oct** **24 Oct** **26 Nov** **04 Dec** **05 Dec** **06 Dec**	**B** **F** **F+ D** **D,C** **B** **D** **A** **G**

[1] unrecorded.

[2] Fire Hydrant Replace

Data over the period covering 1 July 2003 to the end of 2008 was analysed to understand the correlation between discoloured water events and the recording of hydraulic events. This was achieved by relating the dates of activities/faults to the specific dates during a discolouration event when high complaint numbers were recorded.

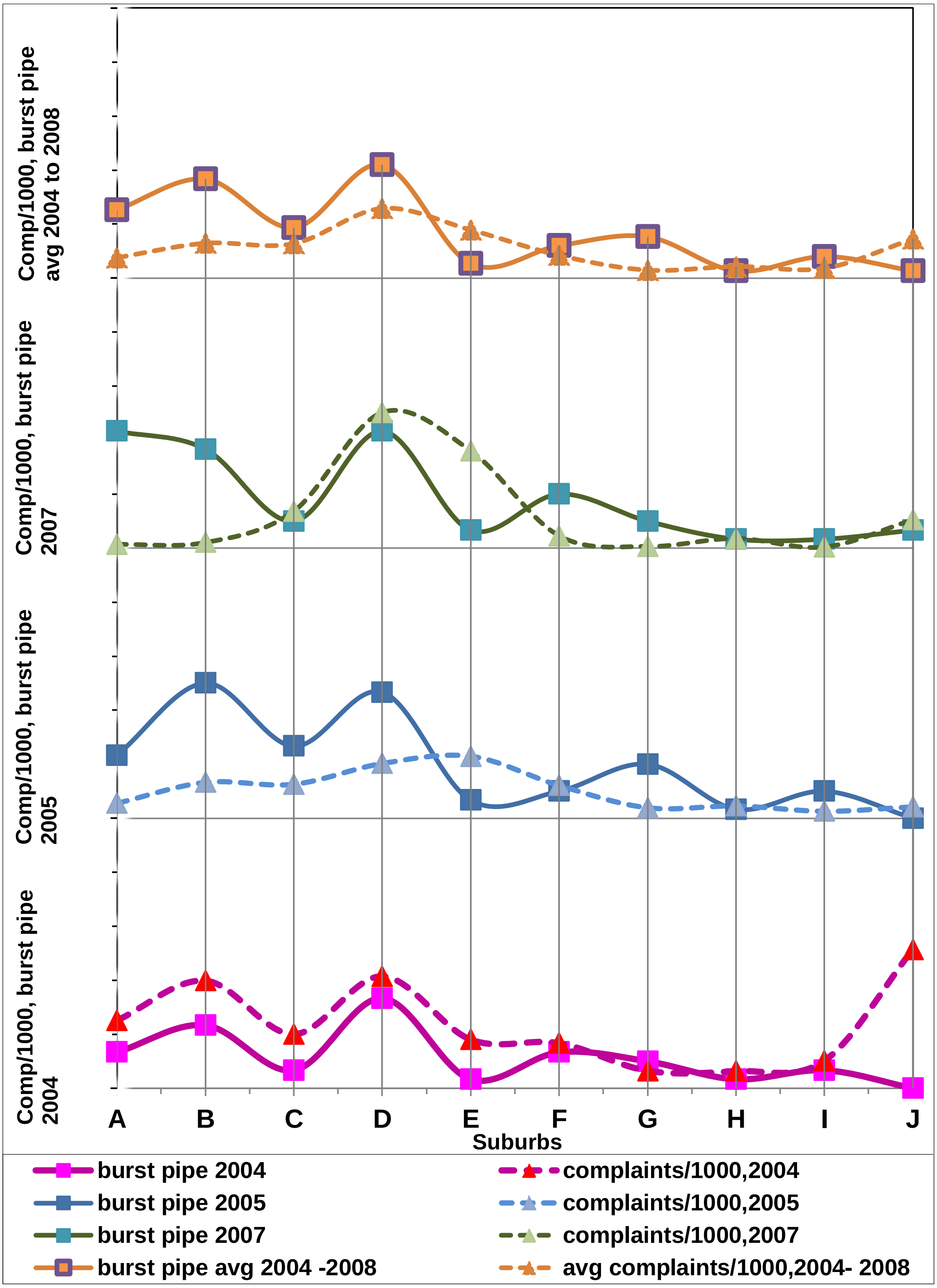


Figure 4.5: Total discolouration complaints events and burst pipes events for three years.

In order to draw a quantitative relationship between the total complaints/1000 persons and hydraulic events; data from 2004, 2005 and 2007, along with the average of complaints/1000 persons and the average of burst pipes for the period 2004 to 2008 were compared in Figure 4.5. In this figure, there was a general correlation between the number of burst pipes/year and complaints/1000 persons per year. However, some suburbs did not follow this trend. These were J, G and E. Suburb J was a new suburb formed at the end of 2003, where many new activities took place which were not necessarily burst pipes events; hence these were not recorded but may have caused a resuspension of sediment. Suburbs D and E were adjacent suburbs and both were supplied from Tank 2. Suburb E was downstream from suburb D. Hence, hydraulic events in either suburb could have mutually affected the complaints pattern in D and E. The same applies to B and G. The same data is presented on the location map as shown in Appendix A, Figure A.3.

Table 4.3: Results summary complaints percentages related to burst pipes.

date	Total comp	Batch comp	Total comp from burst pipe	% Total comp from burst pipe	Batch comp from burst pipe	% Batch comp from burst pipe
2004	566	420	358	63.3	341	81.2
1/7/2003- 2008	1550	988	818	52.77	653	66.1

When analysis was performed for 2004 it showed that 63.3 % and 81.2 % of total and batch complaints respectively could be attributed to burst water mains events as illustrated in Table 4.3. Similar analysis performed for all years in the case study period (1/7/2003 to 2008), showed that approximately 53% and 66% of total and batch discoloured water complaints could be attributed to burst water mains. These instances were recorded in all suburbs; therefore it could be concluded from the analyses that hydraulic events impacted upon the number of batch complaints.

4.7 Nature of Isolated Complaints and Possible Reasons

When the isolated complaints of 2004 were analysed further, it was found that they came from thirteen households and that about 40.5% of all complaints from suburb D over 2004 were related to those individual households. Each of the thirteen households usually made repeated telephone calls, sometimes within a single day.

To confirm these results, the same analyses were repeated for complaints from suburb D over the period from 2003 to 2005. Instead of thirteen households, forty households were found to be complaining regularly which accounted for about 42.2 % of all suburb D complaints over 2003, 2004, and 2005 (Figure 4.6). From Figure 4.6, one can note that eight of the forty households which started to complain during 2003, continued to register complaints during 2004. However, the number of complaints decreased over time, but other complaints were initiated. There could be a number of reasons for this. Firstly, customers had become accustomed to a certain level of discoloured water and stopped reporting to the water utility. Secondly, the level of customer reporting may have been unpredictable as an actual indicator of problems (not all people report problems). Thirdly, the results could have been due to a change of address by the same customer. These facts can also be confirmed if the same forty households were to be followed over a longer period than 2003 to 2005. Those forty households complained 114 times during 2003-2005, but they complained only 12 times during 2006-2009.

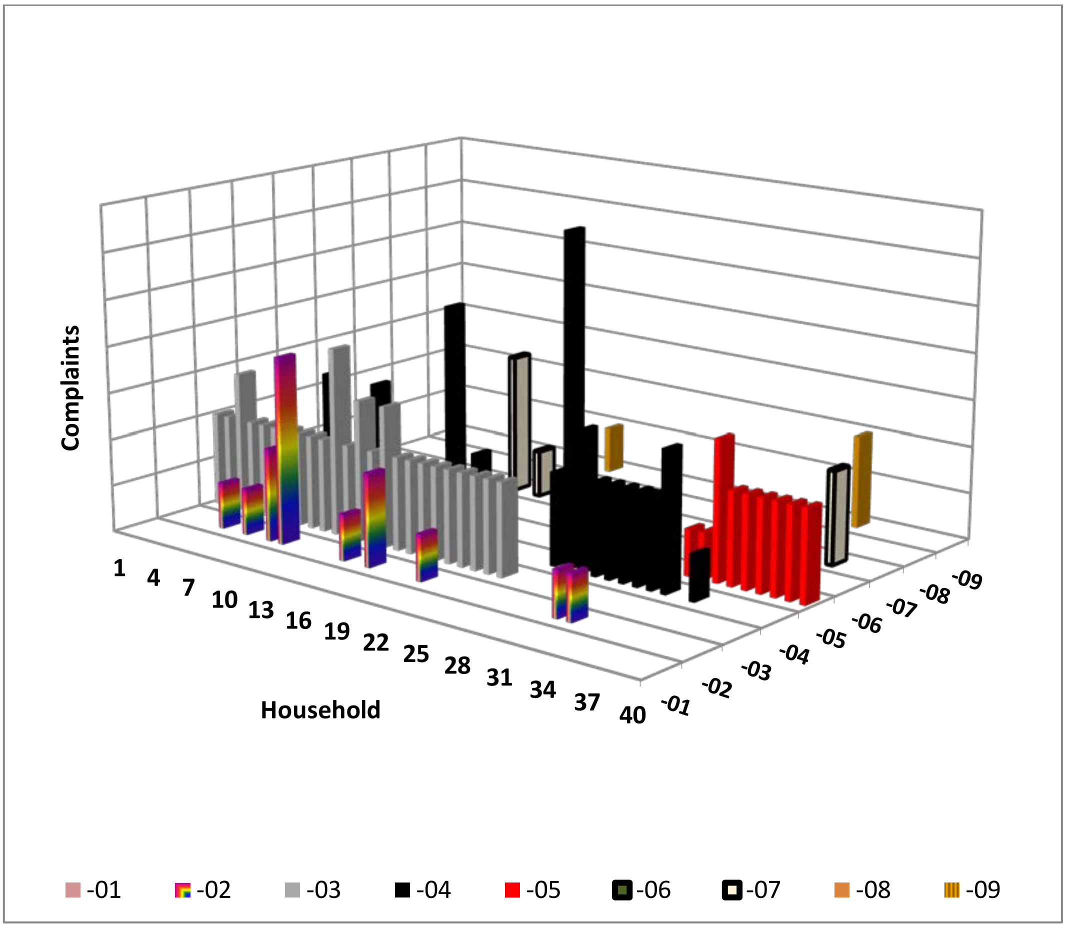


Figure 4.6: Complaints for 40 individual households, for suburb D, repeated complaints over period 2001-2005.

For further analysis, the forty households that complained during 2003-2005, are shown in Figure 4.7. It is clear from the figure that the locations of the forty houses are found in three groups depending on the sources of supply water, as illustrated previously in Table 3.1. Households 5, 17 and 18 were supplied from the subs-system H, M, and Y, respectively. It is very clear from the map, that there are relationships between those households. Therefore, we can conclude that there was a hydraulic reason, rather than social reasons behind the events.

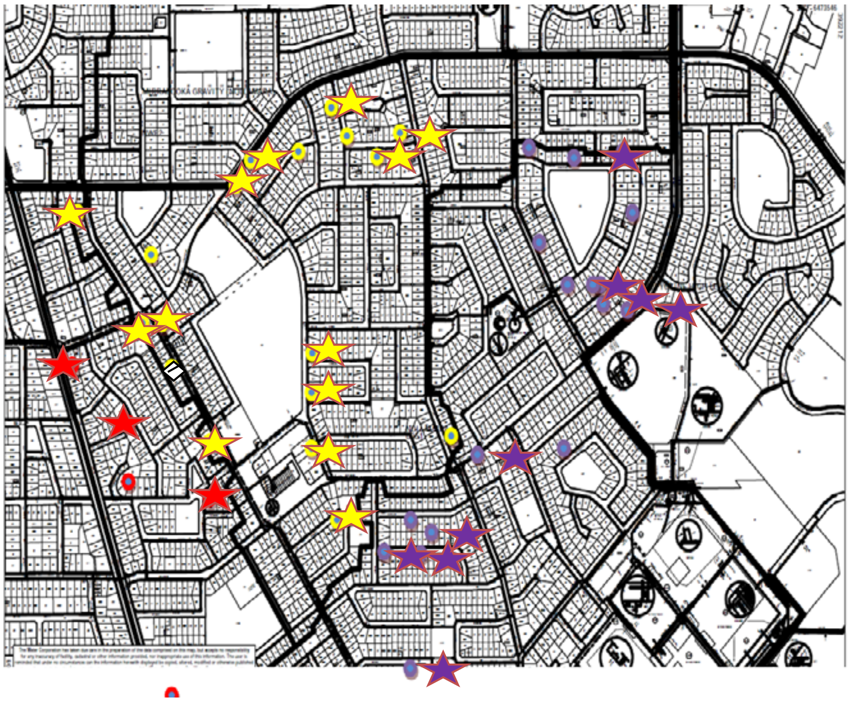


Figure 4.7: Highlighting all 40 household locations in suburb D; the star shape designates property type i.e., unit, duplex or triplex. Each colour represents one sub-system (red for H sub-system, yellow for M sub-system and purple for Y sub-system).

Further scrutiny of the forty households provided strong evidence that complaints were due to hydraulic reasons. The majority of the forty households (22/40 = 55%) were units, duplexes, or triplexes or others co-located with these. Water usage can heavily fluctuate which may have caused hydraulic disturbances in these units compared to an area with single dwellings. Such disturbances are sufficient enough to cause the resuspension of sediment and the carrying of sediment to customers.

Table 4.4: Complaints dates compared with change of property types dates for 22 isolated properties.

Time from change of property type	Before changing the type*	1st year**	2nd year**	3rd year**	4th year**	5th year or more**
Number of households complaining	7	9	….	2	…	4
Percentage of households complaining (% out of 22 households)	(32%)	(41%)		(9%)		(18%)

*Any time before date of change in property type.

**Time after date of change in property type.

Furthe analysis was conducted to confirm the results by comparing the complaints start date for the 22 households in relation to the date of change in property type to unit, duplex or triplex from single dwellings. Each of these units had different dates (ranging from 1990 to 2007) of change of property type. Table 4.4 summarises the results. The results show that 41% of these 22 households recorded complaints within one year or less from the date that the property type changed from a single detached house to one of the above types of dwelling. In the next few years, the number of complaints dropped down to between nil and 2, probably due to the familiarity of the residents with the dirty water.

Figure 4.8 shows the relation between burst pipes and isolated complaints for 2004. It is clear from this figure that the isolated households recorded complaints even if there were no burst pipes as in June. However, complaints from these households had a general correlation to the number of burst pipes. This was confirmed when the complaints data was checked, as each household recorded two or three complaints on the same day.

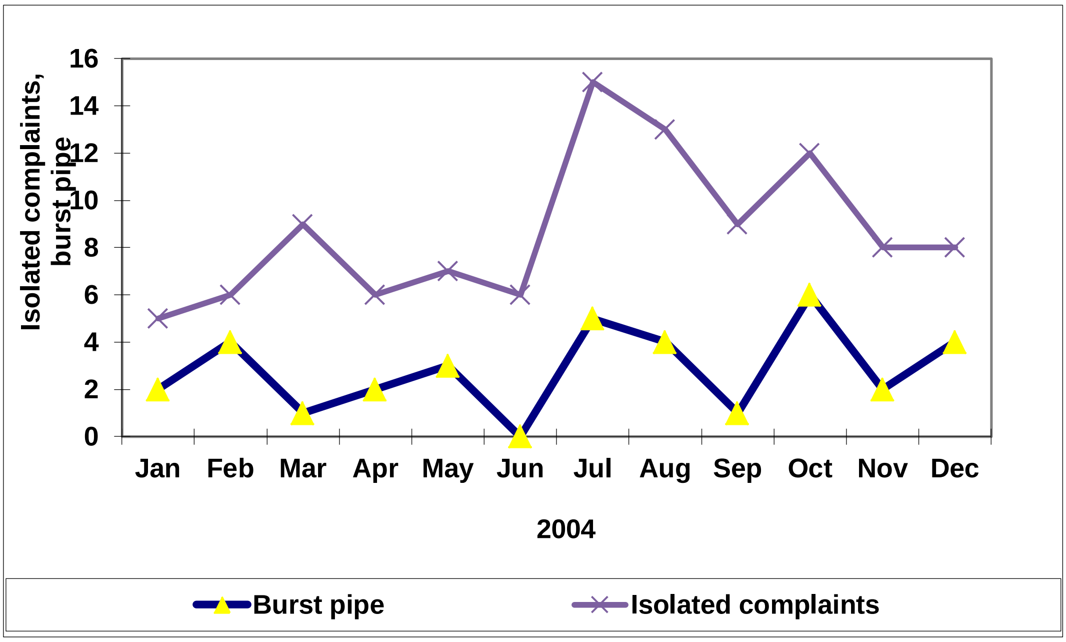


Figure 4.8: Relationship between isolated complaints events and burst pipe events for 2004.

Analyses of isolated complaints clearly indicate that even isolated complaints were due to localised hydraulic events, especially the complaints from multiple dwellings, where highly fluctuating water demands existed.

4.8 Effects of Seasonal Variations

Water demand fluctuates with seasons of the year, which can lead to changes in discolouration events. Seasonal variation of complaints in 2004 is noted in Figure 4.4. October and July recorded the higher percentages of 35% and 24% respectively. Similarly, in three other years, maximum complaints were recorded between July and October, but the actual number of complaints and the time at which they occurred varied greatly between years, the result being the same if the total number of complaints were compared. The months noted are in the winter/autumn period, coinciding with the rainy season in Perth, Western Australia. However, in two out of the six years mentioned, the maximum complaints/seasonal trend was non-existent, indicating that there was some reason for the variability other than the season. As posited earlier, the complaints were likely to be due to hydraulic events.

Rajani and Zhan, 1996, reported that the high breakage frequency of water mains during winter in Canada and the USA was due to the increased earth load exerted on the buried pipes, which arose from frost load and low soil temperatures and/or low soil moisture content. Similar explanations were given for increased pipe failures towards the end of summer in Melbourne (Gould et al., 2011). This result was supported by several authors who have attributed peaks in failure rate to the action of expansive soils (Clark, 1971; Hudak et al, 1998; Hu and Hubble, 2007).

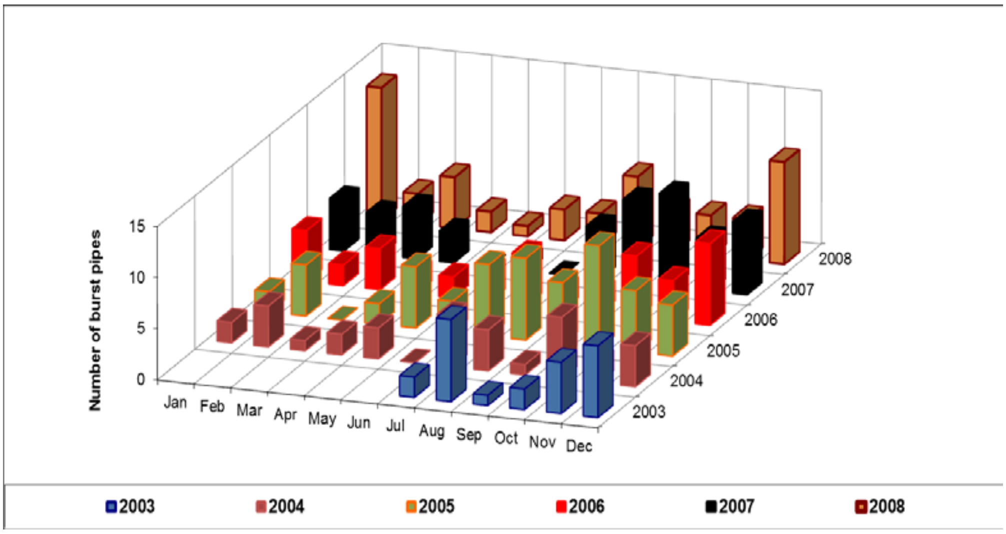


Figure 4.9: Effect of seasonal variation using instances of burst pipes, for all suburbs over five years.

Contrary to this, Boxall et al, 2007 reported no appreciable relationship between soil shrink/swell potential and pipe failure. Similarly, our data analysis did not show any seasonal variability; the seasonal variation was attributed to soil/water interaction which led to differential soil movement resulting in soil shrinkage as the soil moisture content decreased, as illustrated in Figure 4.9. Our observations were based on soil structure, steady water use and less fluctuation between the seasons. In the studied area the soil was sandy and the soil type was stable (unexpansive soils) hence there is no possibility that soil/water interaction heavily influenced the complaints pattern. However, it should be noted that the winter season is between June and August and the area receives rain between April and October, with the highest rainfall usually occurring between June and September. It is therefore unclear whether or how an unexpansive soil contributed to the failure of the pipes.

4.9 Effects of Air-Scouring on Complaints

Figure 4.10 shows the number of complaints per 1000 persons during the seven year period (2003–2009) for each suburb. This provides an understanding of how customer complaints varied across suburbs. On average, the suburbs which belonged to Tanks 1 and 2 (A, B, C, D and E) recorded the highest number of complaints and the suburbs which belonged to Tank 3 (I and J) recorded the lowest number of complaints, while the suburbs which belonged to both Tank 1 and Tank 3 (F, G and H) recorded a medium level of complaints, with the exception of H, which showed the lowest average complaints. Air-scouring took place in pipes of the suburbs served by Tank 3 system, between 9/10/2003 and 11/11/2003 (Table 3.1), but not in Tanks 1 and 2 systems. The discrepancy could have been due to the differences between Tanks 1 & 2 and Tank 3 sub-systems in terms of air-scouring. However, for this conclusion to be validated, the effect of population needs to be taken into account. According to the figures regarding complaints/1000 persons, the four worst suburbs were D, E, C and B. Some more detailed figures are provided in Appendix A, Figure A.4.

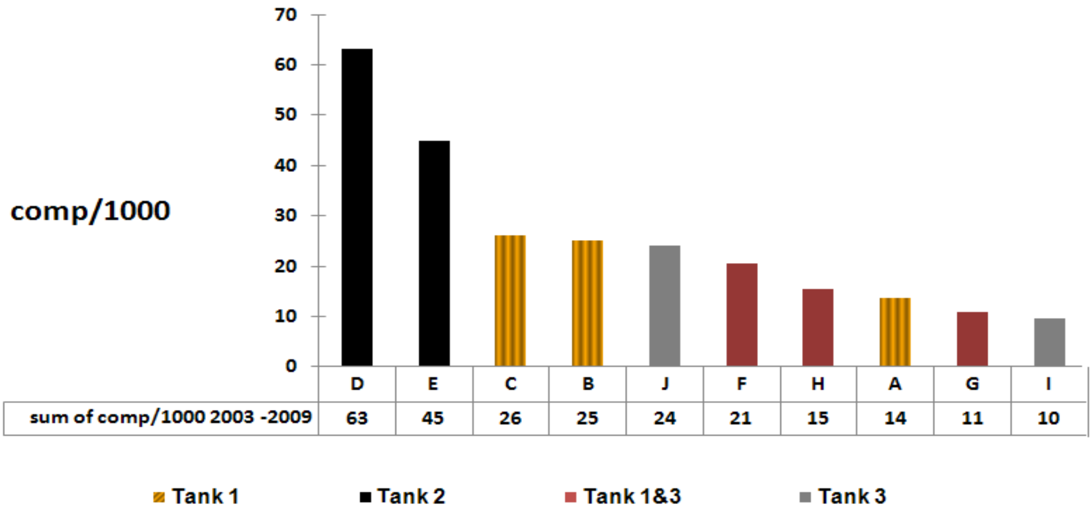


Figure 4.10: Summation of customer complaints/1000 persons each suburb for seven years from 2003 to 2009.

In order to obtain a clear picture as to whether the air-scouring was the influencing factor or there were other factors that have to be considered, Figure 4.2 was further scrutinised. It is clear from Figure 4.2 that the suburbs which received water from Tank 3 recorded the lowest complaints/1000 persons during 2001 – 2003, but this tank was selected as a prototype for air-scouring, the first time this type of cleaning was carried out in WA. Therefore, it can be seen that the decision of the Water Corporation was based on a smaller area to manage within a given budget. In general, air-scoured suburbs, F, G and H, reduced their customer complaints in the following year, 2004. Close inspection of Figure 4.2 also indicates that some suburbs such as H and I had been air-scoured, but still recorded higher complaints/1000 persons during the following years, whereas suburbs such as A and B recorded decreasing complaints/1000 persons in the following years despite not being air-scoured. In other suburbs, complaints fluctuated from low to high. It must be noted that suburb J, which was under construction during 2003-

2004, recorded high complaints/1000 persons during 2004 due to hydraulic events related to the construction of new pipes. Some complaints were recorded despite the fact that suburb J was new during 2003; Figure 4.11 confirms these results.

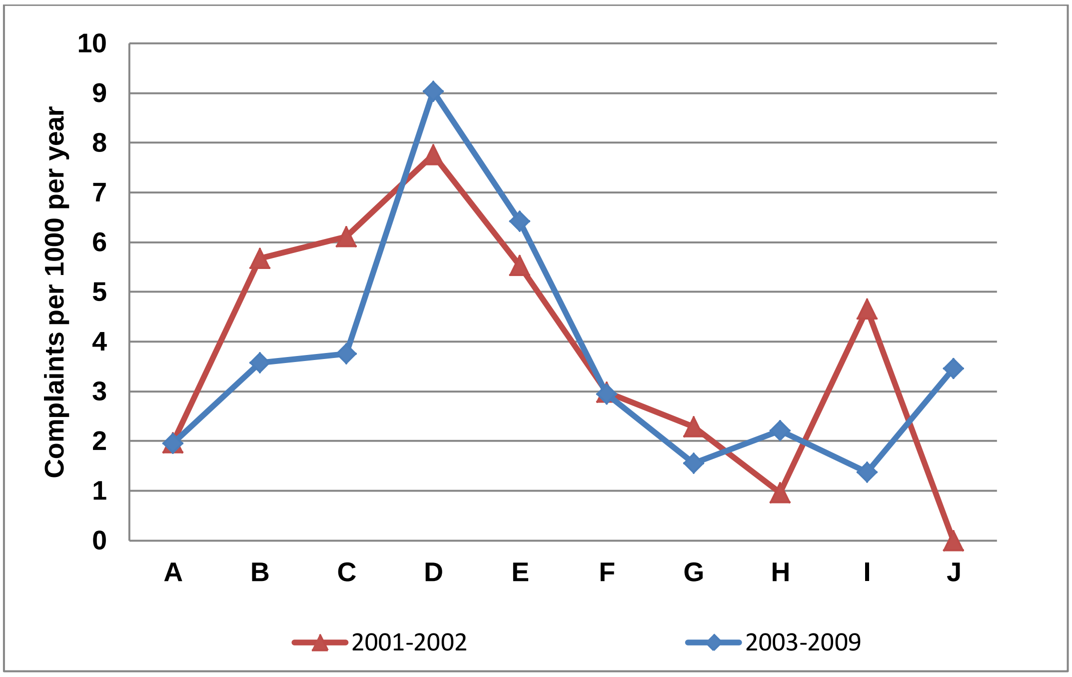


Figure 4.11: Customer complaints/1000 persons/year for each suburb for 2001-2002 and 2003 -2009 (complaints for 2003 were counted only after the air-scouring period).

From the above discussion it is clear that air-scouring did change the number of complaints in the following year in a few suburbs, but in other cases, mixed results were obtained: complaints decreased without air-scouring or complaints increased despite air-scouring. The results therefore indicate that while air-scouring may reduce complaints temporarily in some suburbs, other reasons such as hydraulic events play a bigger role in the effects on complaints.

4.10 Practical Implications of the Study

Despite an obvious logical relationship, no studies have proven the strong relationship of hydraulic events to complaints. Utilities prioritise complaints by spending millions of dollars on cleaning the areas that receive the highest number of complaints. The cost of air-scouring a pipe is around $1000 per km which is made up of $680 for preparation and $320 for scouring, with the budget being around 1.2 million dollars in the last couple of years. The decision to prioritise areas for cleaning might be better based on a more critical analysis of existing historical data, hence the current investigation.

In order to better understand the data, complaints were divided into two categories: batch and isolated. Such separation greatly helped in analysing the complaints in greater detail with the aim of reaching strong conclusions that could help in setting the strategic direction for the prevention of customer complaints. The results indicated that the majority, if not all, complaints were caused by hydraulic events and that air-scouring did not impact upon the number of complaints. Therefore, water utilities may wish to consider this factor when assessing where to direct funds and how to resolve complaints.

4.11 Conclusions

This chapter analysed customer complaints from Zone M by separating them into isolated and batch complaints, connecting the complaints to hydraulic events rather than to air-scouring. The detailed conclusions are as follows:

Of all complaints, 63.8% were batch complaints. In all years, batch complaints per 1000 persons strongly correlated with hydraulic events such as burst mains events. In 2004, a high complaints year, the analyses showed that 63.3% and 81.2% of total and batch complaints respectively could be attributed to burst water main events. When a similar analysis was performed for all years in the case study period (1/7/2003 to 2008), it showed that approximately 53% and 66% of total and batch discoloured water complaints could be attributed to burst water mains. This scenario was recorded for all suburbs.

Isolated complaints were found to be located in places where the water usage pattern was heavily affected by changes in land use patterns, i.e., increases in population/housing density. Therefore, overall hydraulic events played a significant role in bringing about customer complaints. This significant finding should help water utilities to effectively target and minimise discolouration events.

Although air-scouring may have reduced the number of complaints slightly in the year following air cleaning, hydraulic events played a key role in their effect upon the long-term complaints pattern. Due to its short-term impact, it is questionable whether air-scouring should be adopted as a method to reduce the number of complaints. It might be effective if the Water Corporation were to adopt emergency flushing in the locality where complaints are recorded. This operation would make the pipes cleaner, before air-scouring is conducted. For air-scouring to be effective, sediment should not accumulate to a critical level within a very short period of time. However, in Melbourne, sediment accumulated within just two to four weeks, a very short period compared to the five to ten year period observed in the Netherlands. Our studies did not target this parameter; hence it is not possible to estimate the duration for which cleaning might be effective, nor its effect on reducing complaints. However, some pertinent issues and discussion points arising from the data are made in the following chapters.

CHAPTER 5 THE CONNECTION AMONG PIPE DIRTINESS, COMPLAINTS AND HYDRAULIC EVENTS

5.1 Introduction

The majority of customer complaints registered with water utilities (60%-80%) are related to discolouration. In Chapter 4, a detailed analysis of complaints across a water supply sub-system M in Perth, Western Australia revealed that the majority of the complaints occur in batches (i.e., two or more complaints registered in a single day in a locality). Further comparison with events in the system (such as the burst pipe events database) showed that the dates of batch complaints were associated with such events. The locations of isolated complaints were also closer to highly fluctuating water demand areas such as units or apartments. These conclusions collectively showed hydraulic events as the most important factors in the cause of discolouration events. Following discolouration events, water utilities generally adopt expensive cleaning programs with the view that clean pipes (pipes without sediment) will lead to less complaints. To further understand the role of the suspended materials present in pipes, the Resuspension Potential Method (RPM) is examined here.

The RPM is based on creating additional velocity in a pipe in order to resuspend deposited materials. Following this, the evolution of visually noticeable turbidity levels are measured over time and a ranking score is created. The higher the ranking score, the dirtier the pipe is assumed to be. The RPM is not a quantitative tool; hence its applicability to local conditions needs to be established.

Despite the ready availability of various tools, water utilities have been slow to adopt them, or the true value of the tools to the utilities is not widely reported. The basic assumption is that a discolouration event is caused only when there is appreciable amount of resuspendable sediment in the pipe, in combination with a hydraulic disturbance. So, it is possible that there are areas with a high discolouration risk but no discolouration events or complaints (i.e., the presence of resuspendable sediment that is not visible as discolouration as no hydraulic disturbance is present), and areas with high discolouration complaints but a low discolouration risk (i.e., little sediment, but many disturbances and/or many customer complaints). If the latter relationship is conclusively proven, then the cleaning of pipes undertaken by authorities after receiving multiple complaints from a single area may be both redundant and a waste of money in that there could be relatively little sediment/discolouration to deal with.

This study was undertaken in conjunction with the Western Australian Water Corporation. One of the objectives was to establish the connection between the dirtiness of the area (as determined by the RPM) and the number of customer complaints received both before and after the RPM measurements. In addition, the link is also drawn with recorded hydraulic events such as burst pipes. This chapter reports the finding of this study.

5.2 Materials and Methods

5.2.1 Standard RPM

The RPM is applied as given by Vreeburg et al., 2004a and is summarised as follows:

1. Isolate the pipe for which the discolouration risk is to be assessed, as per unidirectional flushing (Antoun et al., 1999). The isolated length should be at least 315m to be sure that only this single pipe is affected.

2. Flush hydrant with a small amount of flow to clean the hydrant point of accumulated sediment. The hydrant flushing in the initial period should be controlled; otherwise a massive movement of water will take place, which will affect the turbidity or the sediment in the pipe.

3. Monitor the turbidity in the main pipe for some time (5 minutes) to determine the **base level turbidity**. This will give an indication of the normal conditions of discolouration in the pipe. There are 5 values used to indicate recommended values. Usually those 5 values should be within same level, i.e., if one value is too high it should be ignored. The lowest value among the closer values is designated as the **base level turbidity** which can be used for comparison with the turbidity after decreasing flow to normal conditions.

4. Open a fire hydrant such that the velocity in the pipe is increased by 0.35 m/s on top of normal velocity and maintained for 15 minutes. Continue monitoring the turbidity.

If the base level turbidity is greater than the turbidity during increased velocity, the results should be ignored. Determine the increase in turbidity in the initial 5 minutes of hydraulic disturbance. This is referred to as **initial increase in turbidity**.

5. Monitor the turbidity in the pipe for the remaining 10 minutes of the 15 minutes hydraulic disturbance with extra velocity. This is referred to as **development of turbidity**.

6. Reduce the velocity back to normal, continue monitoring until the turbidity returns to the initial "base" level. This is referred to as **resettling time and pattern to base (initial) turbidity level or "time to clear"**.

A typical example is illustrated in Chapter two Figure 2.3 which highlights the four regions of the trace that are utilised to rank the discolouration risk.

5.2.2 Equipment Used

AquaMaster™, an electronic flow meter, was used for flow measurement. Figure 5.1 shows how the flow meter was connected to the hydrant. It was connected from both sides with a 100mm U-shaped pipe to ensure that it was filled with water during the flow measurement, as the flow meter required a full pipe flow. The end of the U-shaped pipe was connected to a fire hydrant point and there was a valve next to the flow meter to control the flow as shown in Figures 5.2 and 5.3. The other side of the U-shaped pipe was connected to a 50 mm pipe from which samples were collected and turbidity was measured by a portable HACH2100 Turbidimeter, as shown in Figure 5.4.

Figure 5.1: Flow meter connection with u shaped 100 mm pipes.

Figure 5.2: Flow meter U-shaped pipes are connected to a fire hydrant; 50 mm pipe is left as a free end.

Figure 5.3: Control valve next to the flow meter.

Figure 5.4: The free end to measure turbidity.

5.2.3 Selection of RPM Sites

The sub-system was divided into ten zones according to the number of suburbs and RPM testing was conducted at 25 sites. The selection of sites depended on the analysis of customer complaints data which was carried out previously (Luke et al., 2009; Al-Ithari et al, 2010 and 2012). All results are presented in Chapter 4.

The RPM site selection procedure described by Vreeburg et al., 2004 was used. According to the procedure, the sites selected were 10 km apart, on selected streets where there were no previous burst pipes (within 3 months). A number of staff at Perth Water Corporation's planning team worked cooperatively on the selection of hydrants. For every measurement, two hydrants were selected on the same street or nearby streets. One of the two hydrants was a reserve.

When the RPM locations were chosen, the selected hydrant numbers were handed over to the Water Corporation with valves marked on a map generated by software named LiteSpatial® which was developed by the Spatial Information Management Group. On the map, it was also stated which valves should be closed to create a unidirectional flow. The RPM measurements were undertaken as a team effort between Curtin University and the Water Corporation.

5.2.4 Evaluation Table of RPM Curves

The evaluation method of the RPM curve is described in detail in Chapter 2. Five aspects were considered and rated equally at 20%. These were: the maximum turbidity in the first 5 minutes and the average turbidity in the first 5 minutes and maximum turbidity in the last 10 minutes and average turbidity in the last 10 minutes of the disturbance along with the time to clear. Each of these can be rated on a scale from 0 to 3 and summarised, resulting in a single figure on a scale of 0–15.

Table 5.1: Evaluation table (supply sub-system "M" ranking score (RS)).

Score (points)	0	1	2	3
Absolute maximum first 5 minutes	< 1 NTU	1-5 NTU	5-20 NTU	>20 NTU
Average first 5 minutes	< 1 NTU	1-5 NTU	5-20 NTU	>20 NTU
Absolute maximum last 10 minutes	< 1 NTU	1-5 NTU	5-20 NTU	>20 NTU
Average last 10 minutes	< 1 NTU	1-5 NTU	5-20 NTU	>20 NTU
Time to clear (minutes)	< 5	5—15	15—60	>60

The ranking table can be adjusted based on the results obtained and instrumentation used (i.e., average turbidity levels) to obtain a spread of risk scores, providing the flexibility to tailor the method to different networks, Vreeburg et al. (2004a, b). In our effort to tailor the ranking table to our needs, a different scale was adopted. The rationale is discussed below. Adopted values are summarised in Table 5.1.

In Australia, the maximum allowed turbidity level in distributed water is set at 5 NTU. The Australian Drinking Water Guidelines (ADWG, 2004) recommend that turbidity in drinking water should be kept below 1 NTU to enable effective disinfection and below 5 NTU for aesthetic considerations. Therefore, the ranking table was set up based on these values (1 NTU, 5 NTU, and the most frequent maximum turbidity value found in the sub-system "M" sites).

Table 5.2: Information on selected RPM sites for batches 1 and 2.

No.	Suburb location	Water resource	Last cleaned	Notes	Batch-1 RPM performed date	Batch-2 RPM performed date
1a.	H	Tank 1	Not cleaned	Closed valve at end, near reservoir	July 2008	Feb 2010
1b.	H	Tank 3	9 /10/ 03	Loop point, near reservoir	July 2008	---
2a.	G	Tank 3	31/10/ 03	Dead-end	July 2008	---
2b.	G	Tank 3	31/10/03	Dead-end	---	---
3a.	E	Tank 2	Not cleaned	Through pipe	July 2008	---
3b.	D	Tank 2	Not cleaned	Loop point	July 2008	---
3c.	D	Tank 2	Not cleaned	Loop point,	---	---
4a.	D	Tank 2	Not cleaned	Through pipe	July 2008	Feb 2010
4b.	D	Tank 2	Not cleaned	Loop point	----	---
5a.	A	Tank 1	Not cleaned	Dead-end	July 2008	Feb 2010
5b.	A	Tank 1	Not cleaned	Dead-end	---	---
6a.	G	Tank 1	Not cleaned	Loop point	---	---
6b.	G	Tank 1	Not cleaned	Loop point	July 2008	---

7a.	B	Tank 1	Not cleaned	Loop point	---	---
7b.	B	Tank 1	Not cleaned	Dead-end	July 2008	Feb 2010
8a.	E	Tank 2	Not cleaned	Closed valve at end	Feb 2009	Feb 2010
8b	E	Tank 2	Not cleaned	Closed valve at end	---	---
9a	I	Tank 1	Not cleaned	Dead-end	Feb 2009	---
9b	I	Tank 3	28/10/2003	Dead-end	---	---
10a	F	Tank 1	Not cleaned	Dead-end	---	---
10b	F	Tank 1	Not cleaned	Loop point	Feb 2009	---
11a	J	Tank 3	**Not scoured	Dead-end	---	---
11b	J	Tank 3	11/11/2003	Dead-end	Feb 2009	---
12a	C	Tank 1	Not cleaned	Closed valve at end	Feb 2009	---
12b	C	Tank 1	Not cleaned	Dead-end	---	---
*Tank 1 and 2 have yet to be air-scoured ** This part of the suburb J was formed only after 2003						

5.2.5 Three batches of RPM Measurement

Table 5.2 provides the detail of 25 selected sites. The RPM fieldwork was carried out in three batches. The first batch contained two parts, with the first part taking place in July 2008 for sites 1 to 7, and the second part taking place in February 2009 for sites 8 to 12. To confirm the findings from the first batch, second and third batch work was undertaken in February 2010 and October 2011, respectively. The second batch included sites 1, 4, 5, 7 and 8. The third batch contained two sites which were selected as those with one through pipe and one loop pipe located in the same area.

5.2.6 Burst Pipe and Complaints Data

In the previous chapter, a relationship between complaints and burst pipe events was established. The ranking score (RS) could have been related to associated hydraulic events such as burst pipes. To determine whether the RS had any relationship with burst pipe events or complaints/1000 persons, the number of burst pipes across each suburb was compared with the respective RS. The selection of the period was based on tracking the burst pipes and complaints over six months (0.5Y) or one year (1Y) prior to the date the RPM was undertaken. For ease of discussion, complaints received within the six month period prior to the RPM measurement are referred to as C0.5Y. Similarly, those within one year are referred to as C1Y. Burst pipe events for the same periods (six months and one year before the RPM measurement) are referred to as BP0.5Y and BP1Y, respectively. In addition, an average value of complaints per 1000 persons per year over a five year period (2003-2007) (C_{avg}5Y) was tracked for each suburb.

5.3 Results and Discussion

5.3.1 First Batch RPM Results

All batch-1 results are illustrated in Figures 5.5 to 5.18. Most sites followed the typical pattern shown in Figure 2.3. However, the time at which maximum turbidity occurred varied from one site to the other, depending on the distribution of sediment along the isolated length. Using the information in Figures 5.5 to 5.18, individual scores were generated and summarised in Table 5.3. Data from the third to the seventh columns for each aspect were considered in calculating the score point for each site, as illustrated below. Using site 1a H as an example:

1. The first value of the turbidity was too high, 87 NTU, compared to subsequent values. Therefore, it was ignored and one more value was measured. The rest of the values were 60.5, 50.8, 48.4, 56.9 and 49.9 with the lower but closer turbidity values being 48.4, 49.9 and 50.8. The lowest value among the three values was 48.4 which is considered as the base level turbidity.

2. Maximum Turbidity in the first 5 minutes = 93.5 NTU; the score for the first aspect = 3 (Turbidity > 20 NTU; See Table 5.1).

3. Average Turbidity in the first 5 minutes = 78.3 NTU; the score for the second aspect = 3 (Table 5.1).

4. Maximum Turbidity in the last 10 minutes = 85.9 NTU; the score for the third aspect = 3 (Table 5.1).

5. Average Turbidity of last 10 minutes = 43.9 NTU; the score for the fourth aspect = 3 (Table 5.1).

6. Time to clear = 1 minute; the score for fifth aspect = 0 (Table 5.1).

7. The ranking score is 12 points (RS = 3+3+3+3+0 = 12).

In general, the ranking scores from two different sites in the same suburb were approximately the same. For example, sites 1aH and 1bH were from the same suburb H, and had ranking scores of 12 and 9 respectively. This was observed despite the difference in many factors that could affect the cleanliness of the pipes. The RPM measurements were undertaken on the same date (Table 5.2), but interestingly the pipes on one site (1aH) were cleaned by air-scouring (Table 5.2) while the pipes on the other site (1bH) were not cleaned. One site was a loop point (1bH) and the other (1aH) was near a closed valve. Cleaned pipes had relatively less dirtiness, but in terms of the turbidity they were generating, they were similar - any turbidity above 5 NTU usually induces complaints. The tanks supplying these two sites were separate (Tanks 1 and 3). Similar phenomenon could be observed at the sites in suburb G, such as 2aG and 6bG. However, the sites from suburb E, 3aE and 8aE, had two significantly different ranking scores. It can be noted from Table 5.2, that the RPM testing dates for sites 3aE and 8aE were July 2008 and February 2009. It is possible that there could have been some (hydraulic, cleaning) activities in between these two dates that affected the ranking scores. This required further investigation (see paragraph 5.3.2).

Site 3bD had a higher initial turbidity than the turbidity obtained after flow velocity was increased. It was suspected that the initial turbidity was the result of sediment settled in a hydrant and therefore it was excluded from further discussion.

Table 5.3: RPM results summary and (RSP) ranking score points for all sites Zone M.

Site no.	Tank No.	Max. Tur. of first 5 min	Avg. Tur. of first 5 min	Max. Tur. of last 10 min	Avg. Tur. of last 10 min	Time to clear	Ranking Score (points)
1aH	1	93.5	78.3	85.9	43.9	1	12
1bH	3	18.7	8	7.5	3.4	39	9
2aG	3	5.0	4.0	9.1	6.8	9	8
3aE	2	2.2	0.8	0.5	0.4	7	2
3bD	2	Ignore the results (Initial turbidity larger than the turbidity when the flow velocity was increased)					
4aD	2	3.8	3	2.8	2.5	3	4
5aA	1	20	6.8	6.0	3.2	>60	10
6bG	1	5.6	5.1	49.8	17.4	>60	12
7bB	1	4.1	1.3	2.7	0.9	3	3
8a E	2	15.6	13.7	14.6	9.2	35	10
9aI	1	6.8	3.1	6.8	3	28	8
10bF	1	16.3	15.1	20.5	15	28	11
11b J	3	2.1	1.4	2.0	1. 2	11	5
12aC	1	16.2	10.9	10.9	7.2	27	10

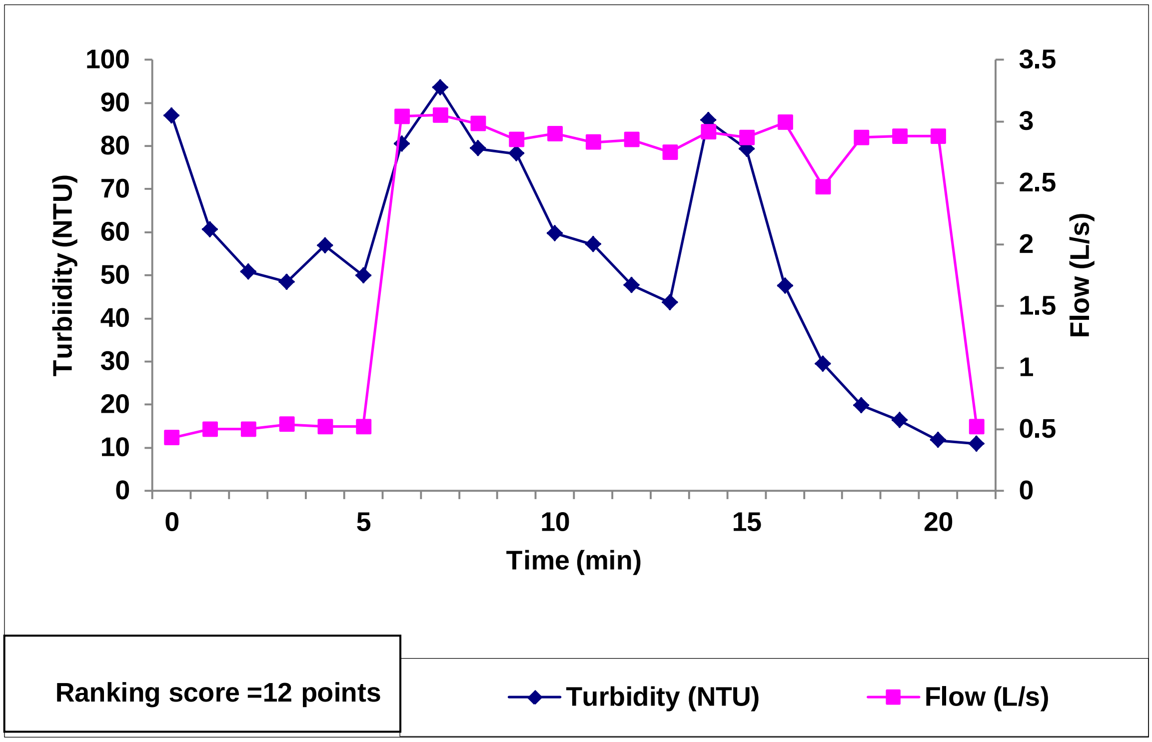


Figure 5.5: RPM results for site 1aH.

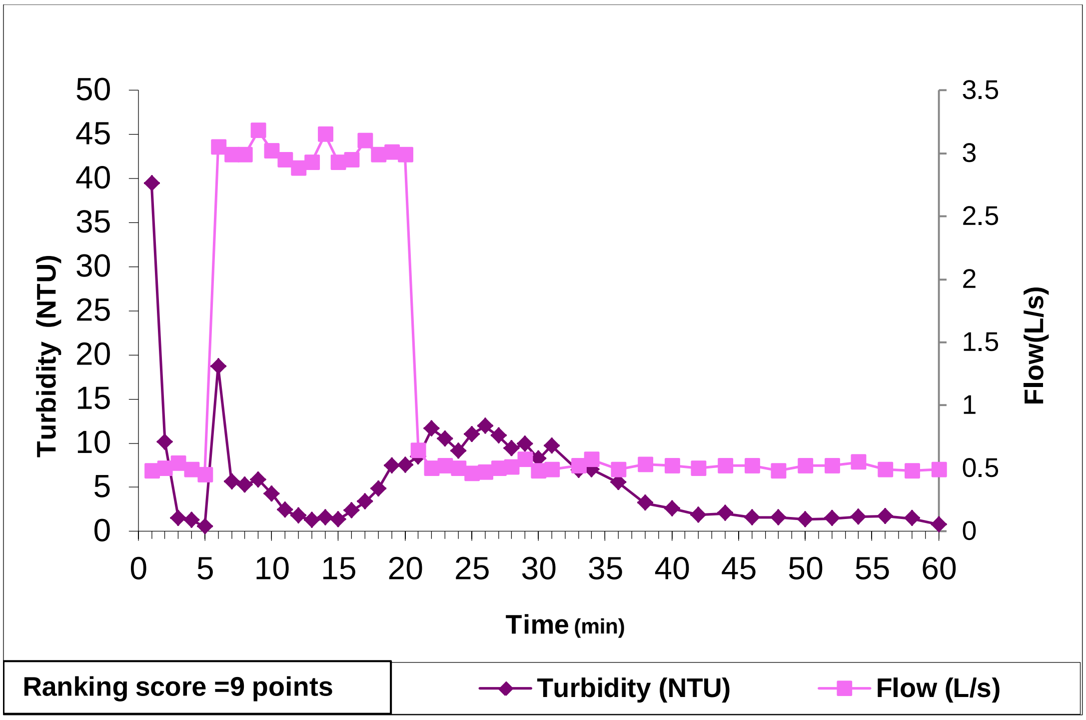


Figure 5.6: RPM results for site 1bH.

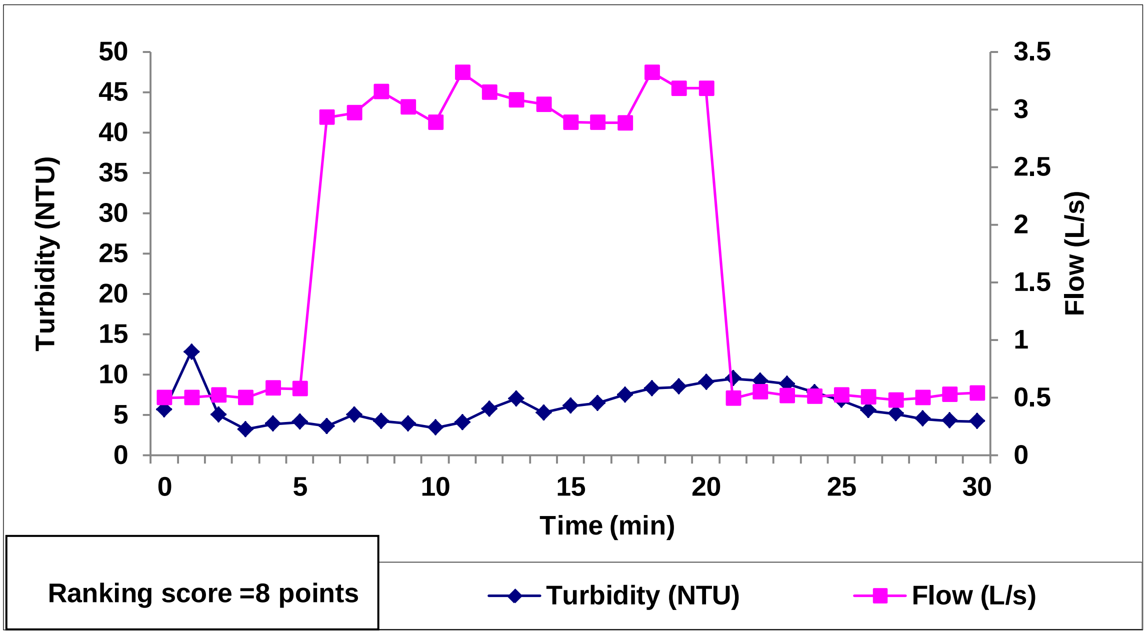


Figure 5.7: RPM results for site 2aG.

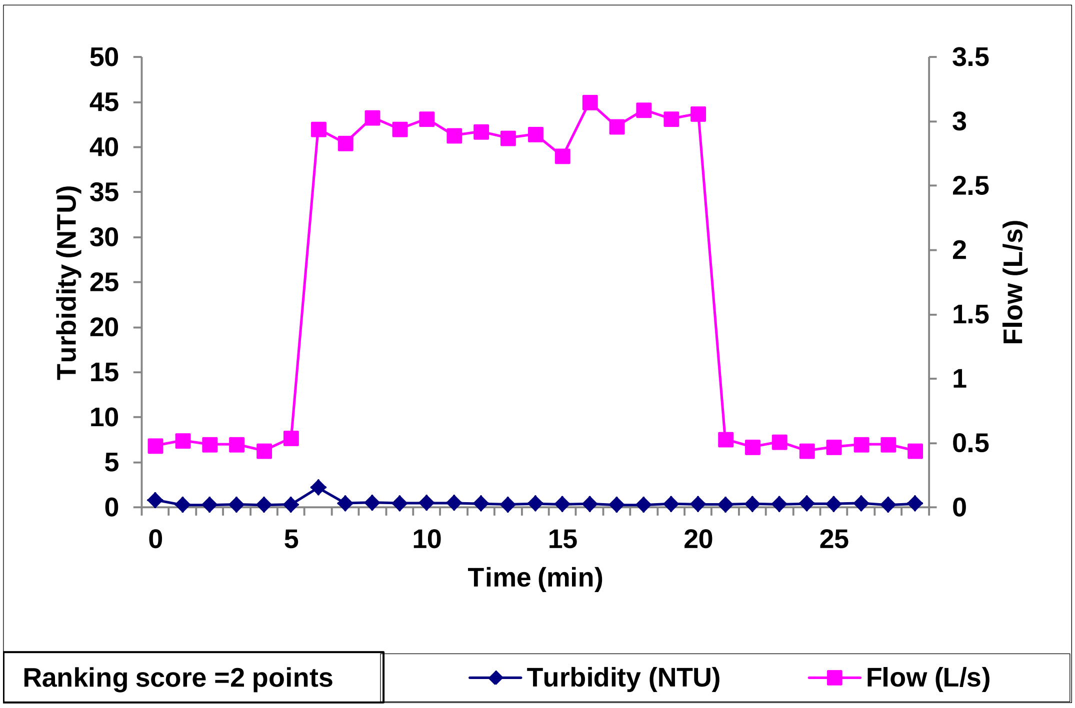


Figure 5.8: RPM results for site 3aE.

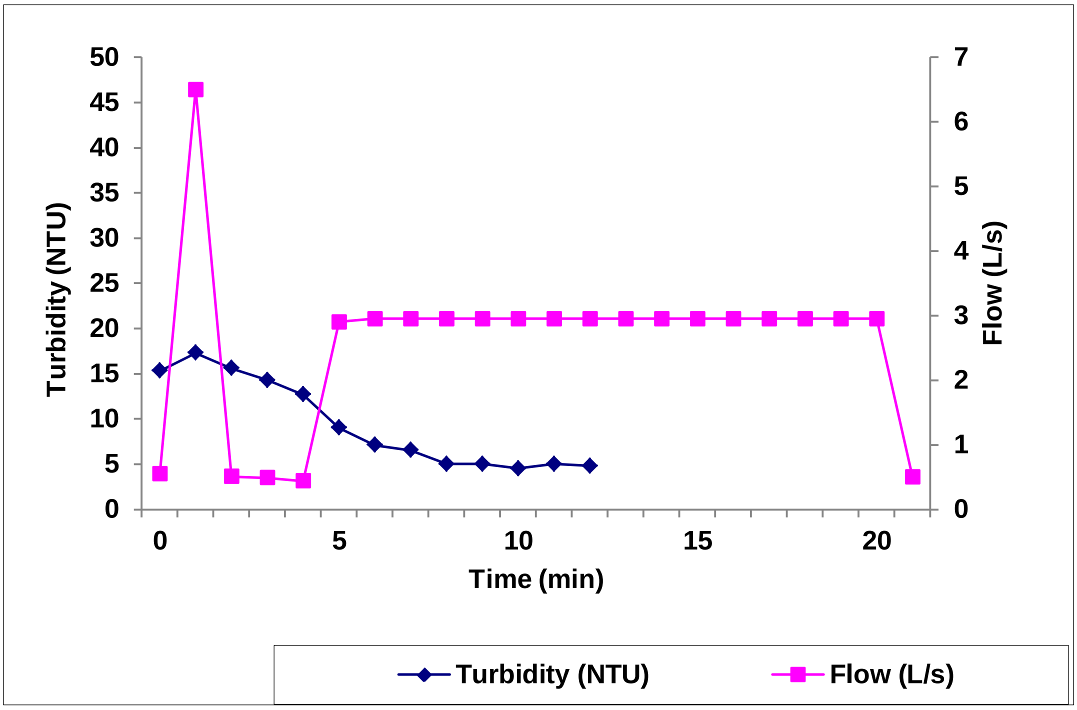


Figure 5.9: RPM results for site 3bD (Ignored).

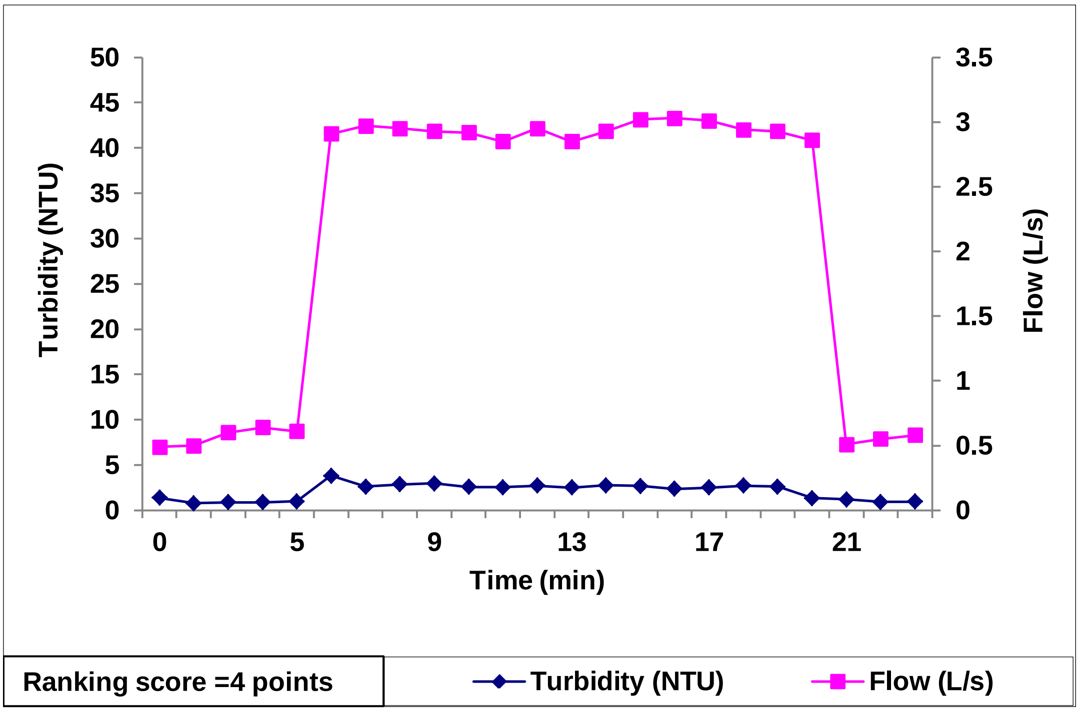


Figure 5.10: RPM results for site 4aD.

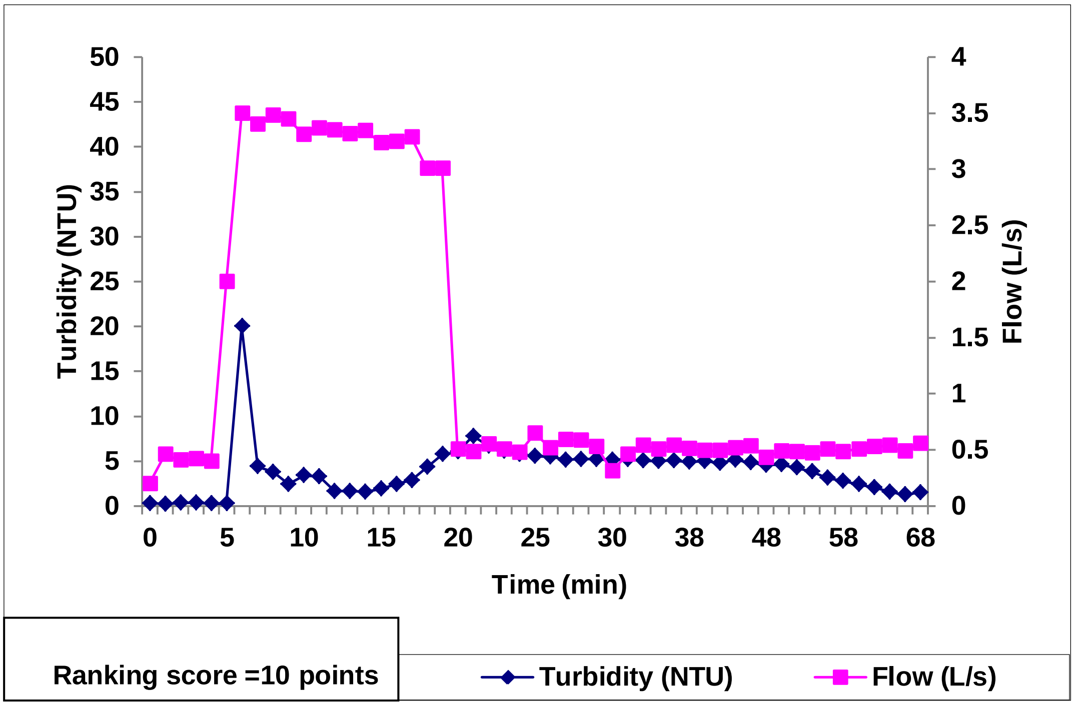


Figure 5.11: RPM results for site 5aA.

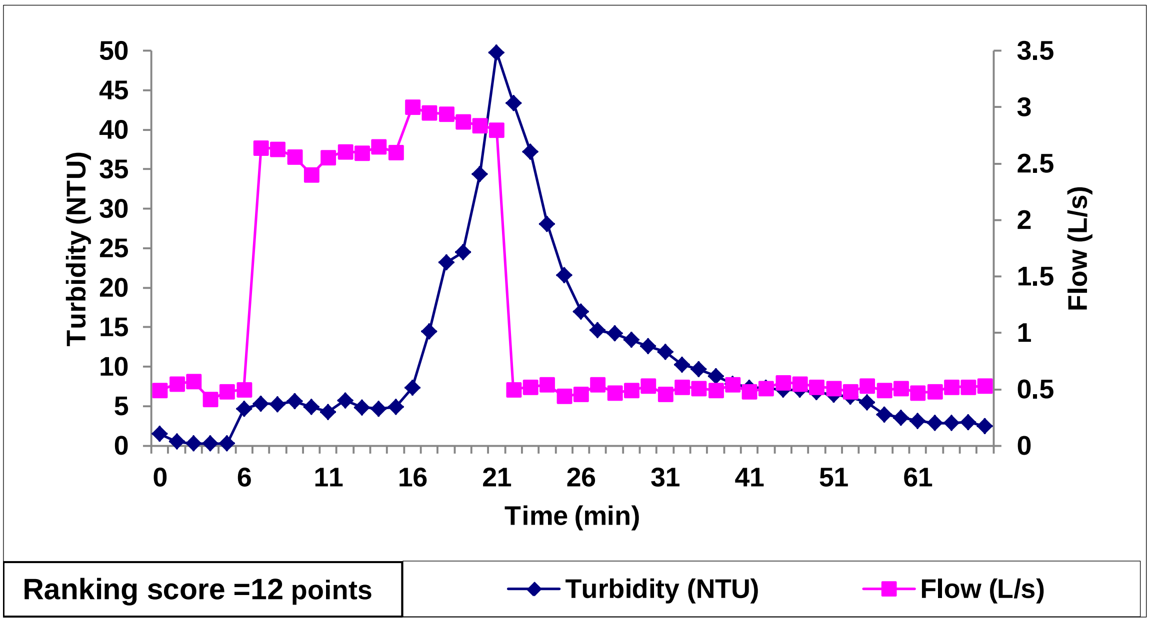


Figure 5.12: RPM results for site 6bG.

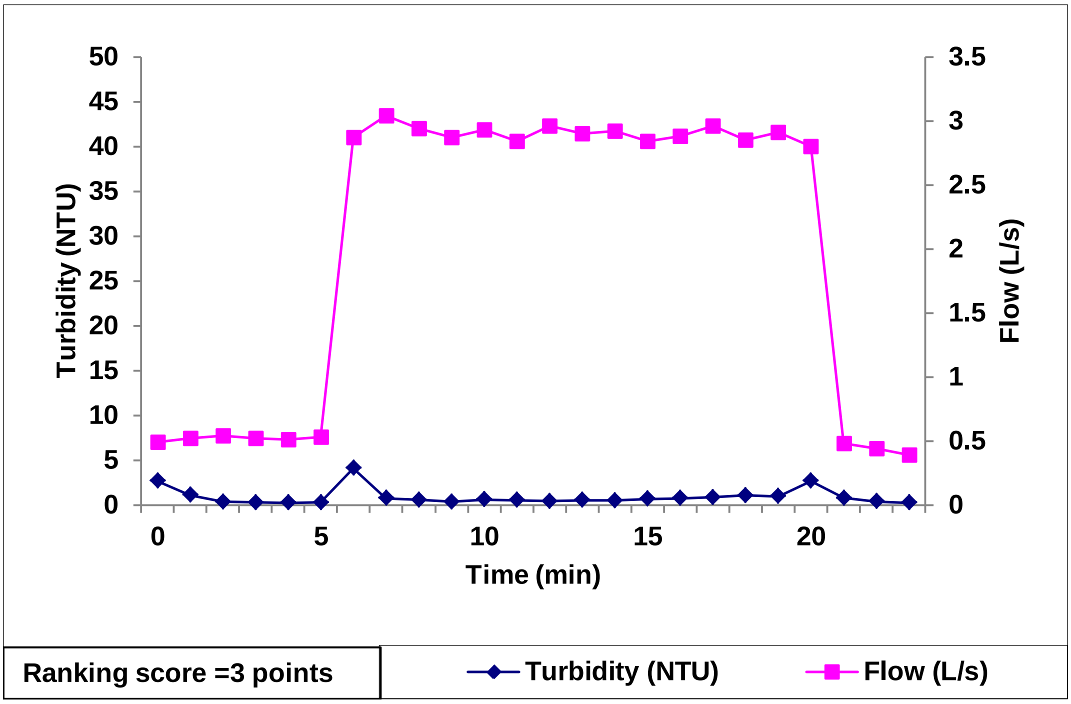


Figure 5.13: RPM results for site 7bB.

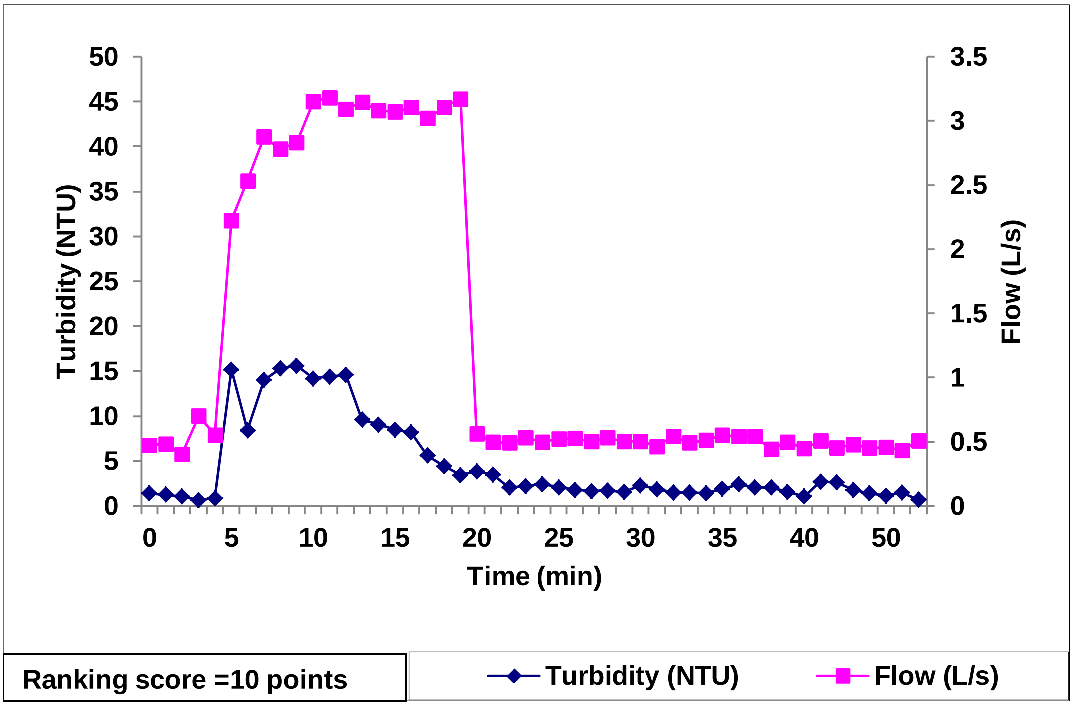


Figure 5.14: RPM results for site 8aE.

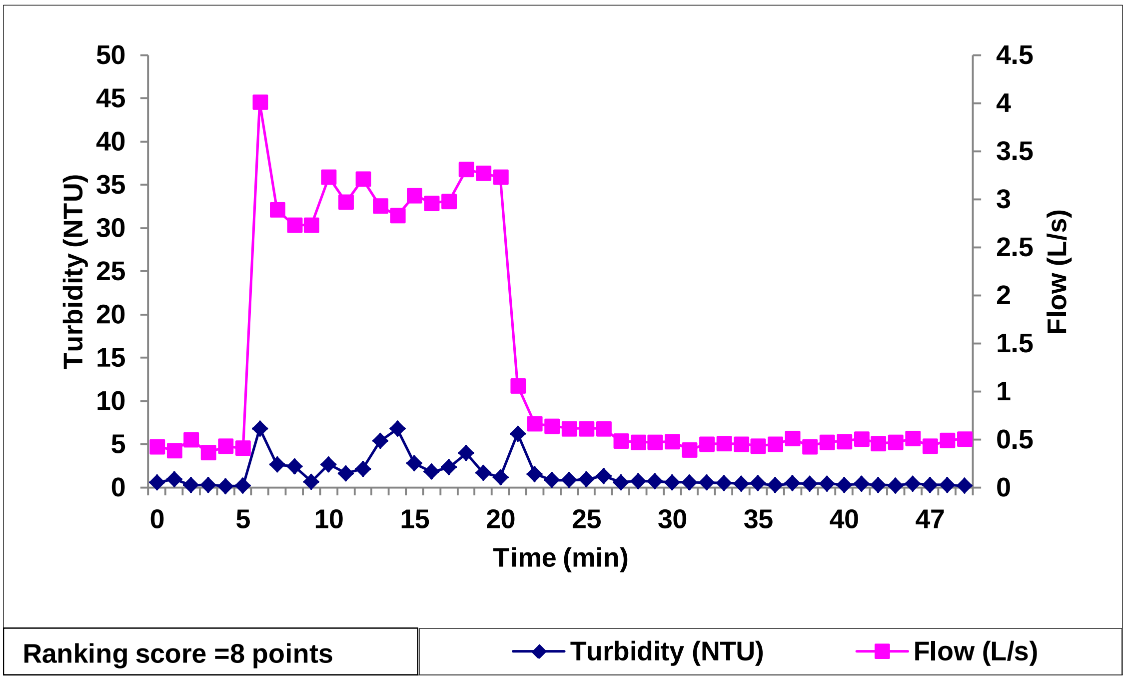


Figure 5.15: RPM results for site 9al.

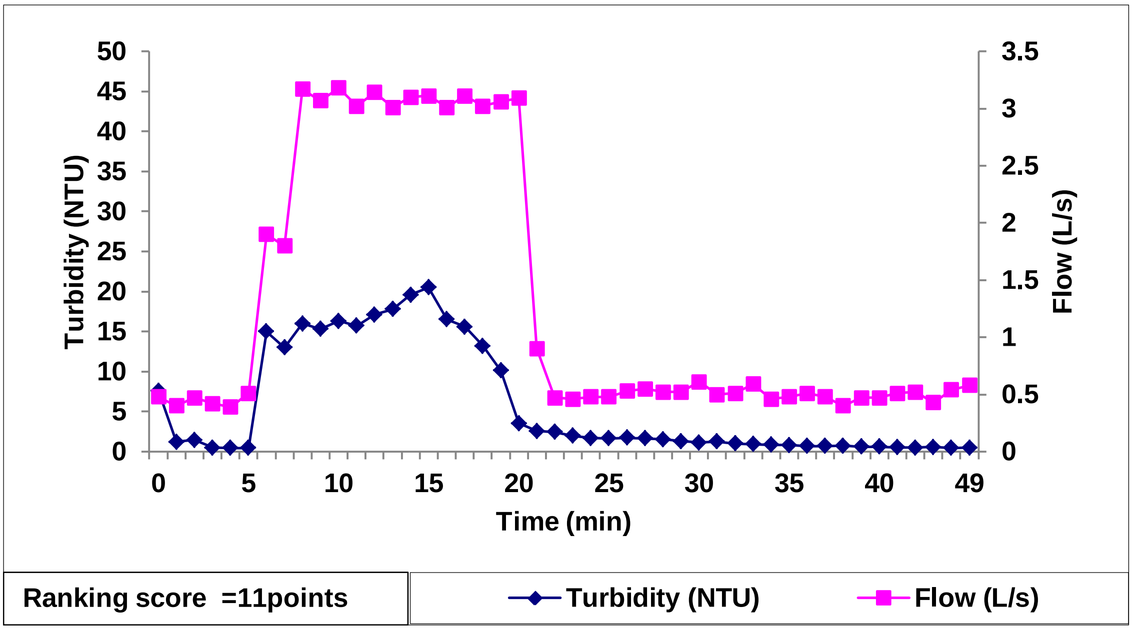


Figure 5.16: RPM results for site 10bF.

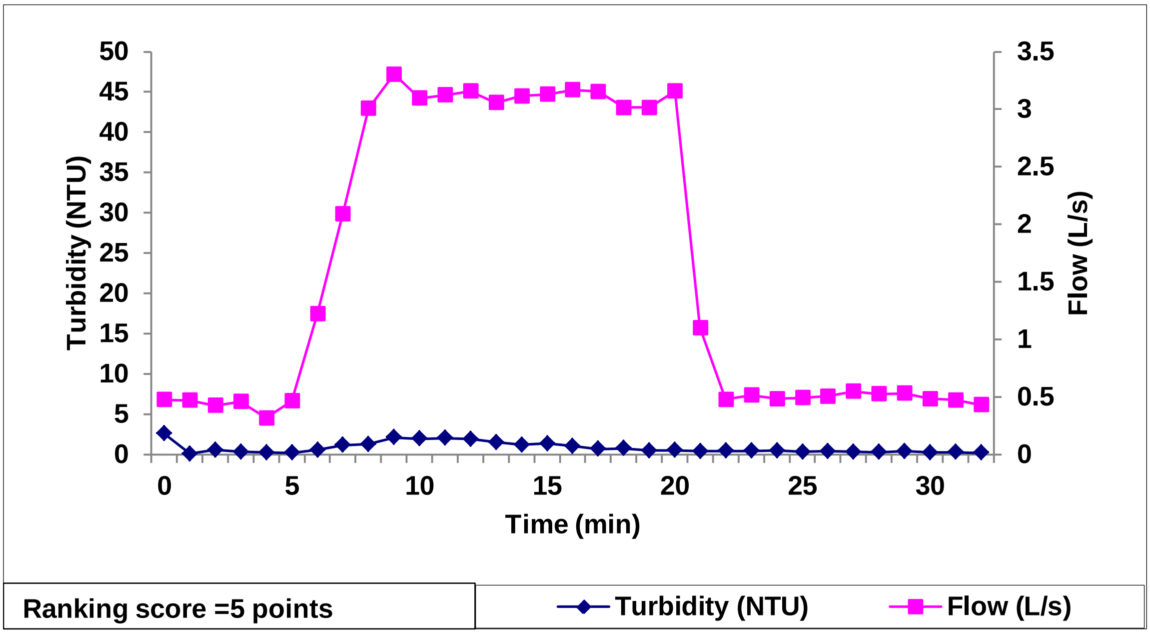


Figure 5.17: RPM results for site 11bJ.

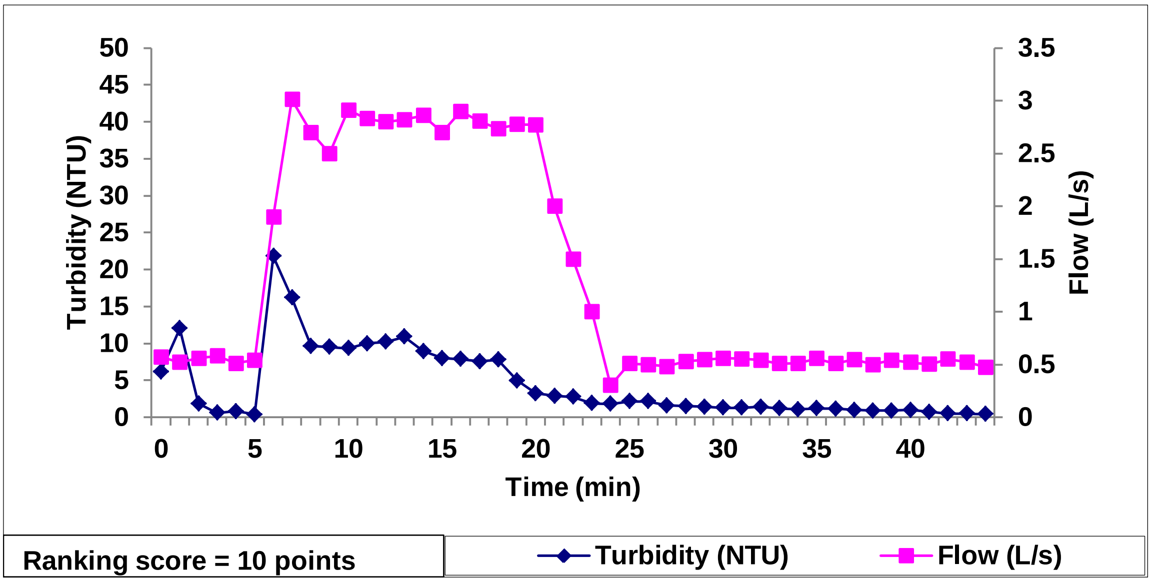


Figure 5.18: RPM results for site 12aC.

On the other three sites (2aG, 6bG and 1aH), the behaviour did not fit the expected pattern. The first was site 2aG shown in Figure 5.7. This site belonged to Tank 3, in which pipes were air-scoured in 2003. On this site, sediment did not resuspend within the initial period of increased flow regime, but it did occur at the end the period. Further, the turbidity returned to the base turbidity level within a short time (< 9 minutes) after the disturbance (increased velocity conditions) ceased. The behaviour on the second site, 6bG, was similar, as shown in Figure 5.12, but this site was not air-scoured. Therefore air-scouring could not have been the reason behind this phenomenon. The pipes on site 2aG and 6bG were in a dead-end and loop point respectively and despite being in the same suburb both of them were supplied from different tanks. Therefore, further investigation is needed to understand the underlying reasons which are beyond the scope of this thesis. Similar explanations can be made for site 1aH.

Some sites 9aI, 10bF and 12aC had a very low baseline turbidity and a long waiting period was required to achieve such a level of turbidity after the disturbance was stopped that made the time to clear longer and in turn the ranking score became unnecessarily high, although such turbidity would not usually cause any complaints. If the ranking score is to be used to understand the dirtiness and/or discolouration risk then a lengthy waiting period is not necessary. Therefore, a modification of the last criteria is required and will be dealt with in the next chapter.

In general the ranking score obtained from the RPM test was shown to measure the dirtiness or discolouration risk of the pipe, although some issues were raised regarding the interpretation of the turbidity profile produced from the controlled disturbance.

5.3.2 Relationship between Burst Pipe Events and Complaints with Ranking Score Points (RSP)

To determine whether there is a general correlation between ranking scores and burst pipe events or complaints/1000 persons, Table 5.4 was established. The number of burst pipes that occurred in each suburb for a six month (BP0.5Y) and one year (BP1Y) period prior to the RPM testing were determined. Complaints for the six month (C0.5Y) and one year (C1Y) periods before the RPM test date, along with the average number of complaints/1000 persons over five years (2003-2007) (C_{avg}5Y) for each suburb were calculated. The results are given in Table 5.4. Before starting the detailed analysis, a general view of the results is shown in Figures 5.19 and 5.20 and Table 5.4. It is very clear from Figure 5.19 that high ranking scores recorded a low number of complaints; although there were some instances that were dissimilar to this pattern. The same pattern was obtained even if it was related to complaints/1000 persons instead of complaints in Figures 5.19 and 5.20.

Figure 5.20 compares ranking scores with burst pipe events. A low number of burst pipe events should have shown a higher ranking score (RS), as the pipes were cleaned during the burst pipe event while more complaints were generated. In Figure 5.20, a low number of burst pipe events did not always show high ranking scores, possibly because the burst pipe events in adjacent suburbs affected the results or because the value of the ranking score was affected by complaints and burst pipe events together. To demonstrate such a relationship between events and complaints, complaints (Cavg5Y, C0.5Y, and C1Y) were plotted, along with the burst pipe events (BP0.5Y and (BP1Y) against ranking scores for each RPM site in Figure 5.21.

Table 5.4: Summary of number of burst pipes events, complaints and ranking scores.

Site number - suburb name	Water sources	Ranking score (points)	Date of RPM work	Com./1000 /year 2003-2007	Number of complaints		**No. of burst pipe		
				$C_{avg}5Y$	C0.5Y	C1Y	July-Dec. 2007	Jan.-June 2008	July-Dec. 2008
1aH	Tank 1	12	9/7/2008	2.54	2	5	1	0	
1bH	Tank 3	9	9/7/2008	2.54	2	5	1	0	
2aG	Tank 3	8	9/7/2008	1.9	1	1	3	4	
6bG	Tank 1	12	9/7/2008	1.9	1	1	3	4	
3aE	Tank 2	2	9/7/2008	7.37	38	41*	0	0	
8aE	Tank 2	10	19/2/2009	7.37	4	10*		0	1
4aD	Tank 2	4	9/7/2008	10.76	106	111	9	6	
5aA	Tank 1	10	9/7/2008	2.47	5	10	7	3	
7bB	Tank 1	3	9/7/2008	4.67	6	8	6	6	
9aI	Tank 1	8	19/2/2009	1.25	2	6		0	1
10bF	Tank 1	11	19/2/2009	3.45	3	5		2	1
11b J	Tank 3	5	19/2/2009	4.40	0	5		1	0
12aC	Tank 1	10	19/2/2009	4.45	5	12		5	5

(C0.5Y) Complaints six months before RPM

(C1Y) Complaints one year before RPM

($C_{avg}5Y$) Complaints/1000 persons as average of five years (2003-2007)

***This represents complaints made at a different period for 3aE and 8aE, because RPM tests for these sites were conducted on different dates.**

**** depending on the date of RPM performance the number of burst pipes was calculated**

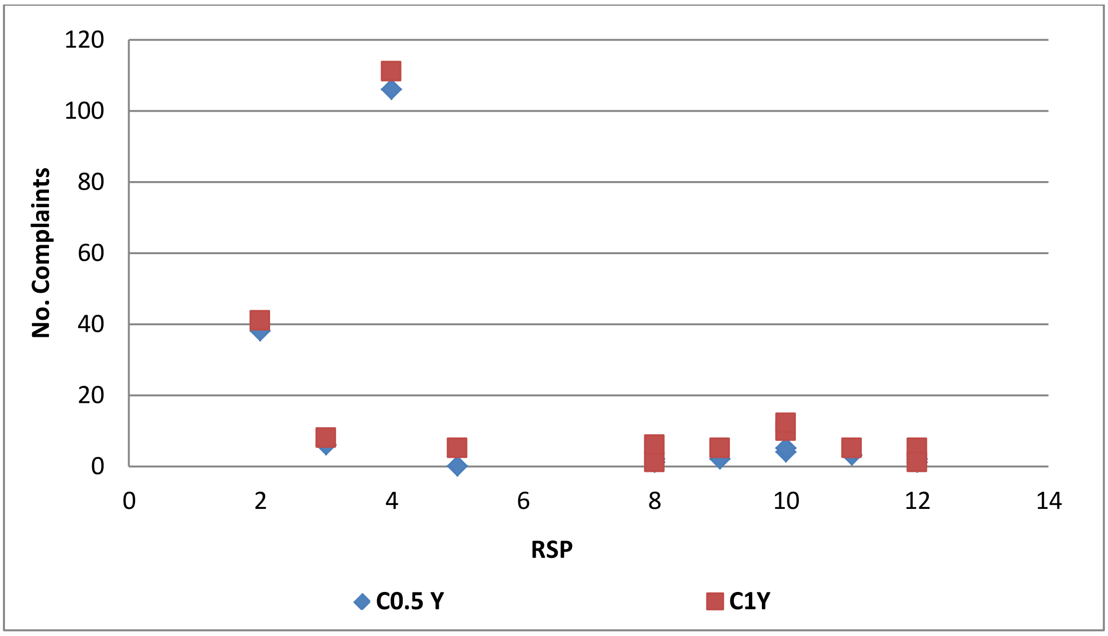


Figure 5.19: Relationship between the RPM ranking scores (RS) and number of complaints in a six month (C0.5Y) and one year (C1Y) period prior to the RPM test date.

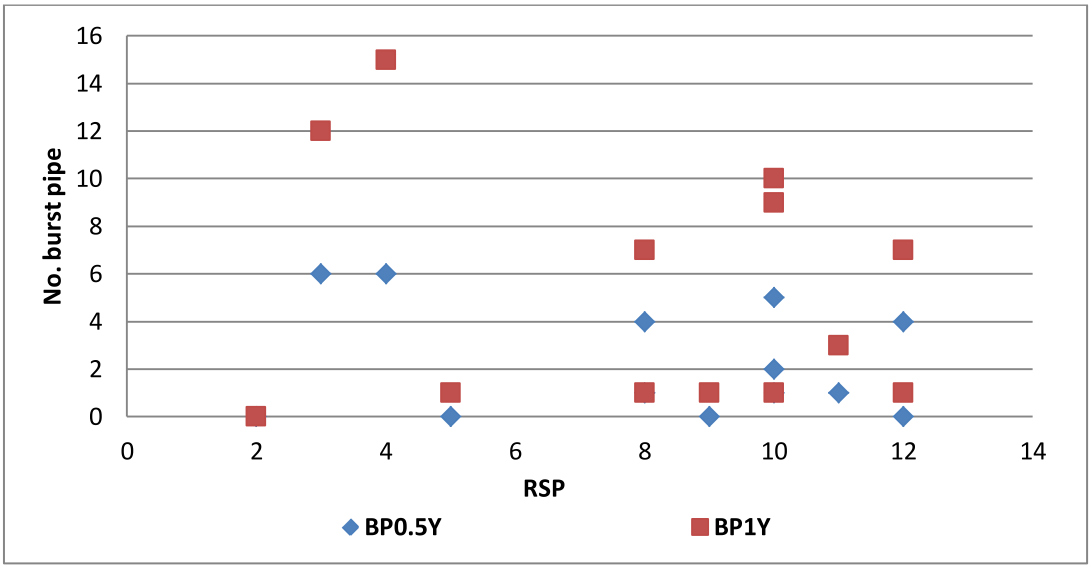


Figure 5.20: Relationship between the RPM ranking scores and number of burst pipes events for a six month (BP0.5Y) and one year (BP1Y) period prior to RPM performance date.

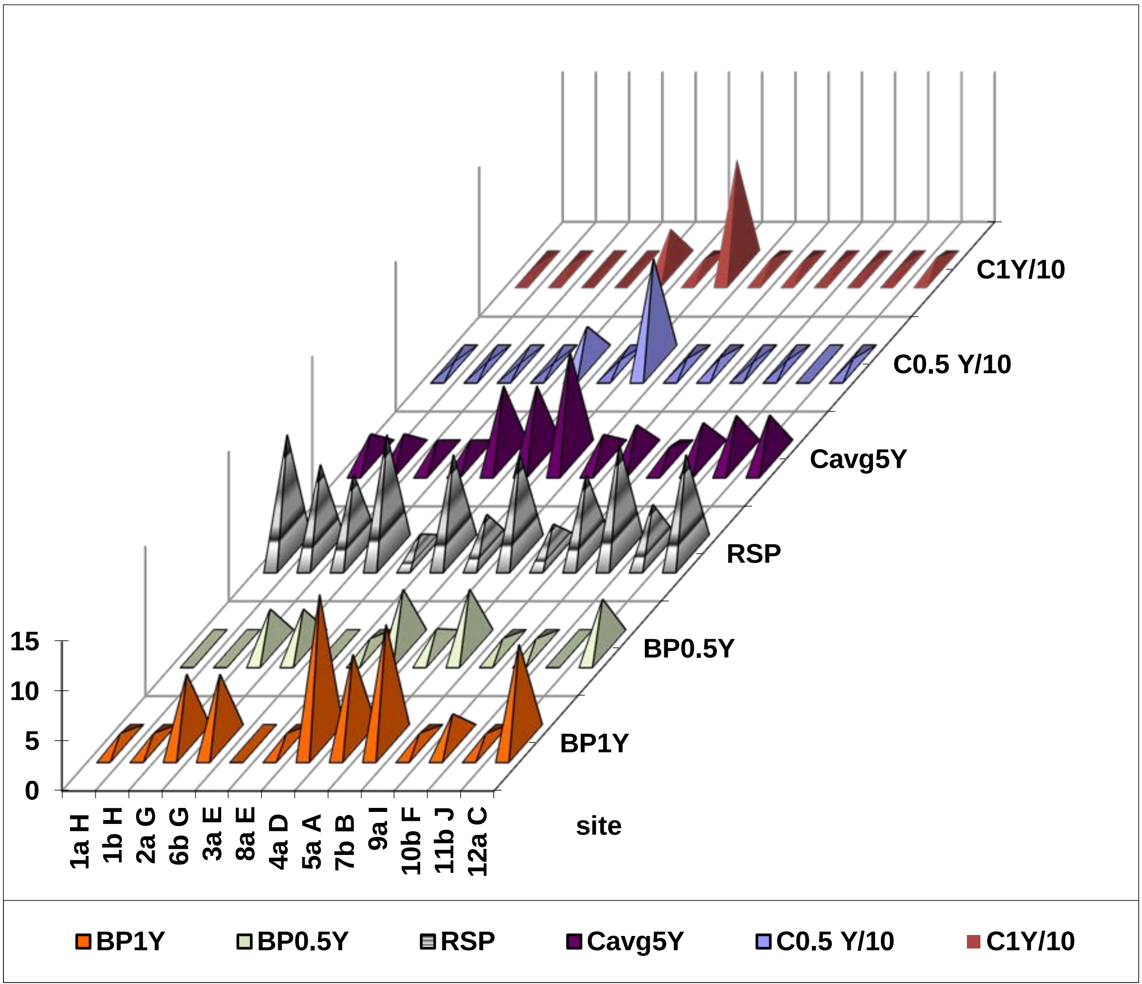


Figure 5.21: Relationship between ranking scores in points (RSP), with complaints/1000 persons/year as an average taken over five years (2003-2007) (C_{avg}5Y); the number of complaints in a six month (C0.5Y) and one year (C1Y) period before the RPM test date, and the number of burst pipes events over a six month (BP0.5Y) and one year (BP1Y) period before the RPM test date.

Figure 5.21 and Table 5.4 show a high number of complaints for suburb E. The average number of complaints over five years (C_{avg}5Y) was 7.37 (per 1000 per year) and the total complaints for six months (C0.5Y) and one year (C1Y), before the RPM test date of the site 3a were 38 and 41. This site was clean, and recorded a ranking score of 2 points in July 2008. This fits with the rationale that the more complaints, the cleaner the pipes. According to an earlier explanation however, there should have been some burst pipes events within the suburb or in the adjacent suburb to affect the complaints. For a period of one year prior to the RPM test date, there were no burst pipe events (BP1Y), but in downstream suburb D there were 15 (8 of them belonging to sub-system M) which should have caused complaints and subsequent cleaning of the pipes in suburb E. Figure 5.22 locates the relative position of site 3aE with the locations of burst pipe events in suburb D. It is clear from the figure that burst pipe events are within close proximity of site 3aE. Similarly the pipe type, i.e., the through pipe, makes the results more understandable as this can be greatly affected by burst pipe events.

The second site, 8aE, had a pipe with closed valve at the end (i.e., a pipe with a dead-end); which recorded a ranking score of 10 points (RS = 10 points) in February 2009. The suburb also had a lower number of complaints (C1Y = 10). The dead-end pipe might not have been affected by burst pipe events, unlike the through pipe. High burst pipes events in the adjacent suburb D (BP1Y = 8), which included five incidents of leaky (cracked) pipes would also not have impacted upon the dirtiness of the site at 8aE. Therefore, the pipe type may have some implications with regard to dirtiness; thus further and thorough analysis is required (see Section 5.3.5).

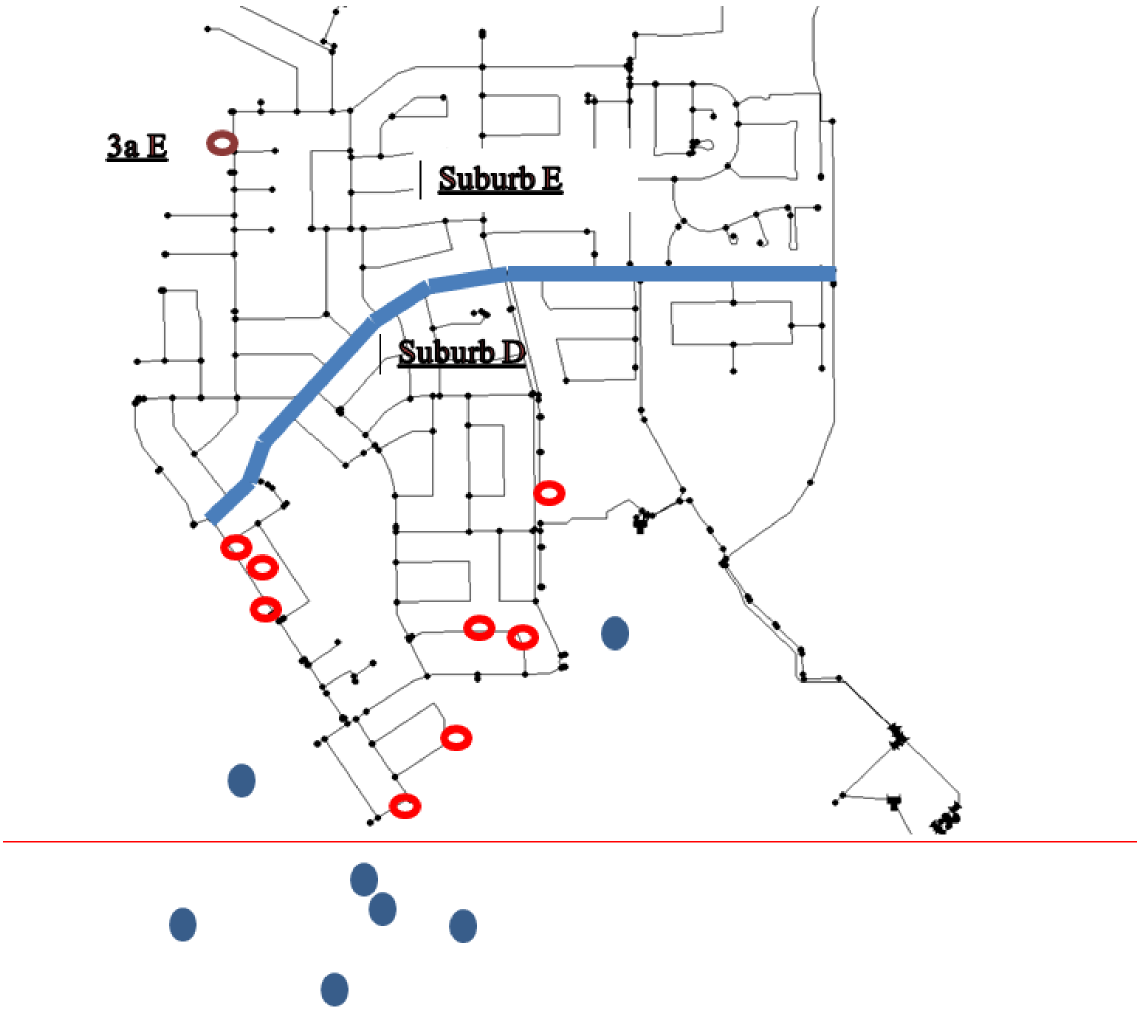


Figure 5.22: Location of site 3aE, with 15 burst pipes in suburb D, seven of which (blue solid circular shape) were not in the M sub-system.

The low ranking score of 4 points at site 4aD indicates that the site had clean pipes. If the pipes were clean, one would expect a lower number of complaints. However, if one compares the complaints in the period prior to the RPM test, the results show the opposite. The number of complaints in the six month (C0.5Y) and one year (C1Y) periods prior to the RPM test date were 106 and 111 respectively, and **(**C_{avg}5Y) = 10.76 per 1000. There were also a high number of burst pipe events; BP0.5Y and BP1Y were 9 and 15 respectively. It is very clear that the number of burst pipes, along with the Water Corporation's policy affected the results regarding clean pipes (low RSP). Here the data fits well with the proposed theory that burst pipe events cause sediment to move from the pipes to the customers, eventually leading to complaints. When customers complain, the Water Corporation cleans the nearby pipes, for more than 5 minutes if necessary, making them even cleaner than before.

The results from suburb B site 7b show clean pipes (RS =3 points). A high number of burst pipes events, or high complaints before the RPM measurements could explain the cleanliness of the pipes. Burst pipe events in the suburb were 6 and 12 in the previous six month and one year periods respectively (BP0.5Y=6 and BP1Y=12). However, this pipe had dead-ends, hence it should have been dirtier than it actually was, implying that burst pipes events have little impact upon the dirtiness of the site. Therefore, the only explanation could be the number of complaints, i.e., the complaints should be higher, but they were relatively low (C1Y =8) in the suburb. The most probable reason is that this site had experienced frequent complaints (3/8=37.5% of all the complaints in the suburb), as shown in Figure 5.23, and that personnel from the Water Corporation cleaned this location (flushing near the complaints locations) as a normal operational protocol, which was prior to the RPM date. Therefore, this pipe required another RPM trial to check the cleanliness of the pipe. This was carried out in the second batch RPM approximately one and a half years later, as discussed in the next section.

Figure 5.23: Map of site 7bB (July 2008) location with eight related complaints, during 10 July 2007 to 10 July 2008.

The results of the RPM testing for site 5a in suburb A showed a dirty pipe (ranking score = 10 points). This implies that the site was either affected by the burst pipes events, or that complaints were not within close proximity of the site in the few months prior. However, suburb A recorded a high number of burst pipes before the date of the RPM; in the previous six months and one year they were equal to 3 and 10 respectively. If there were many burst pipes events one would expect a lower ranking score and higher complaints. Nevertheless, site 5a recorded a ranking score of 10 and a low number of complaints; C1Y = 10, (Cavg5Y) = 2.47. Site 5a contained a dead-end pipe and the area of suburb A was large (it served 19,735 persons, i.e., 0.5 complaints/1000 persons). The large area of suburb A and the corresponding distance between the burst pipe and the RPM tested pipe or the pipe type (dead-end in this case) would have contributed to a higher ranking score. Close inspection of burst pipes data showed that just one of all the burst pipes was close to site 5aA, it was shown as a relatively small leak on 19/10/2007, whilst the RPM for 5aA was on 10/7/2008 (nearly nine months after the date of the leak) as shown in Figure 5.24.

Figure 5.24: Location of site 5aA with 10 burst pipes one year prior to the RPM date.

As suburb J was small and had been under construction since 2003, there were a lot of disturbances which caused a high number of complaints; over a five year period the average number of complaints ($C_{avg}5Y$) was 4.40/1000 persons and complaints within a one year period prior to the RPM measurement (C1Y) were 5. In spite of only one burst pipe event in the one year before the RPM (BP1Y =1) and the policy of the Water Corporation (i.e., pipe cleaning), site 11b recorded a low ranking score (RS =5). As indicated earlier, suburb J was under construction within the study period, hence many complaints were recorded, and in the process the pipes remained cleaner.

Interestingly, the results showed that the suburbs recording a higher number of complaints showed lower ranking scores “RS”, i.e., pipes were found to be clean. Obviously, a higher number of burst pipes resulted in a higher number of complaints. However, the operational method of the Water Corporation of Western Australia (WCWA) is to deal with discoloured water events by flushing the nearest hydrant for a short period of time at a high flow rate until the water becomes clear. If frequent discolouration events occurred or complaints were received then turbid material present in the pipe would have been flushed. In contrast, the suburbs which had registered a lower number of complaints and low burst pipes events did not have a flush out of the turbid material present in the pipes, resulting in a higher ranking score or dirtier pipes. Therefore, dirtiness did not play a key role in affecting the complaints; pipes become cleaner where a suburb experiences frequent complaints or burst pipe events.

5.3.3 Second Batch RPM Results

On 18/2/2010, the second RPM batch was processed to confirm the results obtained from the first batch. The results are illustrated in Table 5.5. All sites had the same results except 7bB which recorded a ranking score of 3 points in the first batch of RPM tests, but in the second batch it recorded 10 points. As explained earlier, this pipe was not affected by a burst pipes events, rather by complaints from adjacent addresses. The number of complaints made in a one year period prior to the RPM test date was just 6. Only three were made within the same area with one made approximately one year prior and the remainder approximately 8.5

months prior. From these site results one gains an understanding that the period necessary to accumulate sediment to dirty levels in a pipe is definitely less than one and a half years or possibly less than eight months, as illustrated in Figure 5.25. The results of site 7bB confirm that the impact of air-scouring does not last longer than one and a half years. However, well- designed experiments are needed to confirm the period within which the impact of air-scouring lasts as this is beyond the scope of the thesis.

Kiwa Water Research (Netherlands) identified that their well-filtered drinking water networks displayed a constant accumulation of sediment over time for a number of years (5-10 yrs). In Australia, Melbourne networks rapidly move to a steady state (within 2-4 weeks) and Croydon networks operate at a steady state after less than 2 weeks, (Cromwell and Ryan, 2007, Cromwell et al, 2007).

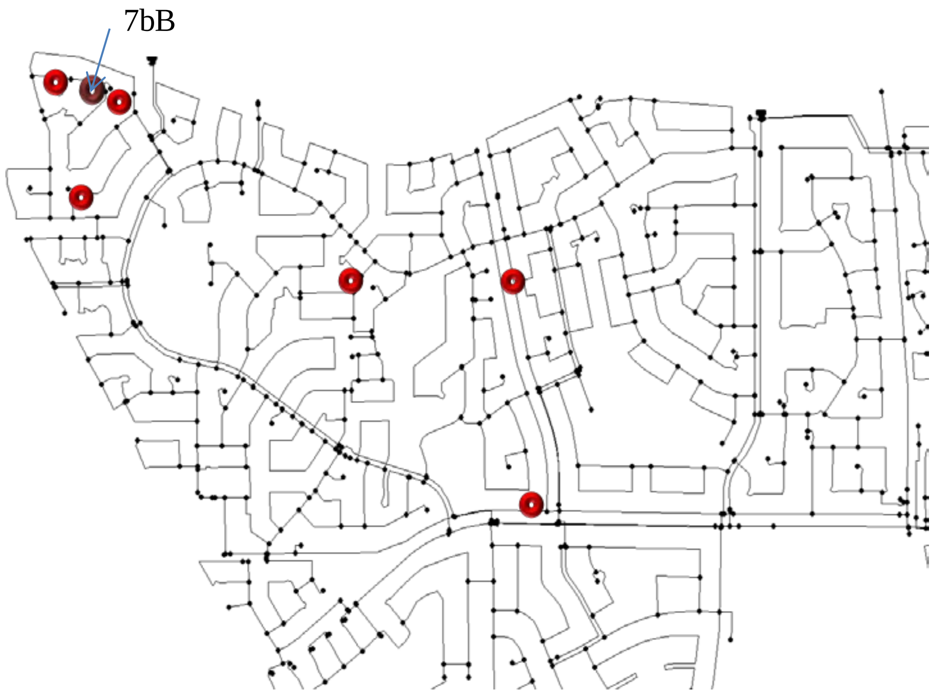


Figure 5.25: Map of site 7bB (Feb 2010) location with six related complaints, from 18 Feb 2009 to 18 Feb 2010.

Table 5.5: RPM second batch results summary and ranking score points (RSP) for all sites.

Site no. , Batch no.	Tank No.	Max. tur. of first 5	Avg. tur. of first 5	Max. tur. of last 10	Avg. tur. of last 10	Time to clear	RSP	
							Zone M	Work date
1aH, 1st	1	93.5	78.3	85.9	43.8	1	12	9/7/2008
1aH, 2nd	1	78.4	67.6	196	72.7	1	12	18/2/2010
4aD, 1st	2	3.8	3	2.8	2. 5	3	4	9/7/2008
4aD, 2nd	2	3.3	3	3.7	3.3	40	6	18/2/2010
5aA, 1st	1	20	6.8	6.0	3.2	>60	10	9/7/2008
5aA, 2nd	1	38.7	23.9	10	6.4	60	13	18/2/2010
7bB, 1st	1	4.1	1.3	2.7	0.9	3	3	9/7/2008
7bB, 2nd	1	33.3	22.5	19.7	7.3	1	10	18/2/2010
8aE, 1st	1	15.6	13.7	14.6	9.2	35	10	19/2/2009
8aE, 2nd	1	5.8	3.7	6.9	5	40	8	18/2/2010

To confirm the relationship between ranking scores and complaints, the ranking scores and complaints/1000 persons obtained after one and six months of RPM test dates were compared in Table 5.6. The results confirm that the number of complaints did not necessarily follow any specific pattern and this again confirms that hydraulic events (either emergency cleaning or burst pipes) have the most influence on complaints. Further, the results from the same site indicate that if the customers living around the area do not experience dirty water incidents, the dirtiness of the pipes increases, resulting in a very high ranking score within just one and a half years.

Table 5.6: Relationship between complaints/1000 persons and ranking score.

Site no.	Water sources	RSP	Date of RPM work	Com./1000 persons		com		com	
				6 month after work	1 month after work	2008	2009	6 month after work	1 month after work
1a H	Tank 1	12	9/7/2008	1.36	0	7	3	5	0
1b H	Tank 3	9	9/7/2008	1.36	0	7	3	5	0
2a G	Tank 3	8	9/7/2008	1.07	0.10	10	4	11	1
6b G	Tank 1	12	9/7/2008	1.07	0.10	10	4	11	1
3a E	Tank 2	2	9/7/2008	0.98	0	9	24	4	0
8a E	Tank 2	10	19/2/2009	2.70	0	9	24	11	0
4a D	Tank 2	4	9/7/2008	1.72	0.13	18	53	13	1
5a A	Tank 1	10	9/7/2008	0.16	0	9	15	3	0

7b B	Tank 1	3	9/7/2008	0.63	0.31	10	6	6	3
9a I	Tank 1	8	19/2/2009	2.17	0	4	22	17	0
10b F	Tank 1	11	19/2/2009	2.25	0	5	22	18	0
11b J	Tank 3	5	19/2/2009	0.31	0	5	2	1	0
12a C	Tank 1	10	19/2/2009	0.71	0.12	17	17	6	1
1a H	Tank 1	12	18/2/2010		0.27			*	1
4a D	Tank 2	6	18/2/2010		0			*	0
5a A	Tank 1	13	18/2/2010		0			*	0
7b B	Tank 1	10	18/2/2010		0			*	0
8a E	Tank 2	8	18/2/2010		0			*	0
* No available data									

5.3.4 Relationship of RPM Ranking Score (RS) to Supplier Tank

The result for the initial turbidity for site (1a) in suburb H, which belonged to Tank 1's water zone was very high (93.5 NTU), but by decreasing the flow it reached 11 NTU after 1 minute, indicating that the initial turbidity was due to sediment accumulated in the hydrant point shown in Figure 5.5. This site was yet to be air-scoured. Suburb H recorded a low number of complaints; C1Y=5 and **(**C_{avg}5Y) =2.54/1000/year. However, the RS of this site was equal to 12 points, implying a high level of dirtiness. This in some way disproves the theory that dirtier pipes always result in a higher number of complaints; however it is also true that some hydraulic events are necessary to instigate complaints. However, suburb H registered only one burst pipe. Possibly the pipes in this region had not been flushed for any emergency or planned cleaning activity. This means that the site incurred an 80% risk of discoloured water. The second site, (1b) was located in suburb H also, but it was supplied with water from Tank 3. There was a sudden increase in turbidity followed by a decrease, and the time required to reach initial turbidity was less than 39 minutes, as shown in Figure 5.6. This means that the site had a 60% risk of discoloured water.

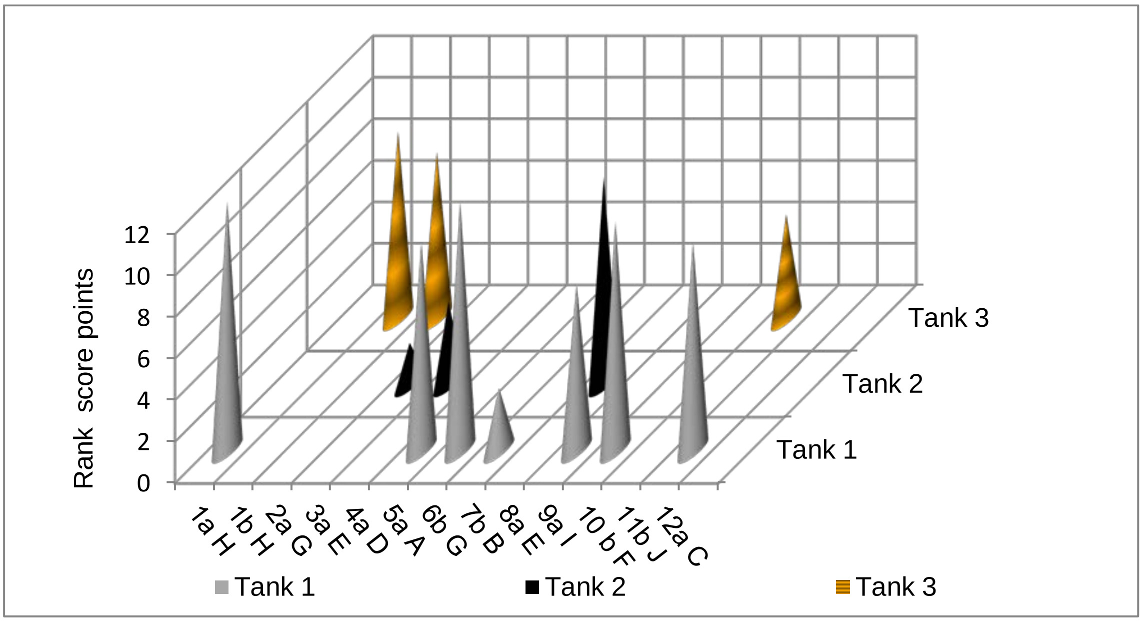


Figure 5.26: Relationship between batch-1 RPM results and supplier tank.

As all the tanks were receiving water from the same source, the difference in dirtiness of the pipes in suburbs supplied by different tanks was not expected. The only possible exception may have been the pipes in Tank 3 which were cleaned by air-scouring in 2003. If air-scouring had a lasting impact from 2003 until 2008 it would have been seen in the results. According to an earlier explanation, the period needed for sediment accumulation is less than one and a half years. It should therefore follow that air-scouring would not have had any impact. Above all, since the hydraulic events or complaints were found to influence the levels of dirtiness, it is highly unlikely that there would be a difference in dirtiness between the tanks. Figure 5.26 confirms that there was no relationship between ranking scores and the supply tank. The average (minimum - maximum) ranking scores for Tanks 1, 2 and 3 were 9 (3-12), 5 (2-10), and 7 (5-9) respectively which did not indicate any relationship to air-scouring. The results confirm that there was no relationship between the supplier tank and the dirtiness of the pipes.

5.3.5 Relationship of RPM Ranking Score Points (RSP) to Pipe Type

To understand the relationship between the ranking scores and the pipe type, Figure 5.27 was drawn. It is clear from Figure 5.27 that there is a positive relationship between the pipe type and the ranking score (RS). For example, the through pipes gave lower ranking scores than the dead-end pipes; both sites 3a and 8a were in suburb E, but the types of pipe were different. The through pipe recorded 2 points while the dead-end pipe recorded 10 points. The average ranking scores for through pipes, loop pipes and dead-end pipes were 3, 8, and 10 respectively. It can be seen that the results of both dead-end and loop pipe were close to each other, considering other factors such as the location being near to the place of complaints or burst pipes, as discussed for site 7b. On different dates, 7b recorded different ranking scores; 3 points for the first batch in July 2008 and 10 points for the second batch in February 2010. The results therefore indicate that different pipe types give different results if all other conditions are kept the same. The results can be confirmed if two pipes are selected: both being from the same area but of different types.

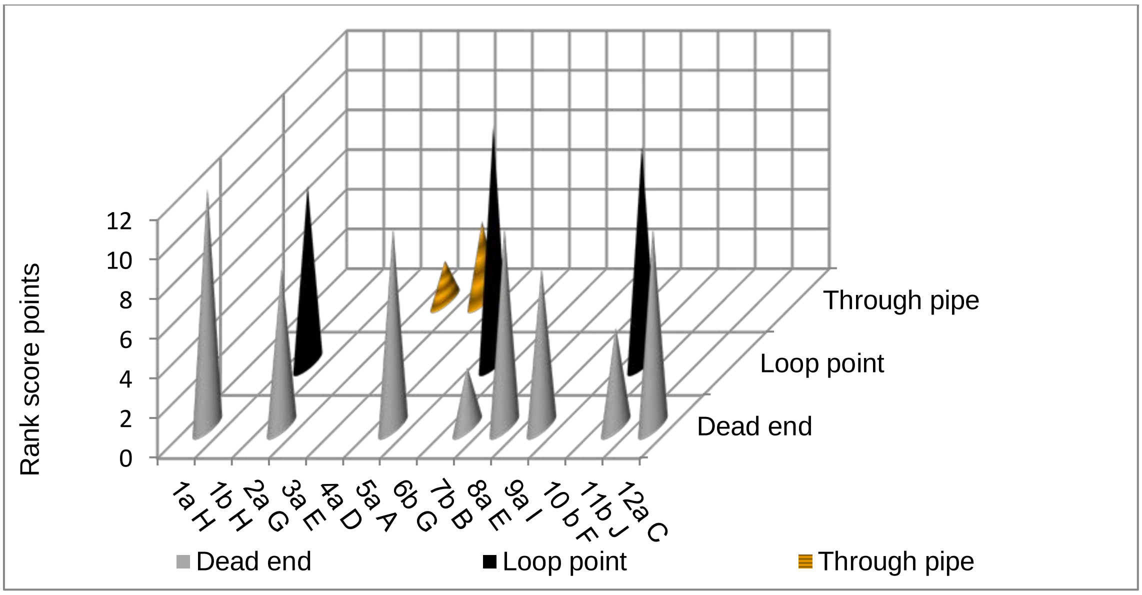
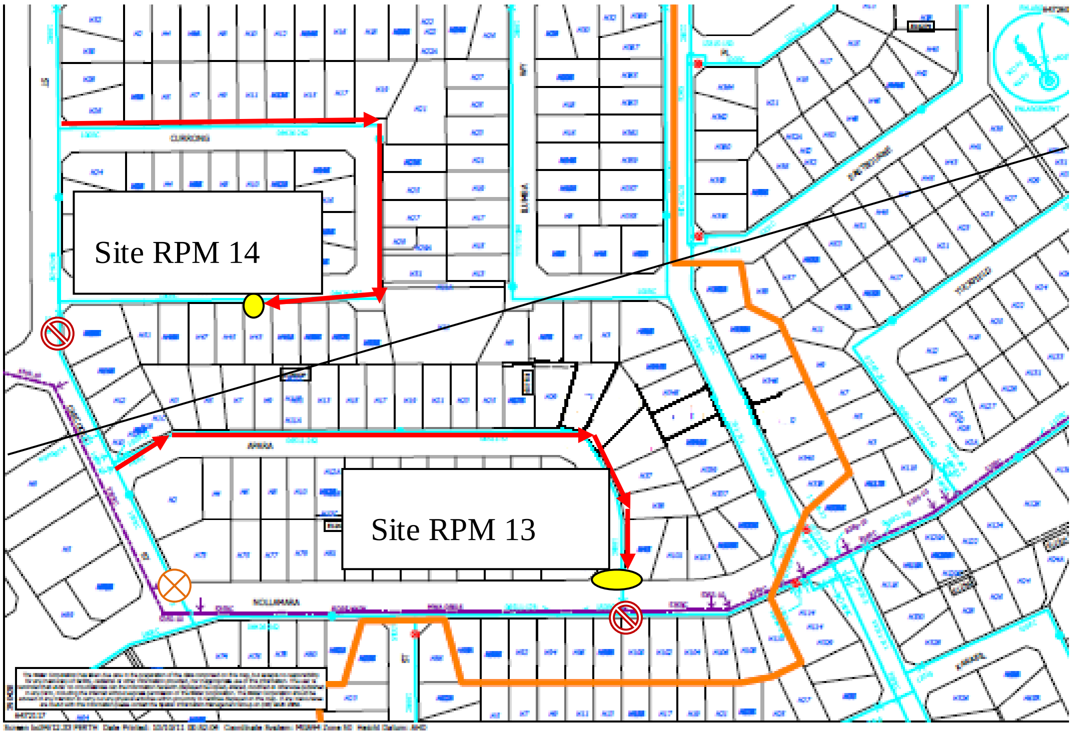


Figure 5.27: Relationship between batch-1 RPM results and pipe type.

Batch-3 RPM contains two sites belonging to the same area, with one street between them but each one having different pipe types. The two sites were selected as a through pipe site (site 13) and a loop pipe site (site 14); both located in suburb D within same area, as shown in Figure 5.28.

The RPM results are illustrated in Figures 5.29 and 5.30. The evaluation of the results of both sites is given in Table 5.7. As illustrated in this table, there were differences between ranking scores due to pipe types but both still gave the indication of a clean site (same suburb).



	Close valve
	Hydrant point
	Flow direction
	Already closed valve

Figure 5.28: Map of RPM sites batch-3.

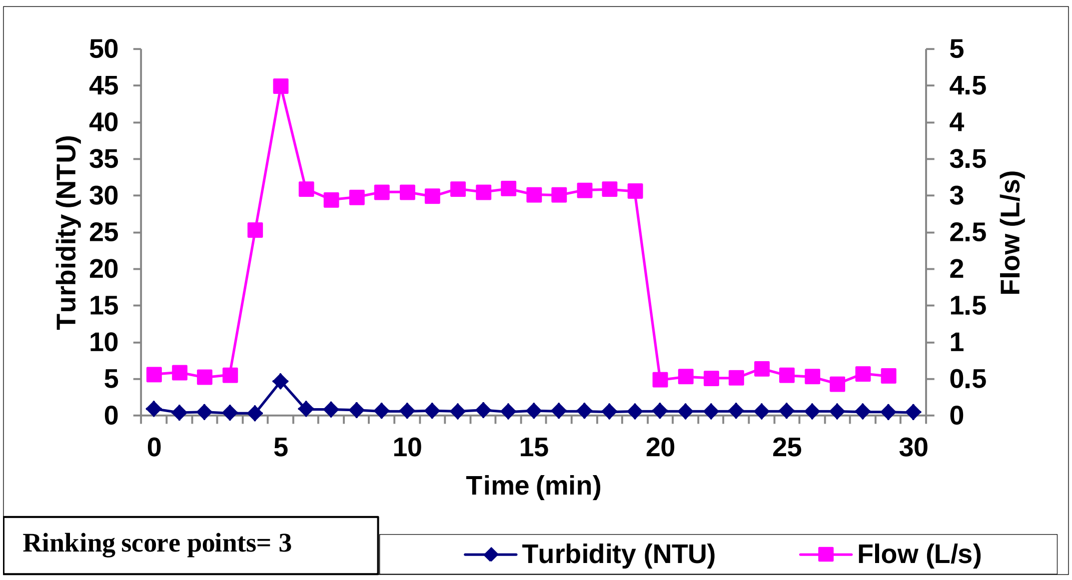


Figure 5.29: RPM results for site 13 “through pipe”.

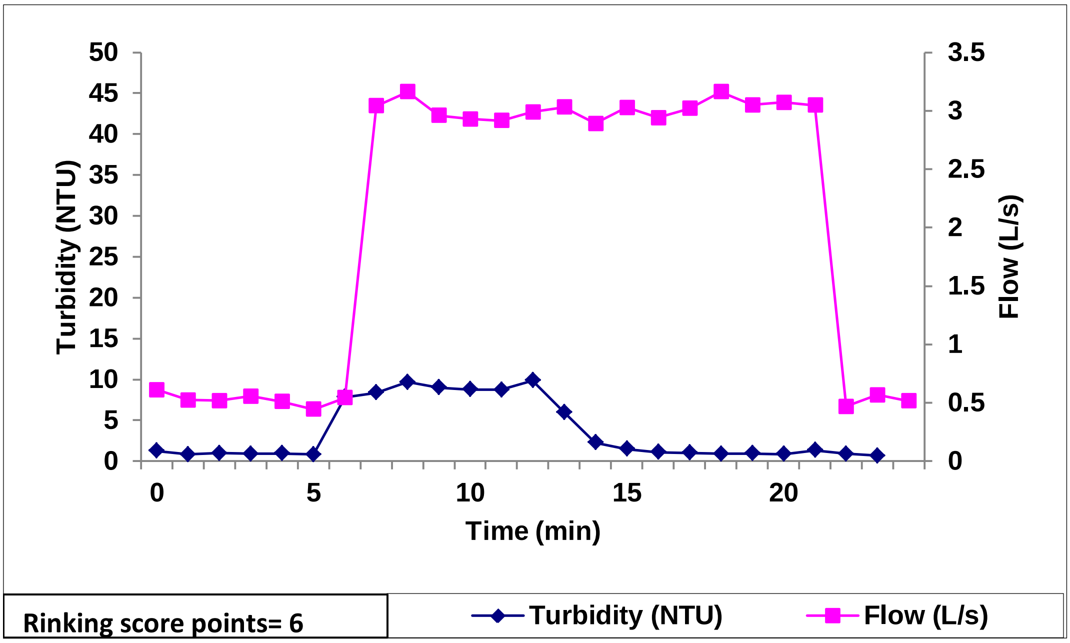


Figure 5.30: RPM results for site 14 "loop pipe".

Table 5.7: RPM third batch results summary and ranking score.

Site no.	Pipe type	Max. tur. of first 5	Avg. tur. of first 5	Max. tur. of last 10	Avg. tur. of last 10	time to clear	RSP
13*	Through	4.7	1.6	0.8	0.6	11	3
14*	Loop	9.7	8.7	9.9	3.3	3	6
* On 12/10/2011, the third RPM batch was processed.							

From these results, it is clear that pipe types play a role in determining the dirtiness of a pipe. However, the dirtiness is not remarkably different as both results roughly indicate cleaner sites. In some cases the difference is imposed by the local hydraulic conditions such as nearby complaints which can change the dirtiness of a given pipe (after it is flushed by the Water Corporation). Therefore, one needs to be aware of the types (loop, dead-end or through) of pipe and the history of a pipe to understand the dirtiness of a suburb.

5.4 Summary of RPM Results

From the RPM testing and comparison of results with complaints, many interesting conclusions were made:

- The RPM testing provides a good indication of the dirtiness of a pipe as a ranking score, although the evaluation procedure to produce a ranking score could be improved. This is taken up in the next chapter.

- Pipes in the same area give approximately the same results in terms of cleanliness (close ranking scores), although the closed end and loop pipes provide slightly higher ranking scores than the through pipes.

- The dirtiness of a pipe (or ranking score of a pipe) is greatly affected by hydraulic events. Pipes closer to burst pipes events were found to be cleaner than those that were further away. Similarly, pipes located closer to the locations of recent complaints were found to be cleaner due to the protocol adopted by the Water Corporation to flush adjacent pipes at high velocity until the water became cleaner. Therefore the higher the number of complaints the cleaner the pipes.

- If a pipe is cleaned, it stays clean for less than 18 months. Defining a more exact time period for which the pipe stays clean needs further experimental refinement which is beyond the scope of this thesis.

- Hydraulic flushing of pipes following a complaint is as effective as air-scouring in terms of reducing the sediment load. If a well-defined hydraulic flushing system is designed it not only costs less but also produces effective results in the cleaning away of sediment.

- The current policy of the Water Corporation in adopting the expensive process of air-scouring in an area with high complaints is questionable on three grounds: Firstly, higher complaints instigate the cleaning process (flushing by the Water Corporation) which makes the pipe cleaner. Secondly, a cleaner pipe stays cleaner for less than 18 months. This means another cleaning program is necessary in another 18 months. This is not sustainable or cost effective. Thirdly, complaints tend to occur as a consequence of hydraulic events, even in an area containing cleaner pipes.

- The number of complaints in a given area is not directly related to dirtiness; therefore one has to be careful in adopting any cleaning strategies to reduce complaints about discoloured water.

CHAPTER 6 RESUSPENSION POTENTIAL METHOD (RPM) IMPROVEMENT

6.1 Introduction

The RPM ranking score determines the extent of dirtiness that instigates complaints regarding dirty water in a given pipe. It may also determine the risk of dirtiness occurring in a given pipe. It is calculated by evaluating the turbidity profile evolving from a known disturbance. The evaluation considers the time to clear the pipe (time to reach base level turbidity after the disturbance has been stopped by intervention), as one of four important considerations. The lower the base level turbidity, the longer the time it will take to reach base level turbidity after the disturbance is stopped. The longer the time it takes, the higher the ranking score, indicating that the pipe is dirty. If the base level turbidity is below the turbidity in question then there can be a problem with this approach. For example, even if the turbidity continued to stay at a higher level than the base level turbidity, it might not cause complaints if it came within the Australian Drinking Water Guidelines (ADWG, 2004). The ADWG recommend that the turbidity in drinking water be kept below 1 NTU to enable effective disinfection, and below 5 NTU for aesthetic considerations. Hence, if the base level turbidity or the turbidity reached after stopping the disturbance is below the turbidity of concern (i.e. below ADWG value), then it should not be given any score. Hence, the RPM evaluation method needs improvement. Two improvements to

RPM evaluation methods will be described and compared with evaluation method of Vreeburg et al., 2004a.

6.2 Demonstration of Problems in RPM Ranking Score Points (RSP) calculation

The summaries of base level turbidity and turbidity after the disturbance has been stopped (TADS) for three sites 9aI, 10bF and 12aC are shown in Table 6.1. The TADS is defined as the average of all the turbidity readings within the first 5 minutes of stopping the disturbance. Site 9a in Suburb I recorded a low base level turbidity of 0.17 NTU, a time to clear of 28 minutes, and the turbidity did not stabilise while being disturbed, (illustrated in Figure 5.15). Within the period of disturbance, the turbidity fluctuated from about 5 to less than 1 NTU; the TADS was 1.1 NTU. Despite remaining at the level observed for some time, it was too low to cause any complaints. However, if the procedure proposed by Vreeburg et al., 2004a, is adopted, the site would be deemed dirty (a ranking score of 10 points). The evaluation procedure requires improvements such as the allocation of a score for TADS (NTU), along with time elapsed until the pipe water is clear. Similarly, base level turbidity could be an effective indicator of the dirtiness of the site. Therefore, it is better to include these parameters in calculating ranking score points.

Similar results were noted at site 10bF and 12aC. Site 10bF took 28 minutes to reach the base level turbidity (time to clear), as illustrated in Figure 5.16. The longer "time to clear" period means that the site was dirty (a ranking score of 11). However, the TADS was 2.2 NTU and turbidity stayed at that level for 28 minutes. Site 12aC was not vastly different. In addition it had been flushed following the cleaning protocol of the Water Corporation, and there had been 10 burst pipes events in the year prior to the RPM measurement (BP1Y=10) in suburb C; Table 5.4. It took 27 minutes to reach base level turbidity (0.39 NTU), but the TADS was 1.8 NTU, as illustrated in Figure 5.18. The result of site 12a in suburb C means the site was clean even though it recorded 10 points as RS according to the method of Vreeburg et al., 2004a. In addition, the base level turbidity (0.5 NTU) provided a good indicator of the dirtiness of the site.

Table 6.1: Base level turbidity and turbidity after the disturbance has been stopped (TADS) for three sites.

Site no.	Water sources	*RSP	Date of RPM work	base level turbidity (NTU)	Time to clear min	**TADS (NTU)
9a I	Tank 1	8	19/2/2009	0.17	28	1.1
10b F	Tank 1	11	19/2/2009	0.47	28	2.2
12a C	Tank 1	10	19/2/2009	0.39	27	1.8

* Ranking score points according to Vreeburg et al., 2004a method

** (TADS) is the average turbidity within 5 minutes after the disturbance has been stopped

In summary, the current RPM evaluation method ignores the effect of base level turbidity and the turbidity after the disturbance has been stopped (TADS). Therefore this evaluation method needs to be improved and this is addressed in the next section.

6.3 RPM Improvement

Two different evaluation methods are proposed.

6.3.1 New Evaluation Method-1

An improvement to the procedure of Vreeburg et al., 2004a was made by giving scores for both base level turbidity and average turbidity in the first 5 minutes after the disturbance had been stopped (TADS). Figure 6.1 highlights six regions of the turbidity trace and the regions of interest. This is incorporated into the ranking points in Table 6.2.

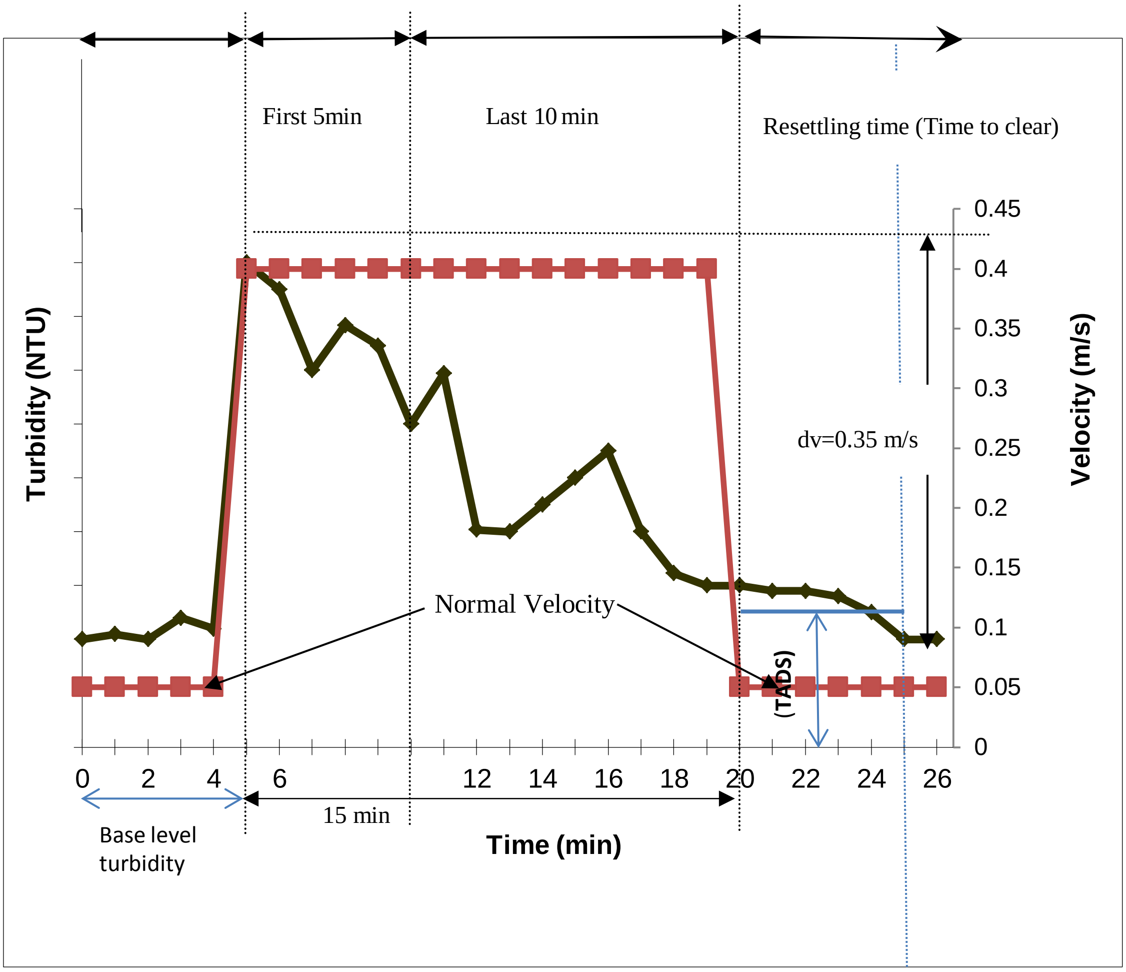


Figure 6.1: Typical turbidity trace resulting from an RPM test, showing the regions used to rate the discolouration risk consideration in RPM methods of improvement, where the (TADS) is the average turbidity within the first 5 minutes of stopping the disturbance.

When evaluating the RPM results according to improvement Method-1, seven aspects are considered and rated equally. These aspects are: the maximum and average turbidity in the first 5 minutes and the maximum and average turbidity in last 10 minutes of the disturbance and the time to clear, as well as the base level turbidity and TADS. Each of these can be rated on a scale from 0 to 3 and summarised, resulting in a single figure on a scale of 0-21. The calculation approach is demonstrated below using site 9aI as an example:

Table 6.2: Evaluation table (supply sub-system "M" ranking points) according to Method-1 of improvement.

Score (points)	0	1	2	3
Initial base level turbidity	< 1 NTU	1-5 NTU	5-20 NTU	>20 NTU
Absolute maximum first 5 minutes	< 1 NTU	1-5 NTU	5-20 NTU	>20 NTU
Average first 5 minutes	< 1 NTU	1-5 NTU	5-20 NTU	>20 NTU
Absolute maximum last 10 minutes	< 1 NTU	1-5 NTU	5-20 NTU	>20 NTU
Average last 10 minutes	< 1 NTU	1-5 NTU	5-20 NTU	>20 NTU
Time to clear	< 5	5—15	15—60	>60
Turbidity after the disturbance stopped; average turbidity of the first 5 min	< 1 NTU	1-5 NTU	5-20 NTU	>20 NTU

Table 6.3: Ranking score (RS) from application of Vreeburg et al., 2004a method for 9al.

Aspects	Absolute max. first 5 minutes	Average first 5 minutes	Absolute max. last 10 minutes	Average last 10 minutes	Time to clear (min)
Values	6.83 NTU	3.05 NTU	6.8 NTU	2.97 NTU	28
Score (points)	2	1	2	1	2

1. The procedure to calculate the ranking score using the method of Vreeburg et al., 2004a has been explained in Chapter 5, section (5.3.1); the results are illustrated in Table 6.3

The ranking score is 8 points (RS = 2+1+2+1+2 = 8) out of 15. The percentage of pipe dirtiness (%PD) = 8/15*100 = 53%.

2. Applying improvement Method-1 resulted in the following:

- The base level turbidity was 0.17, which was also considered in determining the time to clear during resettling time. The score for the base level turbidity was 0 (Table 6.2).
- The maximum turbidity in the first 5 minutes was 6.83 NTU; the score for the second aspect was 2 (Turbidity between 5-20 NTU; See Table 6.2).
- The average turbidity in the first 5 minutes was 3.05 NTU; the score for the third aspect was 1 (Table 6.2; Turbidity between 1-5 NTU).
- The maximum turbidity in the last 10 minutes was 6.8 NTU; the score for the fourth aspect was 2 (Table 6.2).
- The average turbidity for the last 10 minutes was 2.97 NTU; the score for the fifth aspect was 1 (Table 6.2).
- The time to clear was 28 minutes; the score for sixth aspect was 2 (between 15-60; Table 6.2).
- For turbidity after the disturbance had been stopped - the average turbidity for the first 5 minutes was 1.1. The score for the seventh aspect was 1 (Table 6.2).
- The actual ranking score was 9 points (RS = 0+2+1+2+1+2+1 = 9) out of 21.

- The percentage of pipe dirtiness (%PD) = 9/21*100 = 43%.

Table 6.4: RPM results summary and ranking score points (RSP) for all sites by applying Vreeburg et al., 2004a and Method-1 of improvement.

Site no.	Tank No.	base level	Max. Tur. of first 5min	Avg. Tur. of first 5 min	Max. Tur. of last 10 min	Avg. Tur. of last 10 min	Avg Tur. First 5 min after disturbing (TADS)	Time to clear	Old RSP[1] out of 15	New RSP[2] out of 21
1aH	1	48.4	93.5	78.3	85.9	43.9	10.9[3]	1	12	17
1bH	3	0.5	18.7	8	7.5	3.4	11	39	9	11
2aG	3	4.2	5.0	4.0	9.0	6.8	8.5	9	8	11
3aE	2	0.29	2.2	0.8	0.5	0.4	0.38	7	2	2
4aD	2	0.98	3.8	3	2.8	2. 5	0.95	3	4	4
5aA	1	0.22	20	6.8	6.0	3.2	6.3	>60	10	12
6bG	1	0.28	5.6	5.1	49.8	17.4	29.5	>60	12	15
7bB	1	0.28	4.1	1.3	2.7	0.9	0.48	3	3	3
8aE	2	0. 67	15.6	13.7	14.6	9.2	2.8	35	10	11
9aI	1	0.17	6.8	3.1	6.8	3	1.1	28	8	9
10bF	1	0.47	16.3	15.1	20.5	15	2.2	28	11	12

11bJ	3	0.23	2.1	1.4	2.0	1.2	0.43	27	5	5
12aC	1	0.39	16.2	10.9	10.9	7.2	2.3	43	10	11

[1]**Vreeburg et al., 2004a method**

[2]**New evaluation according to Method-1**

[3] **Data collection stopped once base line turbidity was reached (within one minute) therefore it is not possible to calculate the TADS value so it is assumed to be equal to the final turbidity.**

The summaries of RPM results of the first batch, based on Vreeburg et al., 2004a, and Method-1 are illustrated in Table 6.4. Using the data in the third to the ninth columns in Table 6.4, individual scores were generated for each site and results are summarised in the tenth and eleventh columns in the same table.

6.3.2 New Evaluation Method-2

The procedure proposed by Vreeburg et al., 2004a calculates a score for the time to clear by comparing the final result of turbidity with the base level turbidity, irrespective of whether the base level turbidity, and/or turbidity after the disturbance, is too low. The improved Method-2 will cancel the score of time to clear or assign it a value of zero, if the average turbidity in the first 5 minutes after the disturbance (TADS) is < 5 NTU. This will ignore the comparison with the base level turbidity value. The scoring for the base level turbidity is retained, as base level turbidity is a good indicator of the status of the pipe. Each of these aspects can be rated on a scale from 0 to 3 and summarised; resulting in a single figure on a scale of 0–18. The evaluation table is illustrated in Table 6.5.

Table 6.5: Evaluation table (supply sub-system "M" ranking points) new Method-2.

Score (points)	0	1	2	3
Initial base level turbidity	< 1 NTU	1-5 NTU	5-20 NTU	>20 NTU
Absolute maximum first 5 minutes	< 1 NTU	1-5 NTU	5-20 NTU	>20 NTU
Average first 5 minutes	< 1 NTU	1-5 NTU	5-20 NTU	>20 NTU
Absolute maximum last 10 minutes	< 1 NTU	1-5 NTU	5-20 NTU	>20 NTU
Average last 10 minutes	< 1 NTU	1-5 NTU	5-20 NTU	>20 NTU
Time to clear; Time to reach turbidity less than 5 NTU	< 5	5—15	15—60	>60

To find the percentage of pipe dirtiness (%PD), the RSP obtained from Method-2 was divided by 18.

Application of new Method-2 for site 9aI is demonstrated below:

The value of base level turbidity was 0.17. The scour point for base level turbidity was 0 (Table 6.5).

- The maximum turbidity in the first 5 minutes was 6.83 NTU; the score for the first aspect was 2 (Turbidity between 5-20 NTU; See Table 6.5).
- The average turbidity in the first 5 minutes was 3.05 NTU; the score for the second aspect was 1 (Table 6.5; Turbidity between 1-5 NTU).

Table 6.6: Time to clear calculated according to Vreeburg et al., 2004a method and new method-2.

Site no.	base level Tur.	Time to clear Vreeburg et al., 2004a method	Time to clear method-2
1aH	48.4	1	>5*
1bH	0.5	39	18
2aG	4.2	9	7
3aE	0.29	7	0
4aD	0.98	3	0
5aA	0.22	> 60	17
6bG	0.28	> 60	37
7bB	0.28	3	0
8aE	0. 67	35	0
9aI	0.17	28	1
10bF	0.47	28	0
11bJ	0.23	11	0
12aC	0.39	27	0

* This value is not possible to calculate because data collection stopped once base line turbidity was reached, but it would be more than 5 minutes, giving a higher score.

- The maximum turbidity in the last 10 minutes was 6.8 NTU; the score for the third aspect was 2 (Table 6.5).
- The average turbidity for the last 10 minutes was 2.97 NTU; the score for the fourth aspect was 1 (Table 6.5).

- The turbidity after the disturbance stopped was less than 5 NTU; therefore the time to clear score was 0 (Table 6.5).
- The ranking score was 6 points (RS = 0+2+1+2+1+0 = 6).
- Percentage of pipe dirtiness (%PD) = 6/18*100 = 33%.

The results for other sites are summarised in the fifth column in Table 6.7.

6.3.3 Comparison of Three RPM Evaluation Methods

The results of the evaluated RPMs of the first batch of experiments are compared in Table 6.7 and Figure 6.2. The reason for evaluation is to understand where scarce resources should be spent: in cleaning the pipe, or in evaluating other causative factors of dirtiness in the pipe, or complaints due to hydraulic disturbances. This means that the pipe which is likely to cause more dirty water incidents should be targeted. To analyse the data this way, a colour code was introduced. A high level of dirtiness (≥ 60%) category is marked red whereas low (< 40%) and medium (≥ 40% and < 60%) dirtiness are marked green and yellow. This categorisation helps in evaluating the relative benefits of the evaluation methods.

Table 6.7: Results summary of number of burst pipes, complaints/1000 persons and % pipe dirtiness (%PD) for Vreeburg et al., 2004a method, new Method-1, and new Method-2.

Site no.	Water sources Tank	% PD Vreeburg et al., 2004a	% PD new Method-1	% PD new Method-2	Date of RPM work	Com./1000				No. of burst pipe	
						$(Com/1000)_{2007}$	$(Com/1000)_{2008}$	$(Com/1000)_{2009}$	$(C_{avg}5Y)$	BP0.5Y	BP1Y
1aH	1	80*	81	89	9/07/2008	1.1	1.9		2.5	0	1
1bH	2	60	52	50	9/07/2008	1.1	1.9		2.5	0	1
2aG	2	53	52	50	9/07/2008	0.2	1.0		1.9	4	7
6bG	1	80	71	67	9/07/2008	0.2	1.0		1.9	4	7
3aE	1	13	10	6	9/07/2008	10.8	2.2		7.4	0	0
8aE	1	67	52	44	19/02/2009	10.8	2.2	5.9	7.4	1	1
4aD	1	27	19	22	9/07/2008	15.1	2.4		10.8	6	15
5aA	1	67	57	50	9/07/2008	0.4	0.5		2.5	2	9
7bB	1	20	14	17	19/02/2009	0.6	1.1	0.6	3.5	6	12
9aI	1	53	43	33	19/02/2009	0.1	0.5	2.8	1.3	1	1
10bF	1	73	57	50	19/02/2009	1.4	0.6	2.8	3.7	1	3

11bJ	2	33	24	22	19/02/2009	3.2	1.6	0.6	4.4	0	1
12aC	1	67	52	44	19/02/2009	4.1	2.0	2.0	4.5	5	10

(C_{avg}5Y) **Complaints/1000 persons as average of five years (2003-2007)**

(BP0.5Y) **Burst pipes events 6 months before RPM**

(BP1Y) **Burst pipes events 1 year before RPM.**

*** Colour code indicates the severity of the dirtiness: Dirtiness of 60% and above is marked red and is used to indicate that the site needs immediate attention; dirtiness between 40% and 59% indicates medium dirtiness, hence yellow coloured and below 39% is marked low dirtiness, hence green.**

In general, the newly proposed method reduced the percentage of dirtiness ranking. Interestingly, all the methods consistently identified the dirtiest (1aH and 6bG) and cleanest (3aE, 4aD, 7bB and 11bJ) sites. However, the striking difference was seen in the medium dirtiness readings. For example, some sites went from high to medium dirtiness (1bH, 8aE, 5aA, 10bF, 12aC and 9aI). One site of medium dirtiness, 9aI, changed to a low dirtiness category. All three methods gave the same indicators of dirtiness for site 2aG which recorded medium dirtiness for all methods. Sites 5aA, 8aE and 9aI are used to explain why this change is justifiable. Site 5aA had a turbidity level that rose only once during the disturbance period (3-3.5L/s), and for seven minutes at the end of the disturbance, which indicates the turbidity caused by this site was not that serious. Similarly site 8aE had turbidity reaching higher than 5 NTU for 12 out of 15 minutes during the disturbance period. This too did not rise above 15 NTU. It therefore generally follows that even if a disturbance is caused, the customer will not usually experience higher turbidity for more than 15 minutes. Usually, customers can tolerate such periods of higher turbidity. In site, 9aI, the turbidity fluctuated between 7 and 0.5

NTU, rising above 5 NTU only four times out of 15 minutes of disturbance. Hence this site would be rated as a low dirtiness site.

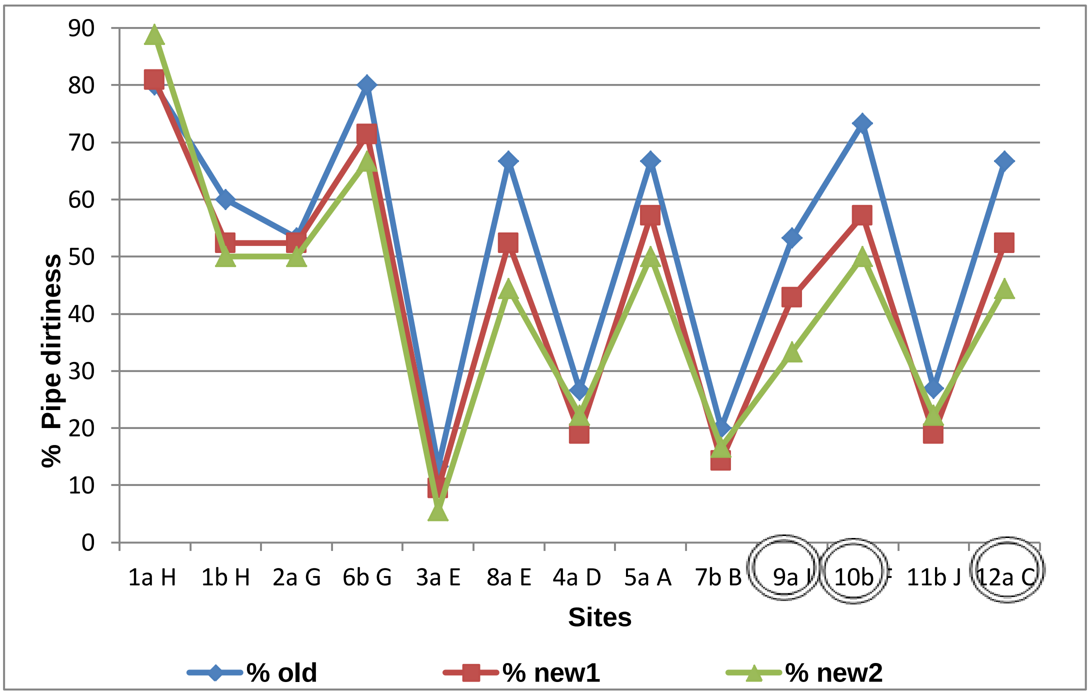


Figure 6.2: Comparison among the three RPM evaluation methods; the % pipe dirtiness for each site of RPM for Vreeburg et al., 2004a method, new Method-1 and new Method-2.

It should however, be noted that dirtiness is not an indicator of the risk of complaints as discussed earlier, hence the results need to be considered in combination with other factors such as burst pipe events. These are discussed below.

The discussion documented in Chapter 5 is used again here to demonstrate its relevance to the newly proposed method(s). The information is repeated in Table 6.7. According to Method-2, site 5a in suburb A recorded a % PD equal to 50; the least number of complaints (0.4 and 0.5 per 1000) with many burst pipes events (11 within one year prior to the RPM test). The higher the number of burst pipe events, the more the chance of the pipe becoming cleaner, if that particular pipe is affected by burst pipe events. Being a dead-end pipe, the chances of cleaning are significantly reduced. The larger area of suburb A and farther locations of burst pipe events can further reduce the impact. For example, a close inspection revealed that out of all burst pipe events, only one burst pipe was near the site location. Hence the dirtiness is least impacted upon by the events, except for localised complaint events or burst pipe events. Hence the %PD obtained from Method-2 is reasonable and indicates that there was some impact but it is not enough to claim that there was a significant impact.

The second site of 8a in suburb E had a pipe with a closed-valve at the end (dead- end); which recorded a %PD equal to 44. Similar to the previous case, a dead-end can be expected to have the least influence on complaints and burst pipe events if it is located far from the site. The suburb also had a high number of complaints $(Com/1000)_{2009}$ = 5.9 and $C_{avg}5Y$= 7.4), and high burst pipe events (BP1Y= 8) were recorded in the adjacent suburb (suburb D). When the RPM data was analysed using the approach by Vreeburg et al., 2004a, it was concluded that burst pipe events did not have an impact as the dirtiness was higher. However, the newly proposed Method-2 identified this as a cleaner pipe. The results again prove that the results obtained from Method-2 lead to a reasonable conclusion with regard to the dirtiness of the pipe.

Site 12aC should have been continuously affected by burst pipe events and complaints. However, the % PDs from three evaluation methods were 67, 52, and 44 respectively. Site 12aC had a high number of complaints in 2007 and $C_{avg}5Y$; therefore it should have been flushed according to the policy of the Water Corporation. Similarly there were

10 (BP1Y) instances of burst pipe events in suburb C. Therefore, the results from Method-2 correctly ascertained the dirtiness of the pipes.

6.4 Conclusions

Both of the new RPM evaluation methods provided reasonable values regarding dirtiness in an Australian context compared with that proposed by Vreeburg et al., 2004a. However, it should be noted that all methods resulted in similar conclusions with regard to relative dirtiness. For example, the cleanest and dirtiest sites were consistently the same. When the results were compared, the new Method-2 resulted in more reasonable values, especially as a result of incorporating base level turbidity and evaluating the resettlement by comparing the turbidity in question (5 NTU), rather than waiting for the turbidity to reach an unrealistic base level turbidity. It should be noted that the use of base level turbidity has its own merits in certain circumstances, for example in evaluating total resettlement. However, it does not have value if the objective is to prevent dirty water complaints. Overall, the proposed Method-2 results provided an effective indication regarding pipe conditions. This should assist in avoiding unnecessary expenditure on pipes if water utilities opt to clean the pipes. Notwithstanding this, the report clearly identified that cleanliness is not an important factor in the long-term prevention of dirty water complaints.

CHAPTER 7 VALIDATION OF THE HYDRAULIC MODEL OF THE SYSTEM

7.1 Introduction

From previous chapters, it has been concluded that the major causes of dirty water incidents and complaints are hydraulic events, and more specifically, burst pipe events. In addition, the dirtiness of a pipe may not control dirty water complaints, as pipes can quickly become dirty again. This can be seen when a pipe is inspected about 18 months after cleaning. This was a significant finding obtained from the results analysis of complaints data (desktop study) which was confirmed by RPM results. If dirtiness is related to hydraulic events then most of the available hydraulic software should be able to predict the magnitude of changes in hydraulic parameters. However, as sediment is transported with certain characteristics (such as settlement and resuspension), it is still difficult to predict sediment concentrations with a hydraulic model alone. To cater for this need, new software, termed the Particle Sediment Model – PSM was developed.

The PSM is modelling software which uses the freely available hydraulic modelling software, EPAnet, as a hydraulic engine. The Cooperative Research Centre for Water Quality and Treatment (CRCWQT) developed and implemented the sediment transport model in conjunction with EPAnet. Hence, the PSM is an option that allows sediment transport to be modelled. It assumes that all particles originate from the treatment plant and are transported with the water. While in motion, depending on their gravity assisted settling velocity, sediment settles. The PSM assumes the settled sediment could resuspend, if the flow velocity reaches the level of the resuspension velocity. Although it is recognised to exist, bed transport (the slow movement of sediment at the bottom of the pipe) is not implemented in the model. The software is able to indicate the relative amount of sediment in different water pipes at different times.

To confidently utilise the PSM to predict dirty water incidents, it should first predict the evolution of sediment for a known disturbance. This is achieved in three major steps: Firstly, the hydraulic model configuration in EPAnet is implemented and validated against a validated WATSYS based model, as all the pipes are currently modelled into WATSYS; another commercial hydraulic software program. Secondly, once reasonable confidence in the calculation of EPAnet has been achieved, a known historical burst pipe event is simulated and the sediment concentrations at respective addresses are checked against the addresses which registered complaints. The third step involves field validation by actually creating a hydraulic event and measuring the evolution of sediment via turbidity. In this chapter, the first step in the hydraulic validation of the model was taken. The remaining steps are outlined in the next few chapters.

7.2 Methods

The following methods are considered to fulfil the requirements for validation of the PSM.

7.2.1 Construction of Hydraulic Network of Zone M

When converting the hydraulic model of Zone M from the WATSYS program into the EPAnet-PSM many problems were encountered. The water droplet icon in EPAnet-PSM, which was used to convert other hydraulic packages into the EPAnet format, would not function. Therefore, a hydraulic network from AutoCAD was used. This had already been transferred by the Sydney Water Corporation under the CRC for Water Quality and Treatment. All data such as tank information and base demand was manually transferred from WATSYS to EPAnet-PSM, but this process required a detailed understanding of both EPAnet-PSM and WATSYS. Other problems were also encountered. These are summarised below:

- A great deal of data was missing in the WATSYS hydraulic model, for example, the diameters of valves were entered as negative values. This demonstrates the fact that data was missing. Some of the valves, which were located at the end of the network, were converted to closed pipes with a length equal to 1m and a diameter equal to the diameter of the nearest pipe.

- The identification types of valves differ between these two programs and therefore the valve type had to be chosen by trial and error. There was also the option of an "opening percentage" for the valve in WATSYS but this was not applicable to the PSM.

- In addition, a great deal of the input tank data differed. For example, the initial tank level in EPAnet-PSM is equal to the initial tank level in WATSYS, minus the bottom level, and the maximum level is equal to the overflow level in WATSYS minus the bottom level and so the sequence continues.

- Tank 1 has a volume curve in the EPAnet-PSM while it is given as surface area in WATSYS, and these area values needed to be converted to volume and entered into the PSM as a volume curve.

7.2.2 Procedure for Validation of the Hydraulic Model of the System

To ensure that the PSM hydraulic behaviour was the same as that of WATSYS, randomly selected PSM main valves, links (pipes) and service tanks had to match those of WATSYS. If there was any variation, various adjustments such as the friction coefficient for the pipe, the valve type and operating conditions, and the pipe material were altered to achieve a reasonable match.

7.2.3 Procedure for Simulation of Burst Pipe Events:

Burst pipes can be modelled in EPAnet-PSM by increasing the base demand at the node downstream of the burst pipe. However, simulating a burst pipe scenario in a distribution system to represent sediment motion is complex, as in the PSM all systems start with zero sediment concentrations in all pipes. Sediment can only come from the reservoir. The PSM does not recognise a preexisting sediment concentration in the system.

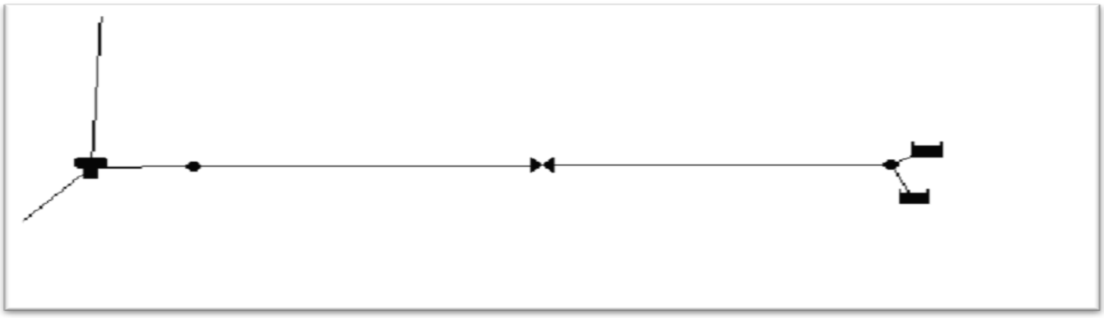


Figure 7.1: Two assumed reservoirs to solve the problem of initial sediment in the pipes.

In the EPAnet-PSM manual, there is an option to add a sediment value to reservoirs and tanks as an initial sediment quality, but this was not possible as the manual assumed that sediment originating from the treatment plant was not stored within these reservoirs and tanks, but transported (or suspended) in the pipes. Therefore, the following procedure was adopted in order to obtain a certain quantity of sediment buildup in the pipe network before any hydraulic events were introduced. Two reservoirs were connected instead of one reservoir (“Reservoir 1”). One of the reservoirs contained a high source sediment concentration (entered in to the software as source sediment quality), and the other had zero source sediment concentration. The reservoir with a high source sediment concentration had the ability to supply water for two days before the source water reservoir switched to a clean reservoir. This was achieved by adding a simple control condition. A sketch is shown in Figure 7.1 above.

7.3 EPAnet-PSM Problems to be Rectified

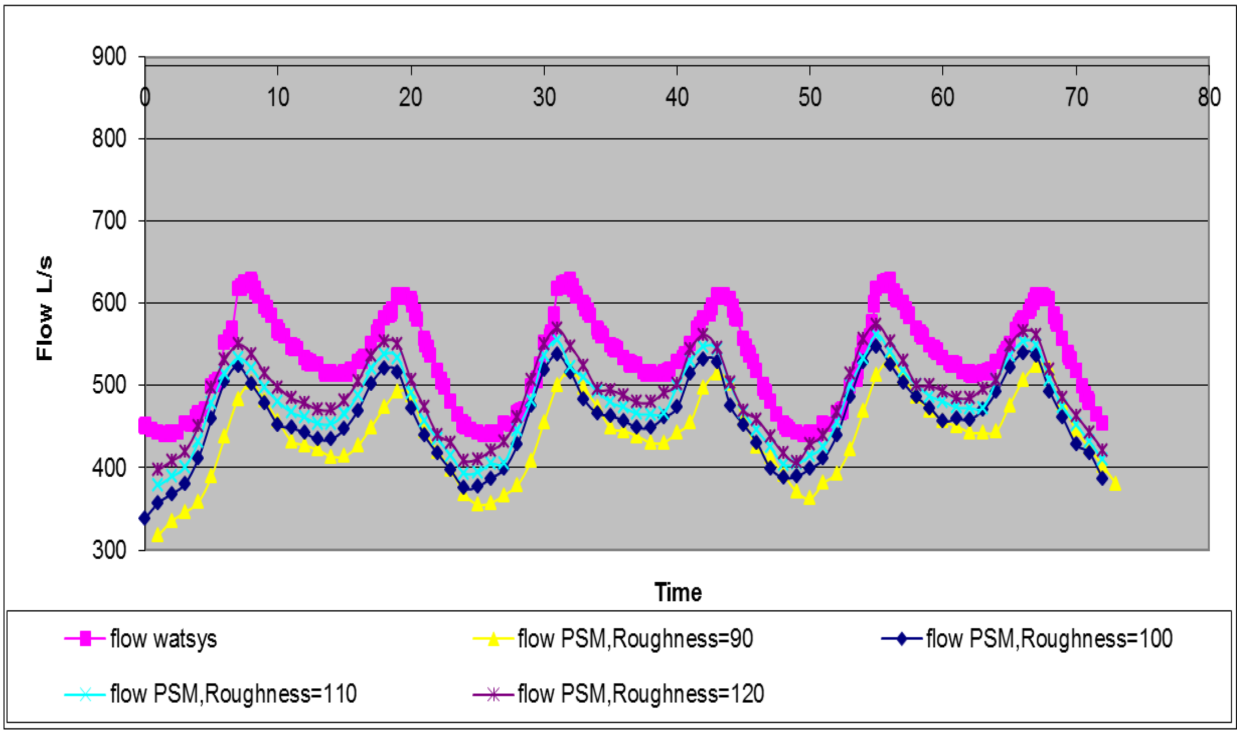
To make the simulation as close as possible to the real situation in water system networks, an option to introduce some sediment in to the pipe at the very beginning of a simulation was deemed a requirement. Currently, at the beginning of a simulation there is no settled sediment on the pipe wall and therefore no deposition, settlement, or movement of sediment, even when the velocity is greater than the resuspension velocity, which is programmed at 0.2, 0.4 or 0.6 m/s. This needs to be considered in setting the initial sediment concentrations.

The option to add sediment to a reservoir or a tank as an initial sediment quality also required activation.

7.4 Validation Results of the Hydraulic Behaviour of the System in EPAnet-PSM with "WATSYS"

Before the EPAnet-PSM software could be used to predict sediment transport, the hydraulics of EPAnet-PSM had to be validated against WATSYS by comparing the head level of all tanks, valves, and randomly selected pipes. The locations of selected items are illustrated in Figure 7.2. During these trials, different values of roughness parameters such as 90, 100, 110, and 120 were utilised in EPAnet-PSM. When the PSM was used for the purpose of prediction, the value of the roughness parameter was 100. Two main valves were selected as an example for calibration. Figures 7.3 and 7.4 show the calibration of the two main valves. Eight pipes all around Zone M system were selected. Figures 7.5, 7.6 and 7.7 illustrate the validation of three pipes (pipes 1, 2, and 3); one in the middle of the network and two at the end of each side. Other pipe samples (pipes 4 to 8) are illustrated in Appendix B (Figures B.1 to B.5). All reservoirs and tanks were also calibrated. Figures 7.8 to 7.12 show the calibration of reservoirs and tanks. All the output calibration curves were similar except that of Tank 1 which had different curves from EPAnet-PSM; and the WATSYS output, as shown in Figure 7.12. This was mainly because of the difference in input data between these two programs for the tank volume, as outlined previously in paragraph (7.2.1).

Figure 7.2: Location of selected pipes in Zone M for the validation of hydraulic model. The brown dot represents the eight selected pipes; the yellow dot represents the two selected valves.



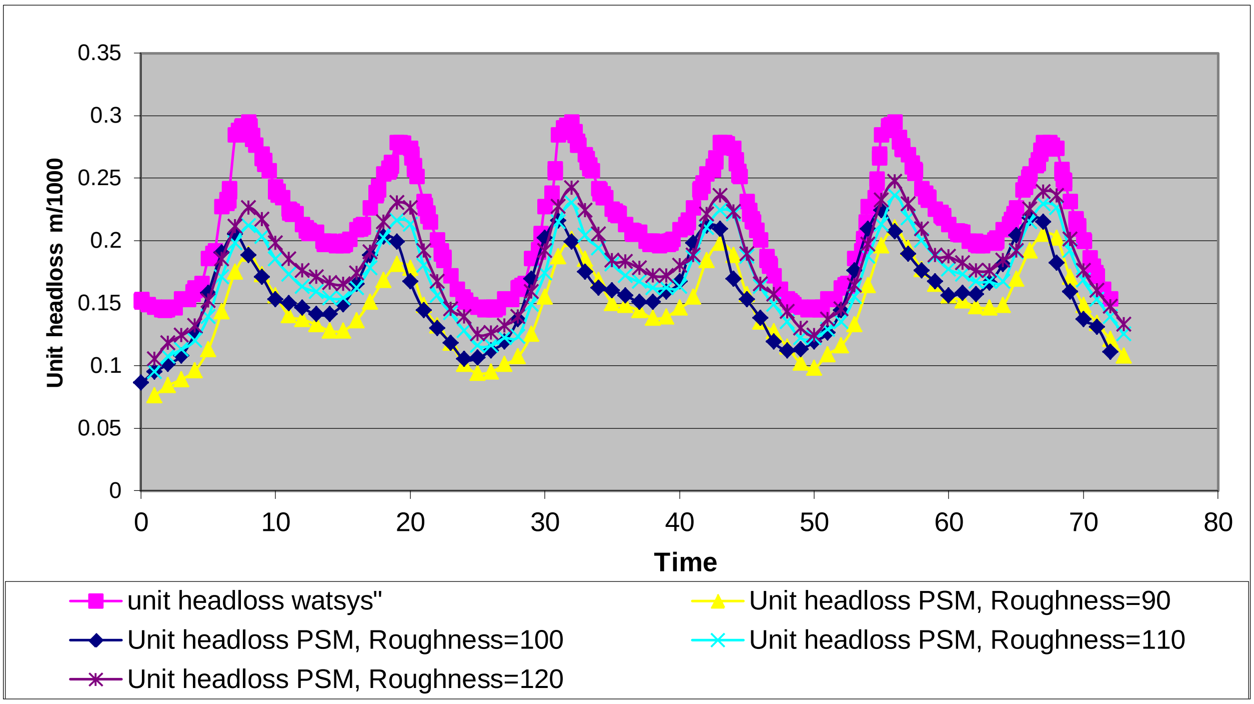
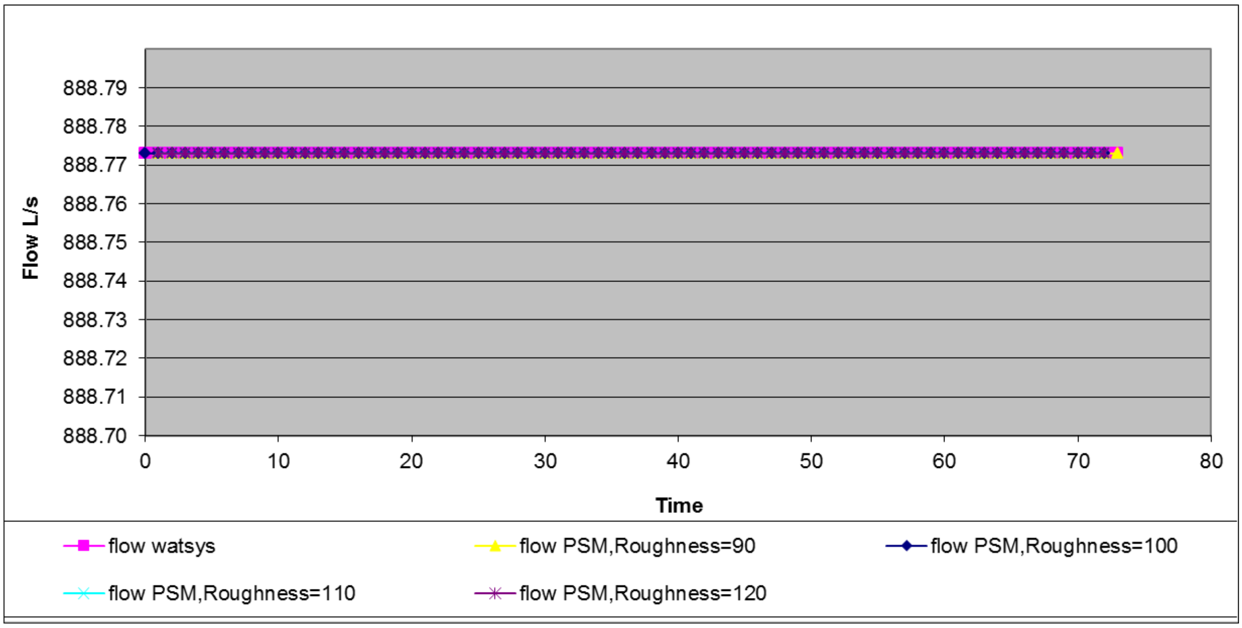


Figure 7.3: Valve 1 flow and head-loss calibrations.



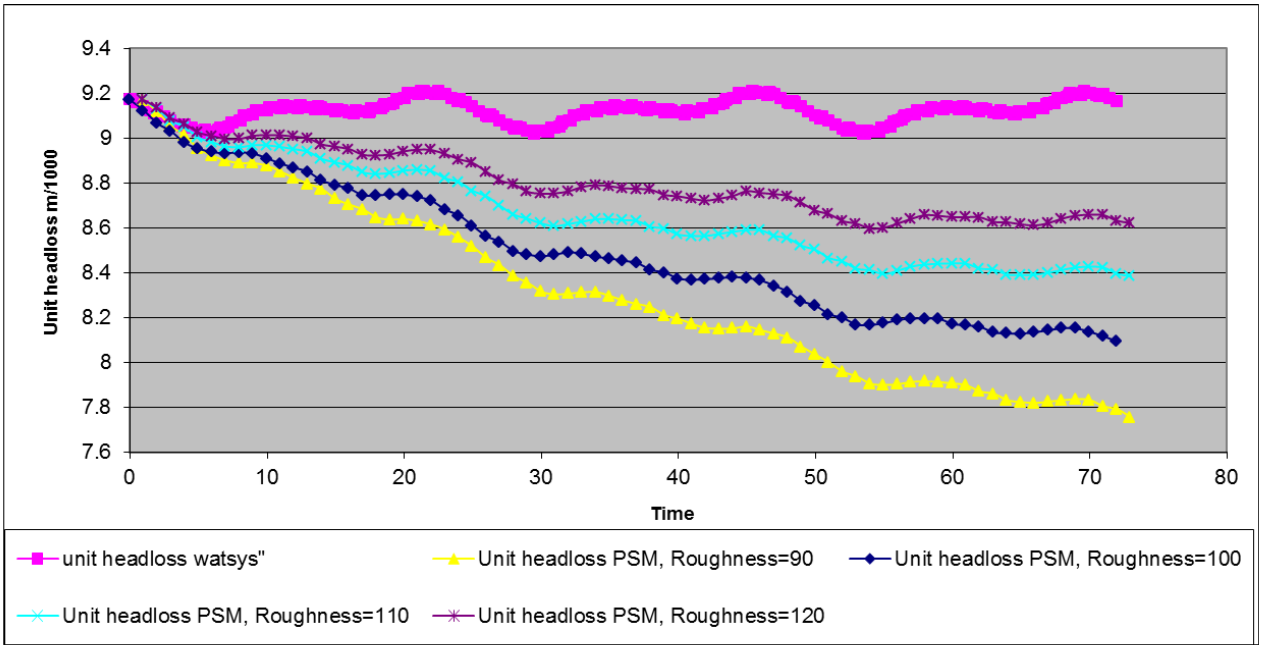


Figure 7.4: Main valve “valve 2” flow and head-loss calibrations.

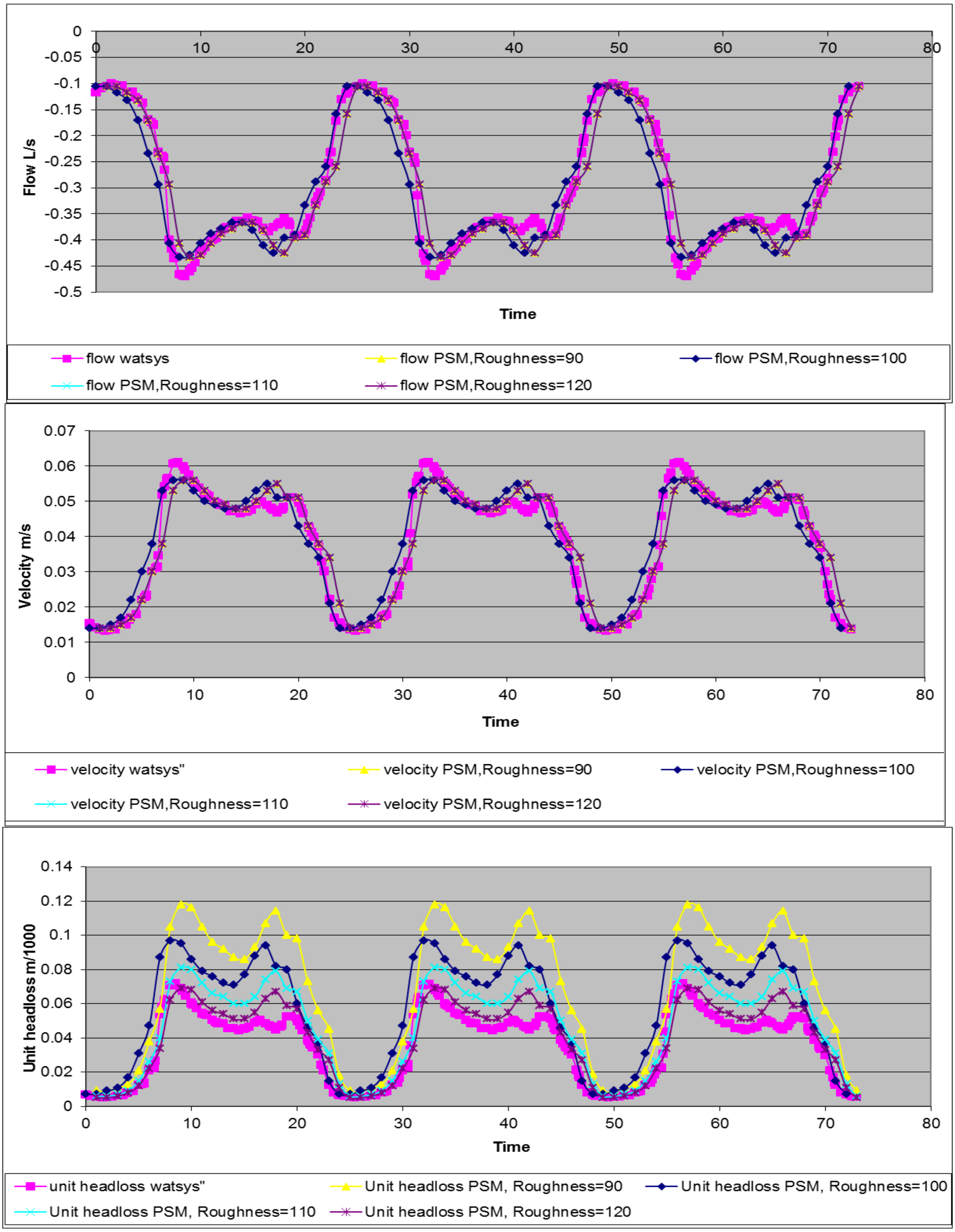


Figure 7.5: Random Link 1 - flow, velocity and head-loss calibrations.

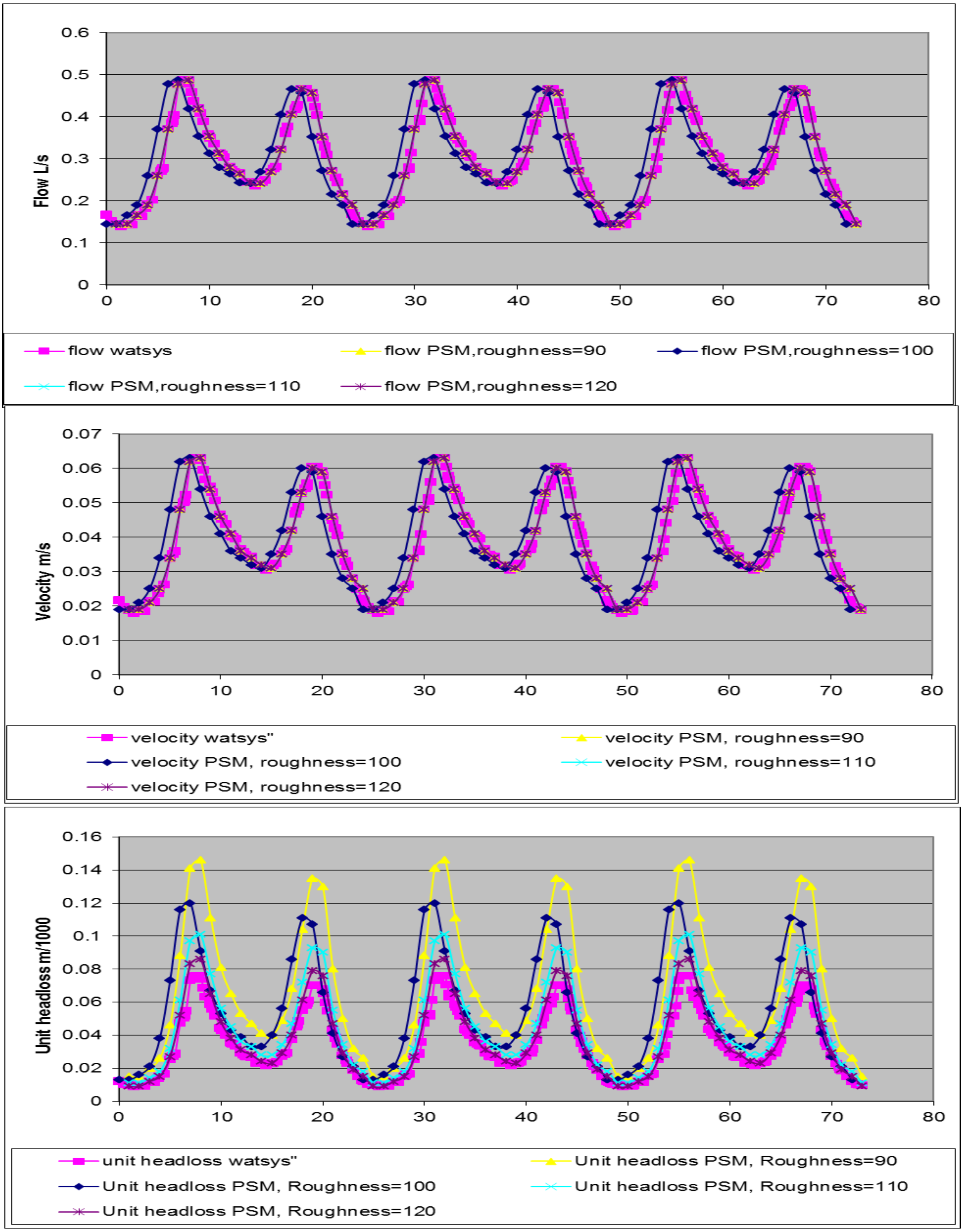


Figure 7.6: Random Link 2 - flow, velocity and head-loss calibrations.

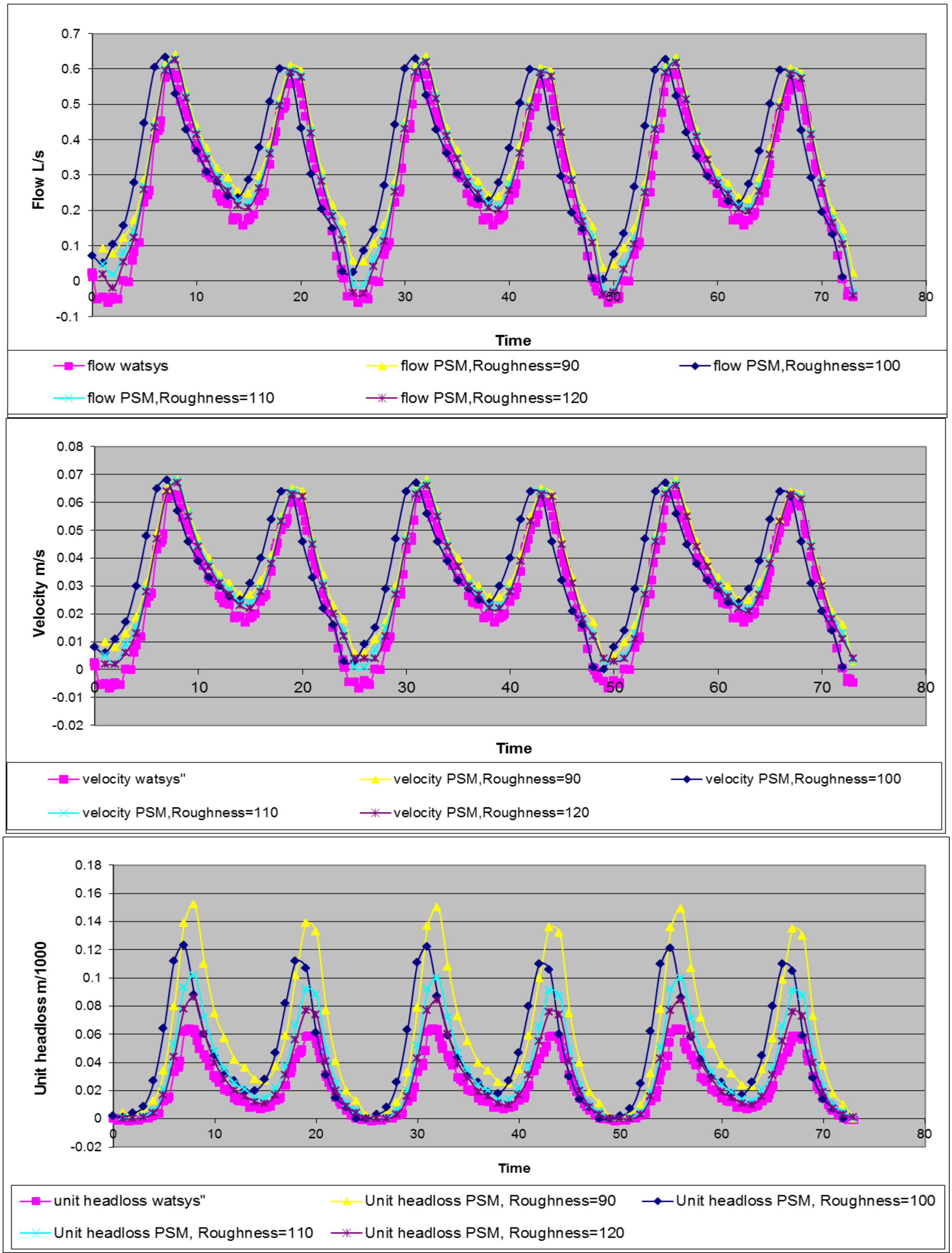
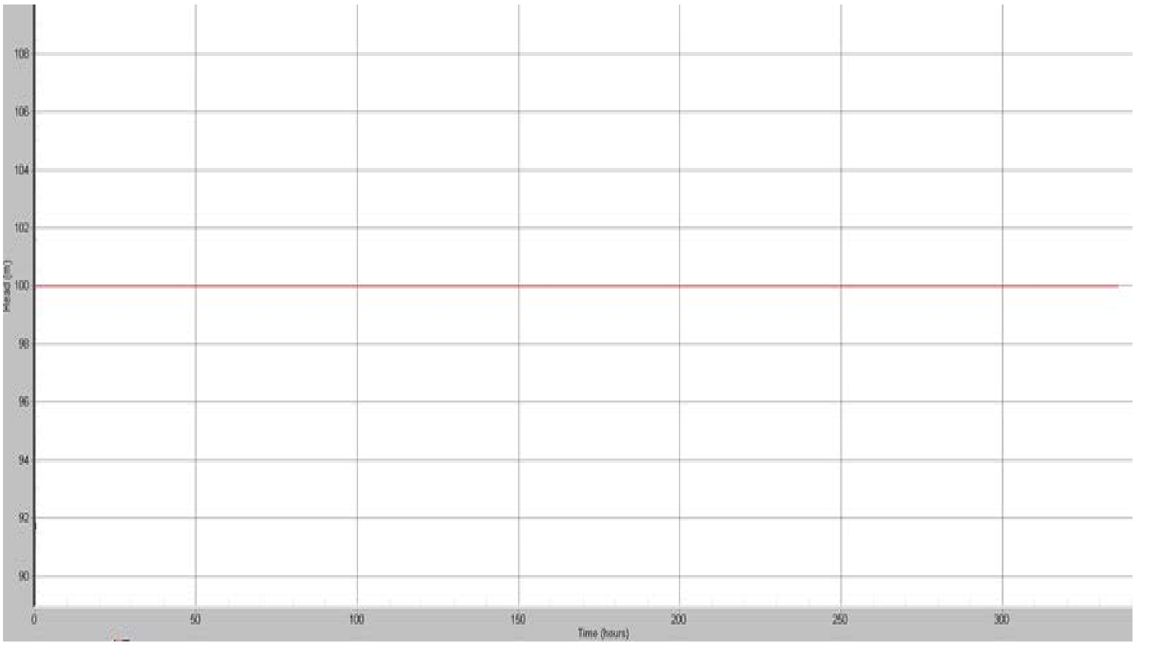
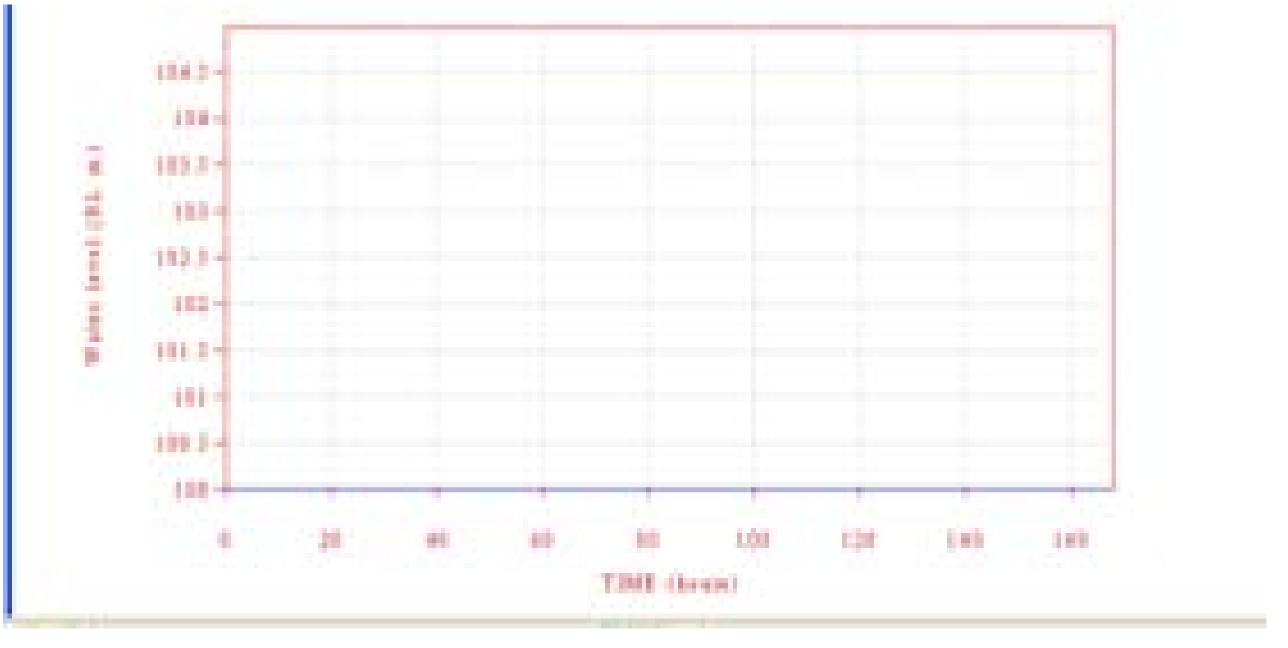


Figure 7.7: Randomly Link 3 flow, velocity and head-loss calibrations.

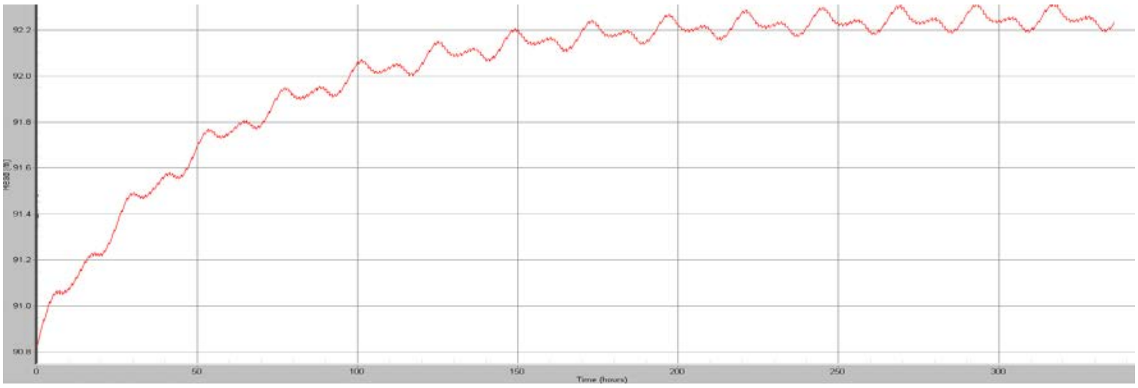


A: PSM, Reservoir 1 head

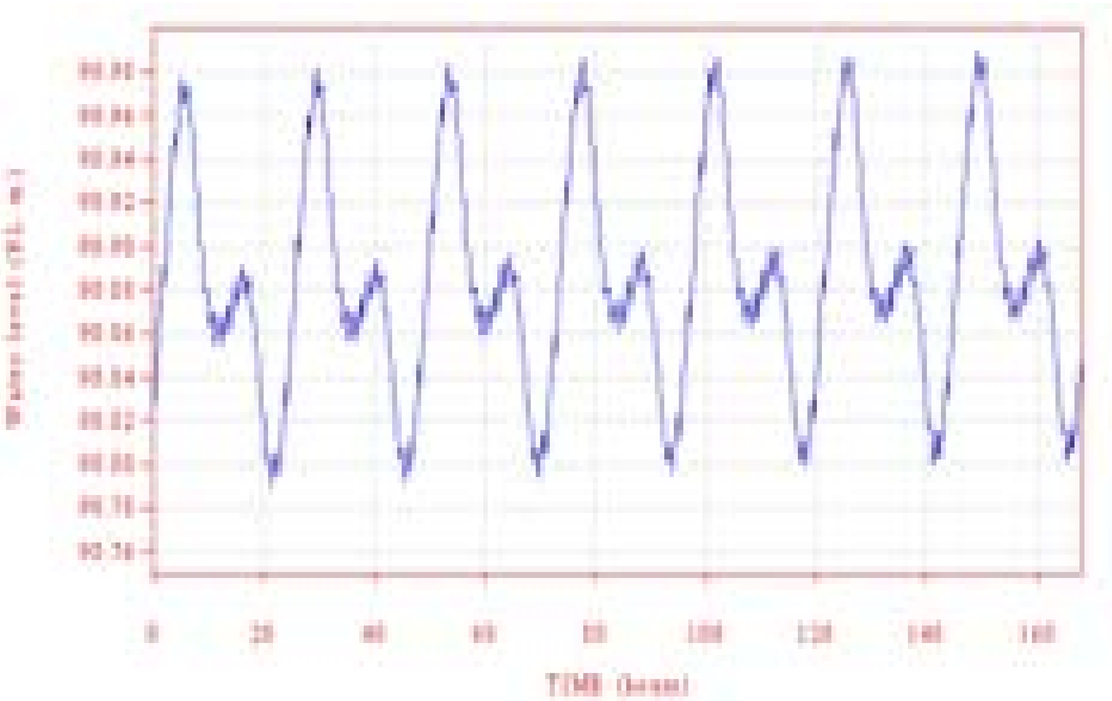


B: WATSYS, Reservoir 1 head

Figure 7.8: Reservoir 1 calibration.

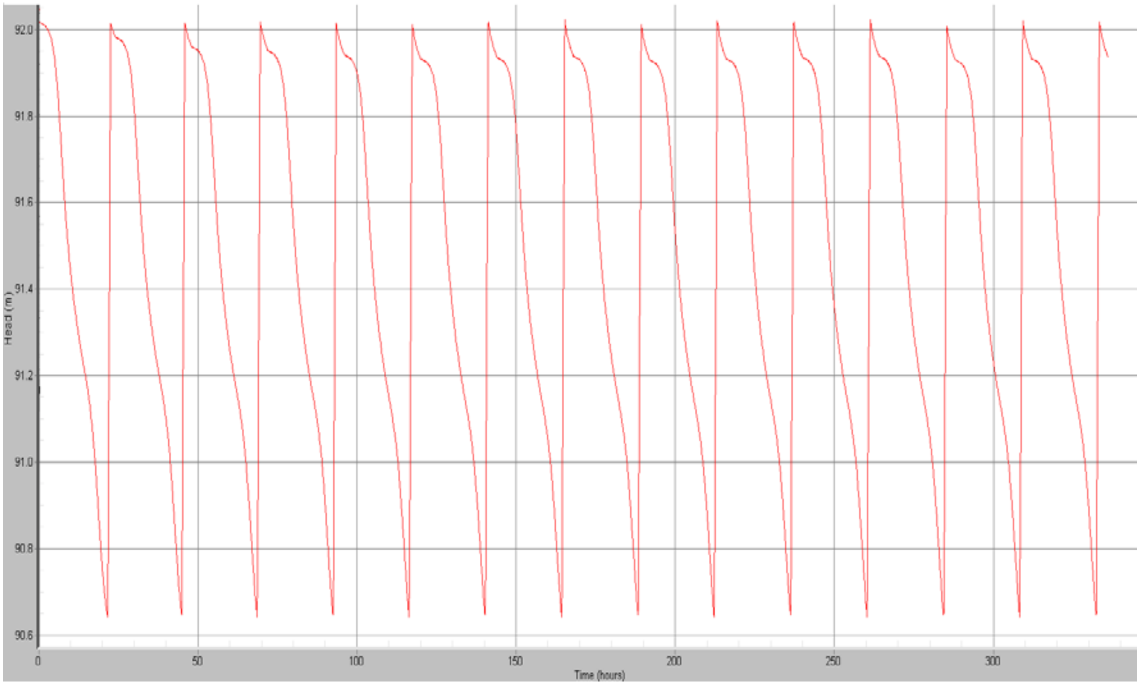


A: PSM, Tank 1 head

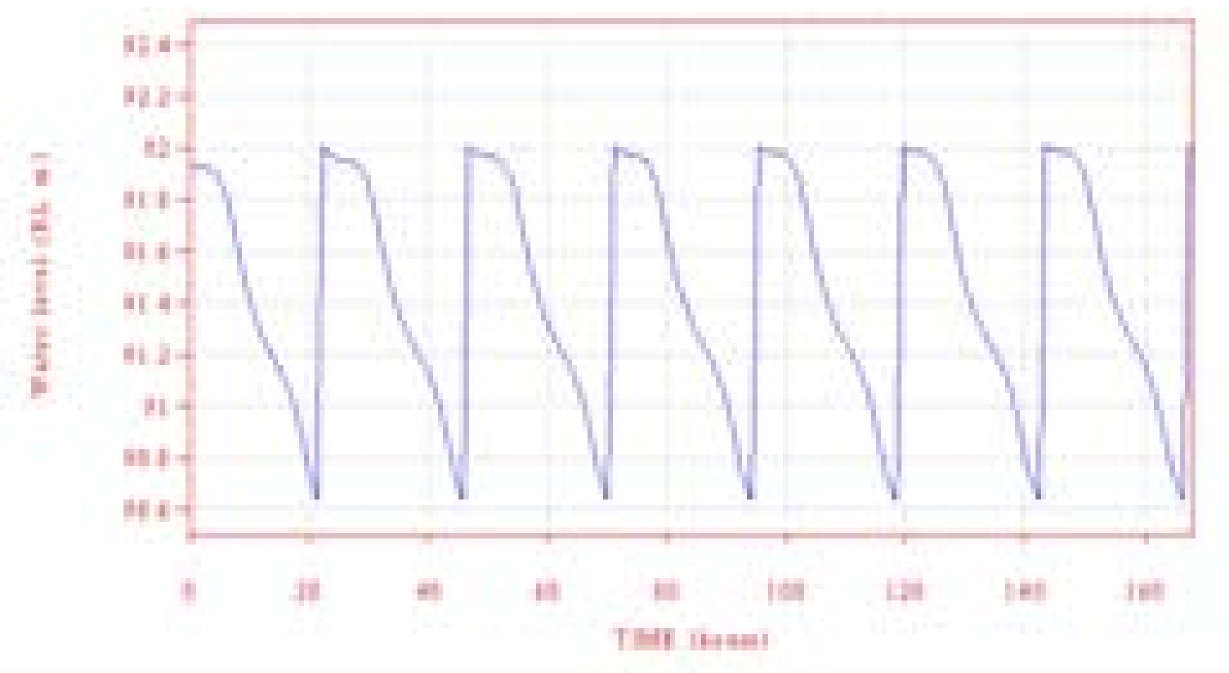


B: WATSYS, Tank 1 head

Figure 7.9: Tank 1 calibration.

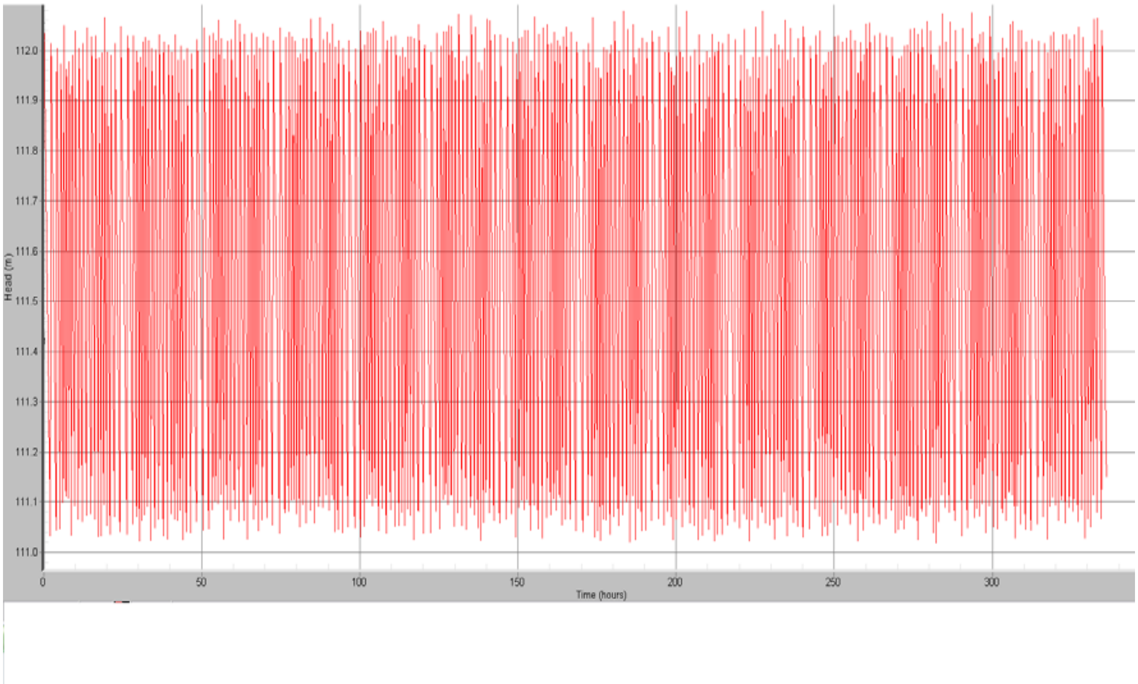


A: PSM, Tank 2 head

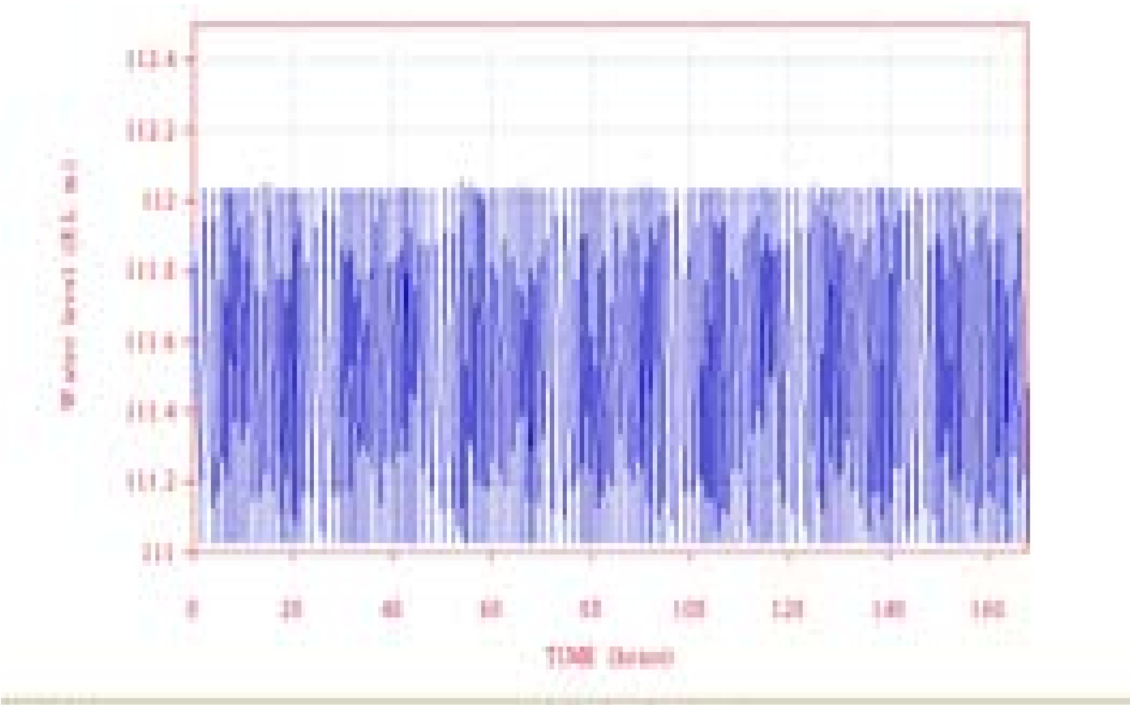


B: WATSYS, Tank 2 head

Figure 7.10: Tank 2 calibration.

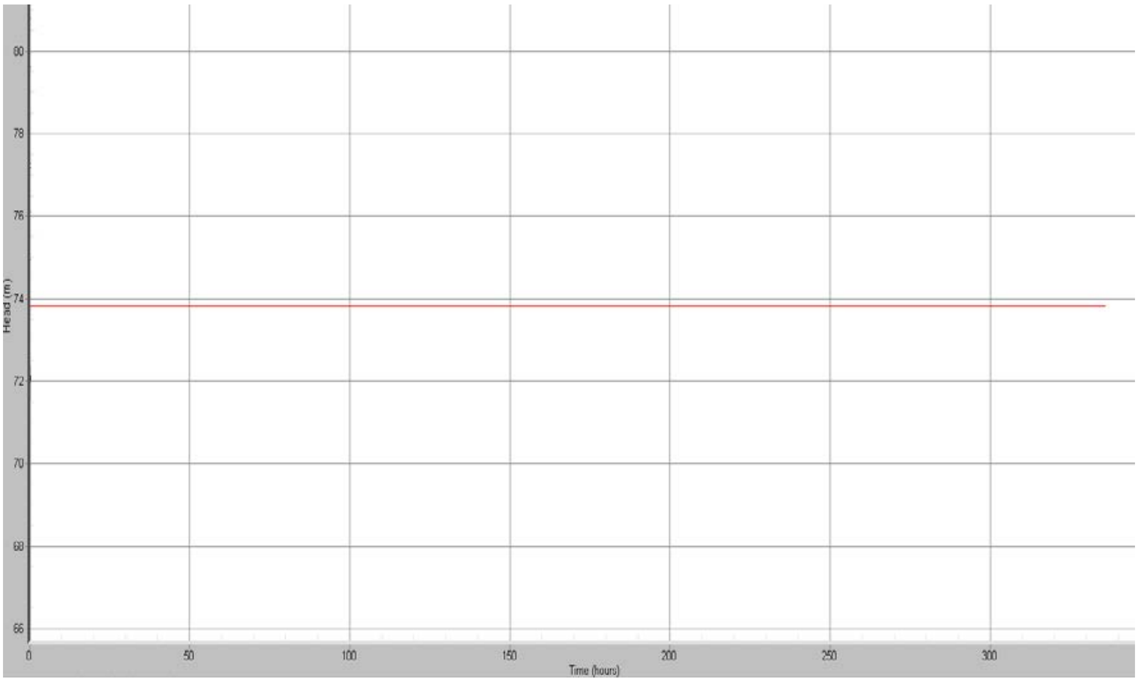


A: PSM, Tank 3 head

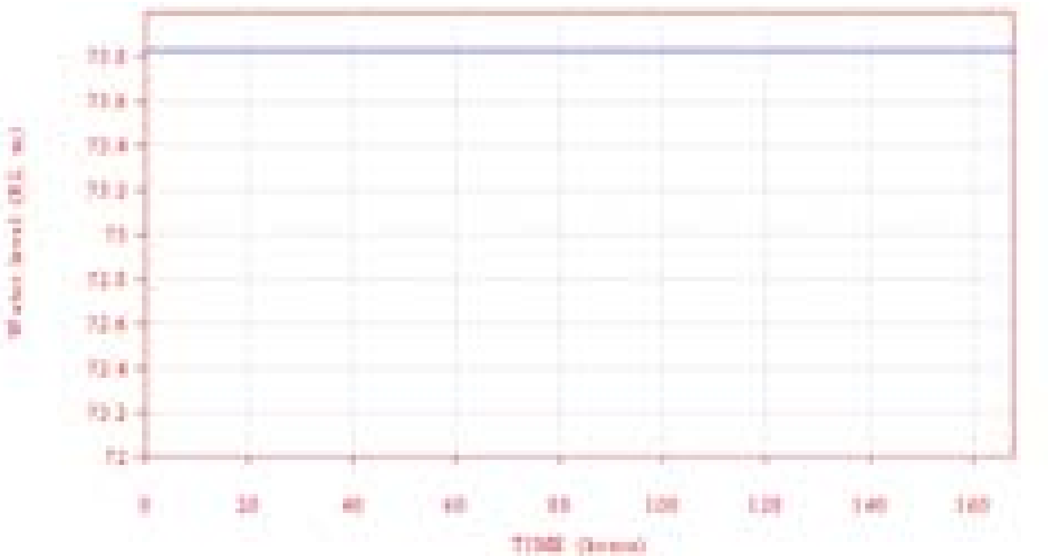


B: WATSYS, Tank 3 head

Figure 7.11: Tank 3 calibration.



A: PSM, Reservoir 2 head



B: WATSYS, Reservoir 2 head

Figure 7.12: Reservoir 2 calibration.

7.5 Conclusion

From the hydraulic validation exercise of the EPAnet-PSM output with that of WATSYS it was found that the newly built hydraulic network performs hydraulically in a similar way in reservoirs, tanks and randomly selected links (pipes) and valves. Hence, this network can be simulated to predict sediment transport using the capabilities of EPAnet-PSM.

CHAPTER 8 SIMULATION OF SEDIMENT TRANSPORT AND ITS RELATION TO COMPLAINTS

8.1 Introduction

One of the aims of this project was to understand the capability of the software (Particle Sediment Model- PSM (EPAnet-PSM)) developed to predict the sediment concentration in pipes of drinking water distribution and reticulation networks. Now that the hydraulics of the PSM for the selected network have been validated against WATSYS, which has been validated by the Water Corporation against field data, it is possible to implement the PSM to predict sediment movement.

The PSM assumes that sediment transport is controlled by gravity settling, and by resuspension due to flow velocity. It assumes that all particles entering the network originate from the treatment plant and that no other processes occur inside the network. These particles are assumed to settle under the influence of gravity and/or resuspend when the flow velocity is above a certain threshold level (a user-defined resuspension velocity). As the run continues, sediment is slowly distributed over the respective network. For the whole network, the model calculates the amount of settled sediment in each location at each time step. In the PSM, bed-load transport is not implemented. Bed-load transport is the (slow) movement of sediment at the bottom of the pipe.

In this chapter, the hydraulics of the Zone M network are assumed to be correct as they have been validated against the WATSYS model used by the Water Corporation. It should however, be noted that traditional calibration usually considers reservoirs, tanks and major pipes rather than individual pipes and nodes. Individual pipes supplying only the local area are subjected to a much higher variation in flow rates compared to main pipes. This implies that the pattern usually derived from demand in major pipes cannot accurately predict velocity or flow in smaller pipes. The accuracy of a sediment transport model to predict complaints requires the model to take into account local hydraulic variations and the history of sediment transport (such as previous hydraulic events, cleaning operations etc) which usually occur in individual pipes. The network configuration is then used to predict the sediment transport to understand whether the PSM model could be utilised to predict complaints. In a typical network, the sediment concentration at the start of a given burst pipe event depends on historical hydraulic events and sediment characteristics.

8.2 Methods and Procedures

The following procedure was applied:

8.2.1 Attaining Initial Sediment Concentration before Burst Pipe Event is Initiated:

In drinking water networks, reservoirs are usually placed in the network to store water, but this is not dealt with separately in the model. It assumes that the sediment coming from the treatment plant is not stored (settled) inside these reservoirs but transported (or suspended) through the pipes. In the EPAnet, a reservoir was utilised with a 100 m "total head". In the PSM, it is not possible to enter an initial sediment concentration for a particular pipe. This was overcome by having two parallel but identical reservoirs; one with a zero "source sediment quality" and the other with 1000 mg/L. The one with a high sediment concentration was allowed to supply water for two days (although this concentration is quite high, it was set to produce a rapid response using the model). The reservoir was then switched to the one with zero sediment concentration by making the "source sediment quality" equal to zero for the rest of simulation time, as illustrated in paragraph (7.2.3).

8.2.2 Settlement and Resuspension Characteristics of Sediment

The PSM model uses the characteristics of sediment as input; this means that velocities at which the sediment suspends, resuspends and/or settles have to be determined. Research has been carried out by Jayaratne et al. 2004, as illustrated in Chapter 2, by obtaining samples of particulates from water distribution systems in Melbourne, Adelaide, Sydney and Brisbane. In the initial phase of the project, the values of the velocities were utilised. In the PSM "sediment options", the "settling velocity" was entered as 0.000016 m/s, the "deposition velocity" was 0.07 m/s and the "resuspension velocity" was 0.2, 0.4, and 0.6 m/s. All other factors were left at their default values. "Enable particles module" in the model was amended from "no" to "yes". Simulations were then run in the PSM over three days (72 hrs) to understand the connection between complaints and burst pipe data (C&B).

8.2.3 Pipe Materials

The majority of the pipes in Zone M network were made of reinforced concrete, although many different materials such as: asbestos-containing, medium density polyethylene, high density polyethylene, steel, ductile iron, mild steel cement lined pipe and cast iron were also used. There were two sets of possible beta factors to choose from. The PSM model allowed selection of two primary pipe types, Poly Vinyl Chloride (PVC) and all other pipe material (a range is available within this second category, Concrete Lined Cast Iron (CICL)). All pipes were assumed to have the same beta factors programmed into PSM as those empirically determined in a cast iron concrete lined (CICL) pipe. The simulation was run using the option “user defined 1” which had factors equal to the second category CICL pipe types. The “user defined 1” pipe was selected by clicking on the “pipe” and selecting “user defined 1” from “material type”.

8.2.4 Time Step in Sediment Calculation

The Zone M EPAnet model was run with the EPAnet-PSM over a period of 72 hours (3 days). Zone M hydraulic patterns were pre-programmed into the model at one hour intervals. In the “time options”, the “hydraulic time step” and “pattern time step” were both set to 1:00 to reflect the way the patterns had been programmed. Both the “quality time step” and “reporting time step” were entered as 1:00 as only hourly results were required. The “source sediment quality” was nominally entered as 1000 mg/L for two days (as outlined previously in paragraph 7.2.3) at Reservoir 1 belonging to the network.

8.2.5 Graphical Display

In order to graphically display the sediment accumulation and resuspension with respect to velocity, the pipes were arbitrarily selected by double clicking on every one. The “graph” icon was then selected, the "graph type" selected was "time series", the "parameters" selected were "velocity", "sediment concentration" and "settled sediment". These displayed three graphs simultaneously of all velocities, sediment concentrations and settled sediment against time (i.e., 72 hours) or the "table" icon was selected to transfer the data to the Excel program.

8.3 Complaints and Burst Pipes Data Validation on PSM

Many simulation runs were undertaken to evaluate the PSM predictions. As an example, burst pipes data from 28/12/2006 was selected and related complaints were used for matching with the PSM results. As illustrated in Figure 8.1, during that particular date, there was a burst pipe in suburb A and there were seven related complaints. Simulations were then run in the PSM over a 3 day (72 hr) time period.

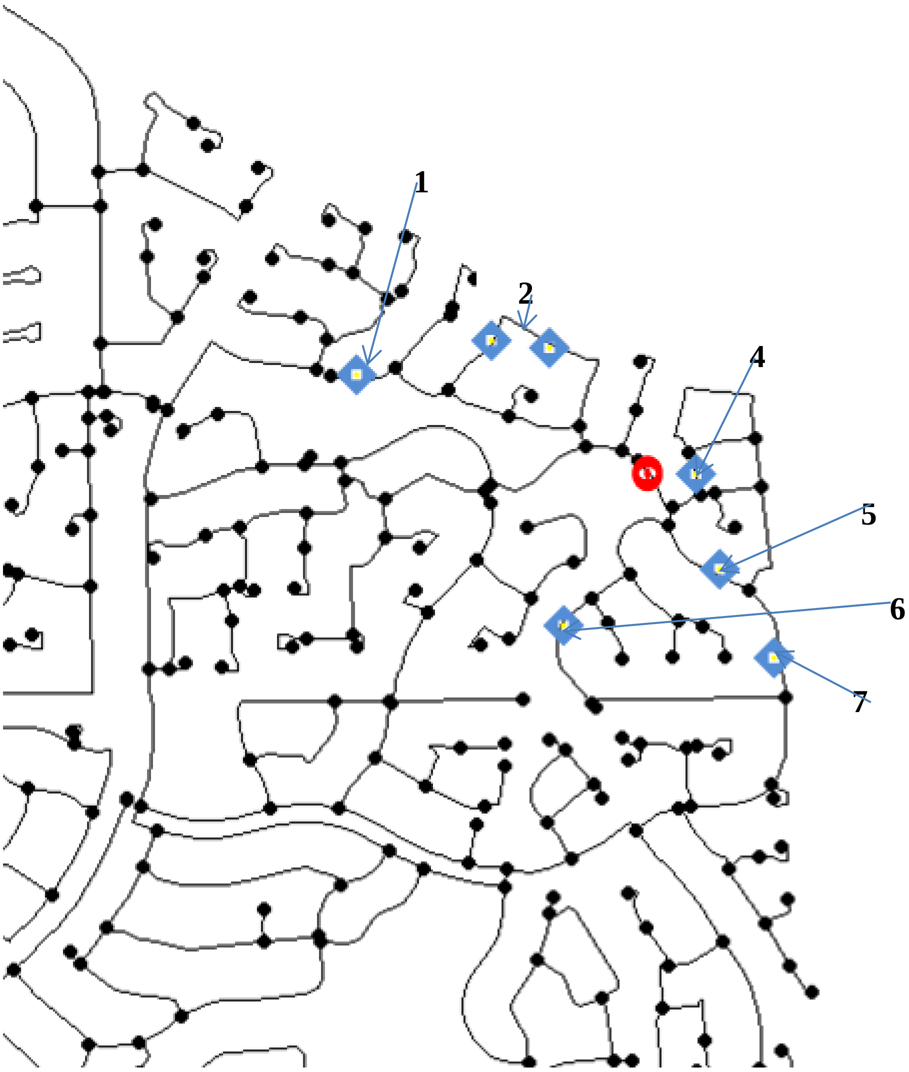


Figure 8.1: Burst pipe in suburb A and seven related complaints on 28 December 2006 (The red mark is the pipe where there was increased demand or it is the location of the burst pipe. The blue mark is the pipe which supplied water to the customer who reported the complaint).

The burst pipe pattern was entered as an increase in demand to 10 L/s for six hours at a downstream node, as shown in Figure 8.2. The pipe was assumed to have burst at the beginning of the 3rd day of the simulation run time of 72 hours (i.e., from 49 hrs to 55 hrs). Figure 8.3 shows the PSM velocity profile before and during the burst pipe event at suburb A. It is clear from this figure that normal velocity was less than 0.2 m/s in all the pipes that experienced complaints, but during the six hour long burst pipe event the sediment concentration changed to different values in different sections of the network, as illustrated in Figure 8.4, with 0.6 m/s as the resuspension velocity. However, affected pipes can change depending on the value of the resuspension velocity (0.2, 0.4, and 0.6 m/s) which is manually entered. This can be tested by assigning a different resuspension velocity for each run.

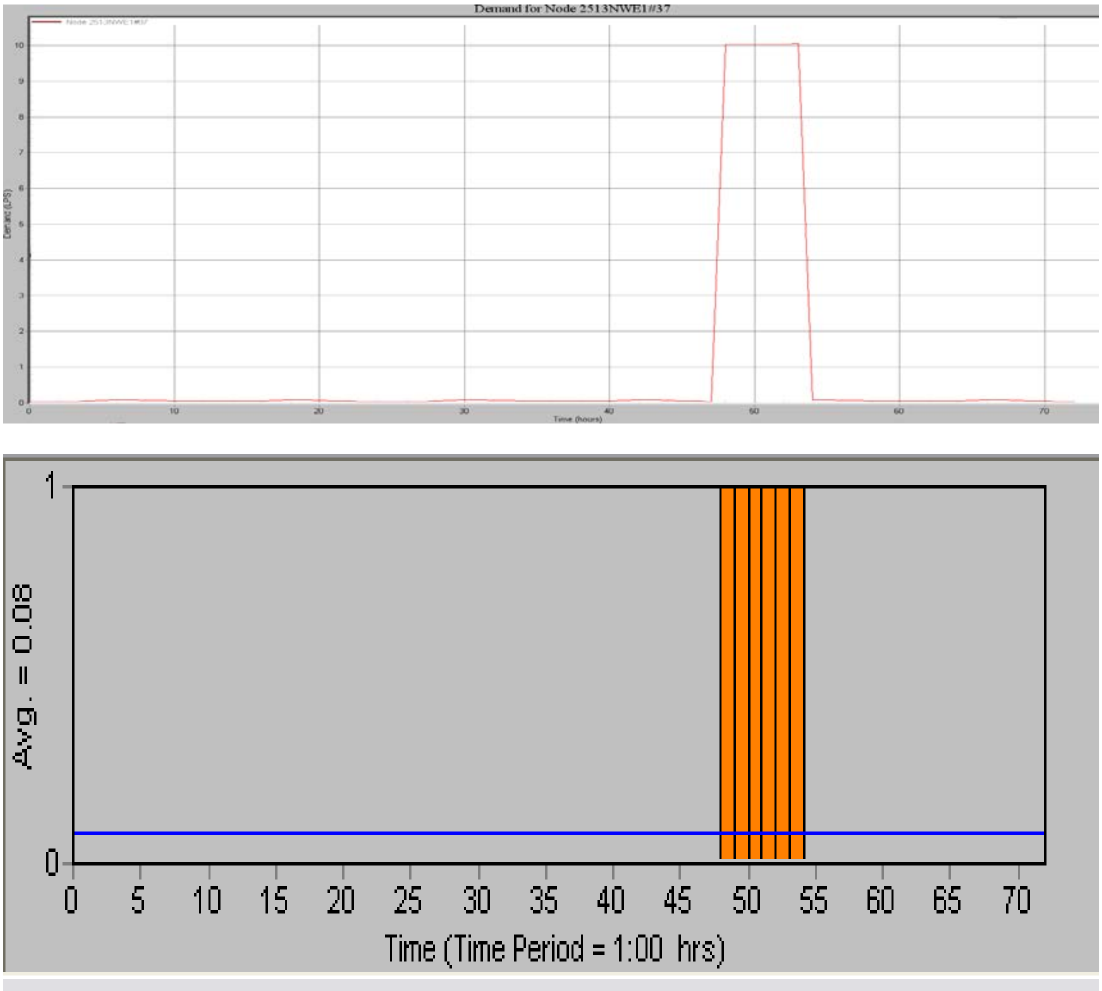


Figure 8.2: PSM graph of downstream node demand.

Figure 8.3: PSM velocity before (left) and during burst pipe event at suburb A.

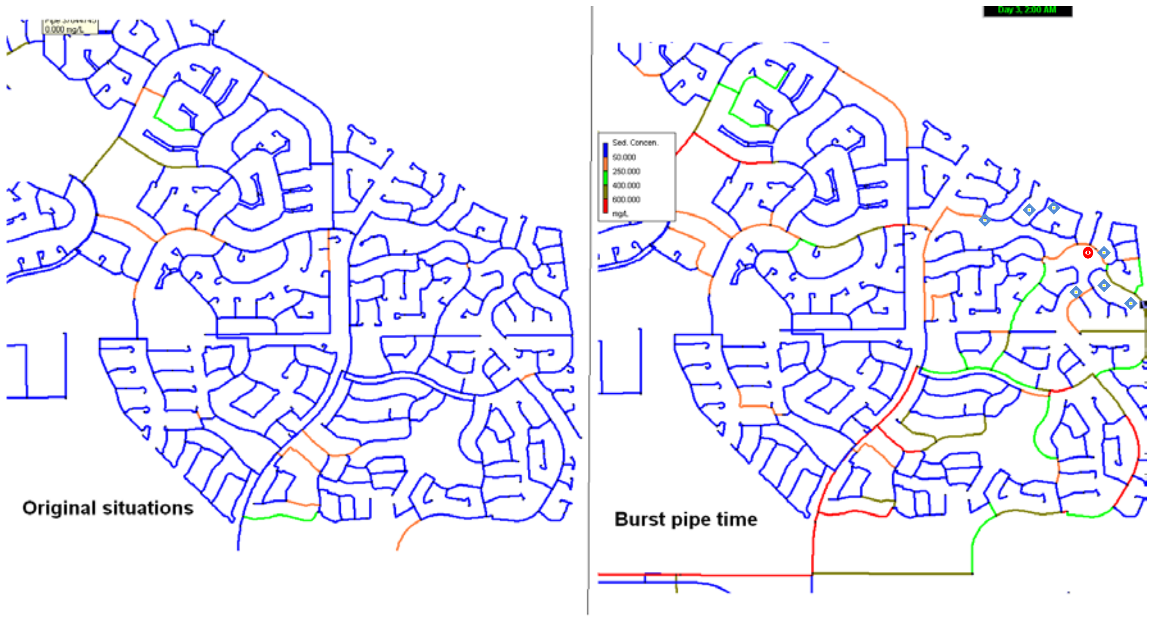
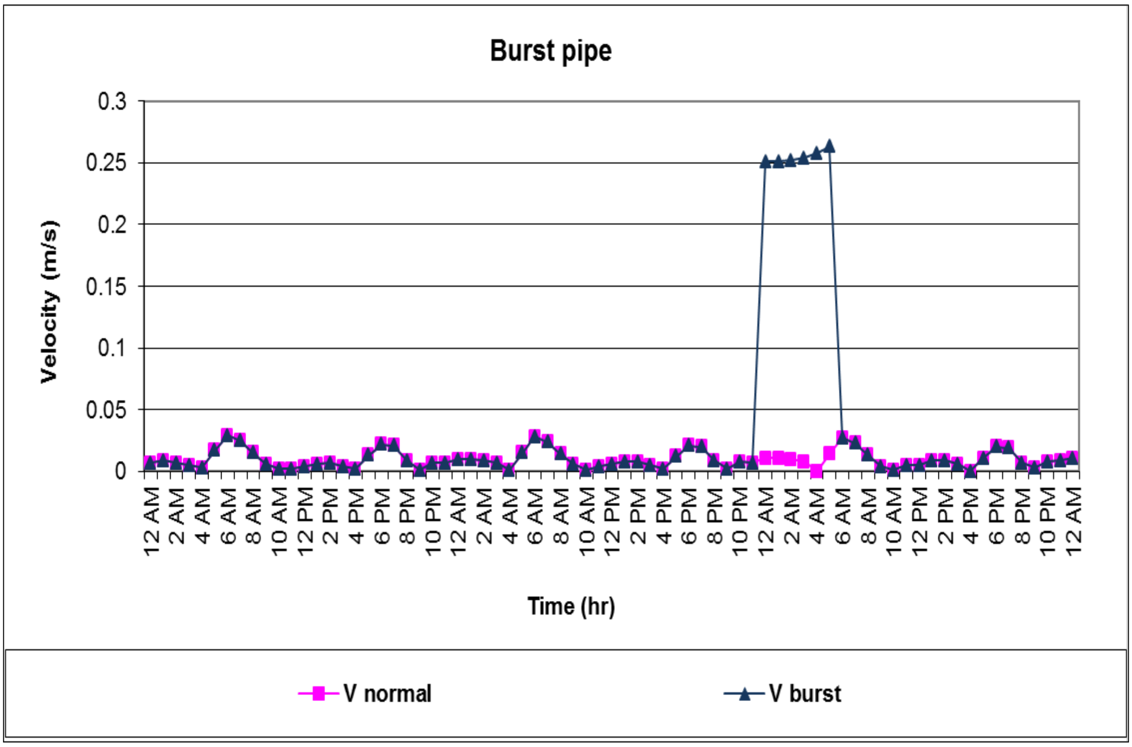


Figure 8.4: PSM sediment concentration (in bulk water) results with 0.6 m/s resuspension velocity during original situation and burst pipe time, at Suburb A, with all complaints and burst pipe locations.

Firstly, from the results, one can notice that sediment concentration increased greatly in numerous locations, which is not surprising given all the pipes started with some sediment in them. Not all increases in sediment concentrations will result in complaints as customers may not be at home to notice and lodge a complaint, or they may just accept the situation. If the overall results of velocities and sediment concentrations were matched with the locations of complaints, as illustrated in Figures 8.3 and 8.4, to obtain a basic understanding of the affected area trends, it may be noticed instantly that there is no relationship between the sediment concentration and the complaints locations. In places where sediment concentrations were higher (not blue), complaints were not consistently registered. Complaint locations are marked with blue squares. In some cases, these matched with higher concentrations, in others complaints were made by customers even when the sediment concentrations were low. It is also obvious that sediment concentrations in other parts of the system were high but complaints were not logged by customers.

Figures 8.5 to 8.11 show the PSM prediction of sediment concentration and velocity with time for, a given burst pipe and all pipes that supplied water to the complaints pipe, using 0.6 m/s as a resuspension velocity.



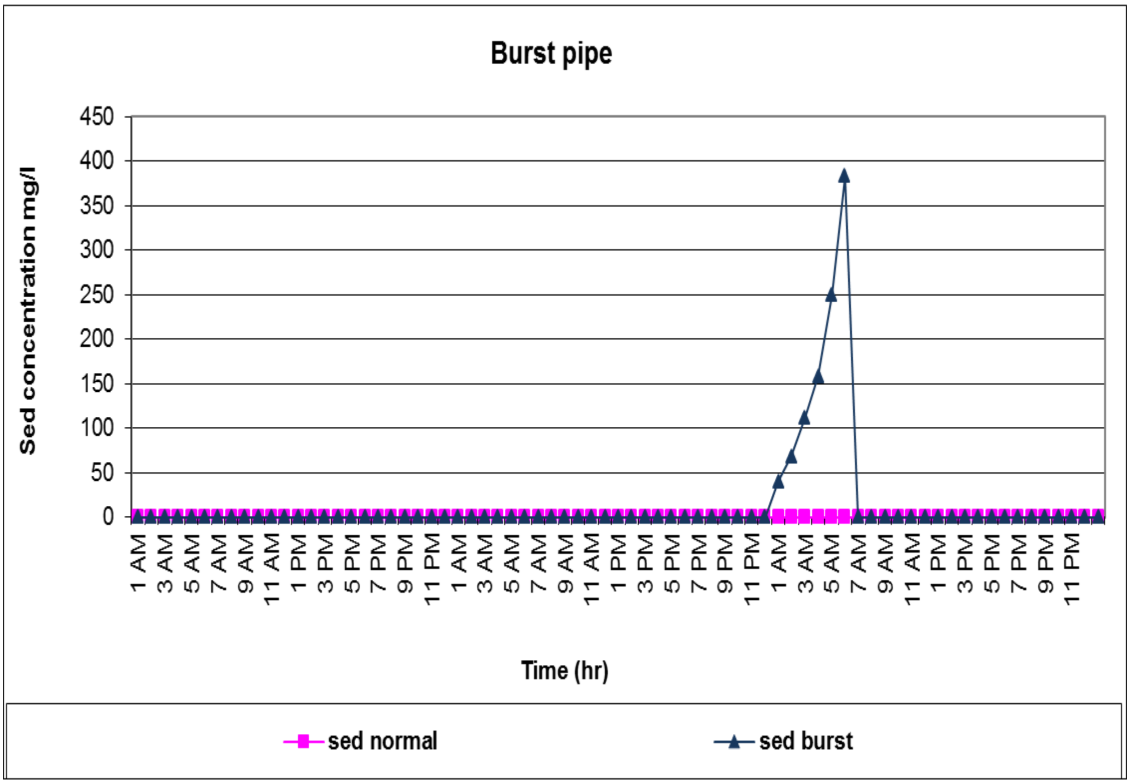
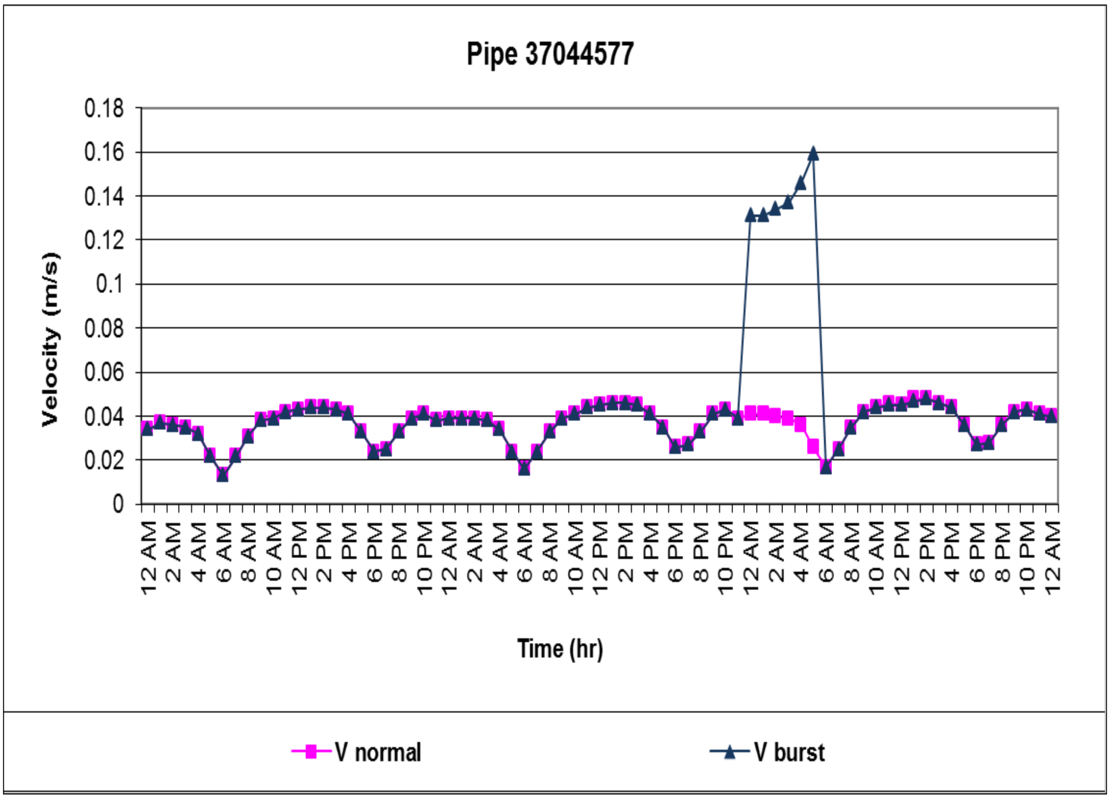


Figure 8.5: The PSM prediction of velocity and sediment concentration in the burst pipe during both a normal (before burst pipe) and burst pipe event, if resuspension velocity is equal to 0.6 m/s.



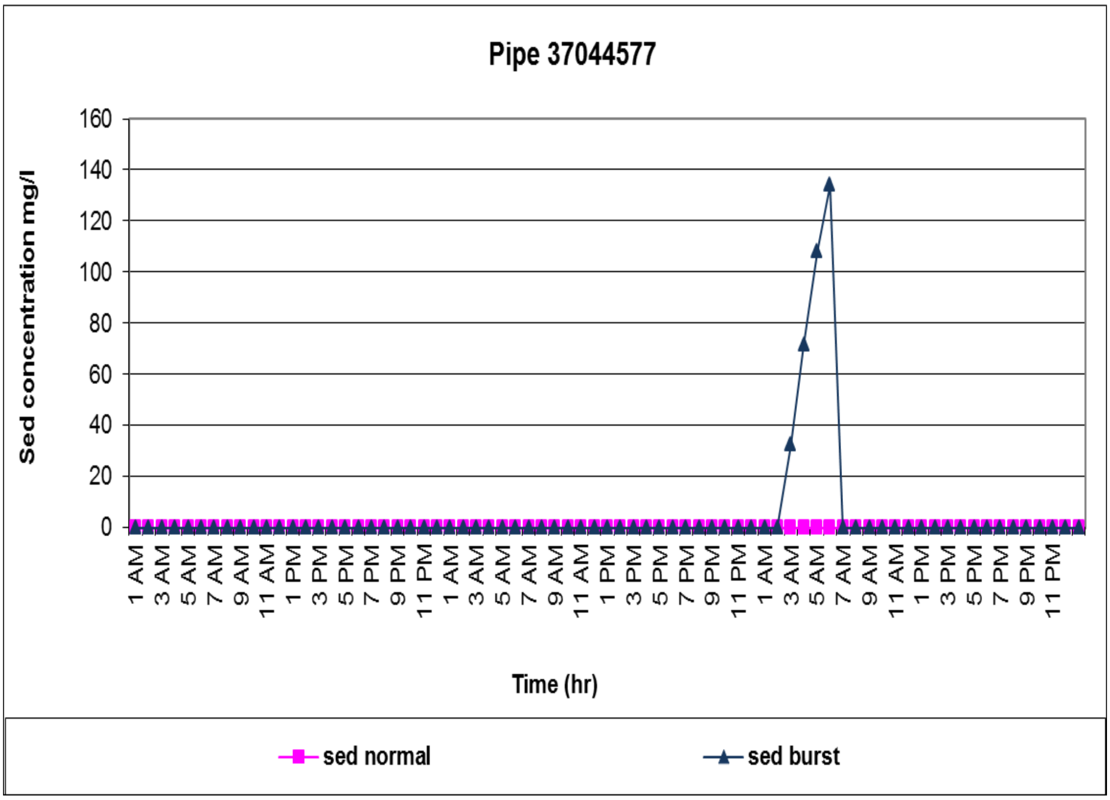


Figure 8.6: The PSM prediction of velocity and sediment concentration in the complaint 1 pipe during both a normal (before burst pipe) and burst pipe event if resuspension velocity is equal to 0.6 m/s.

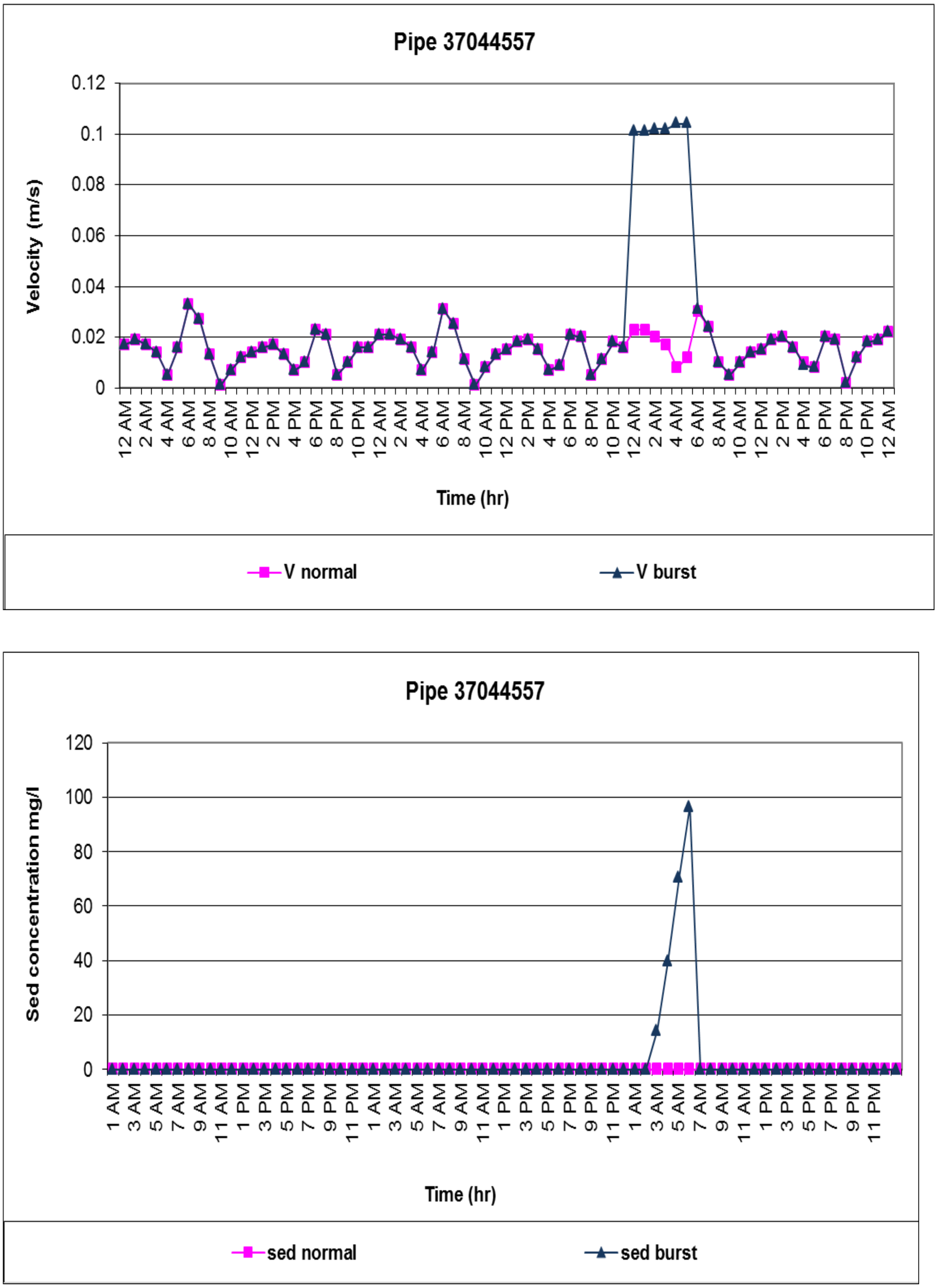
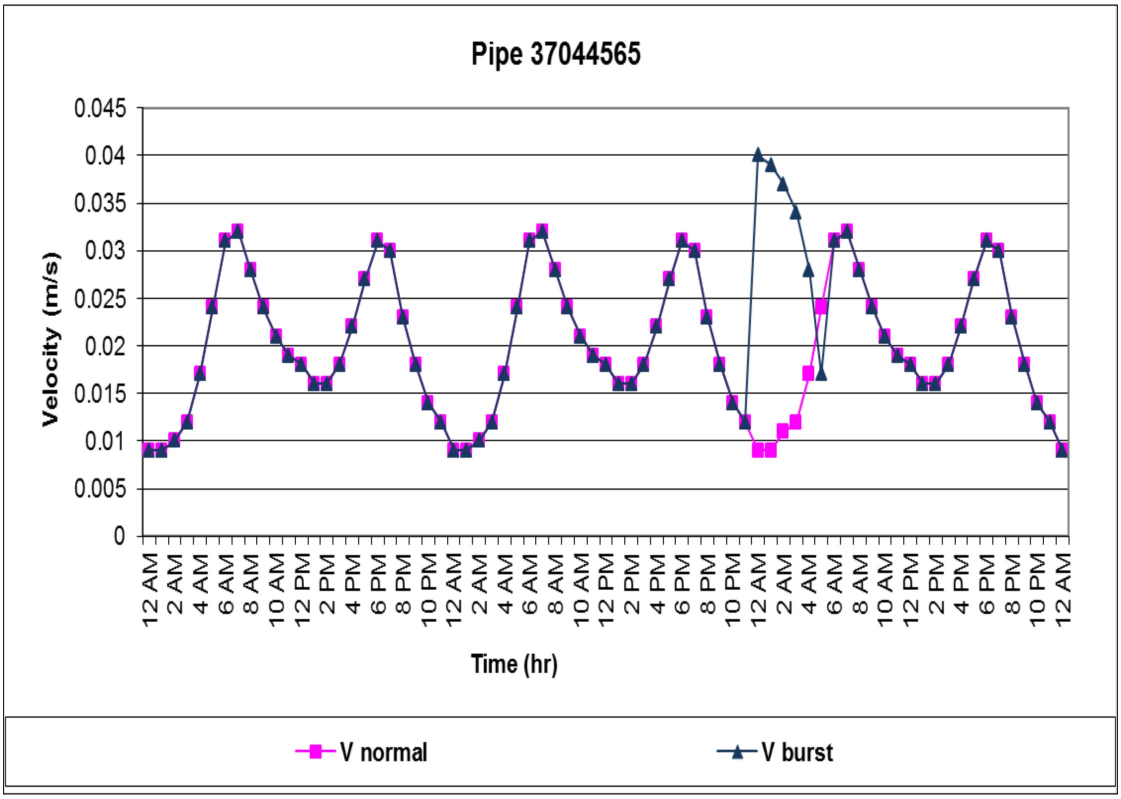


Figure 8.7: The PSM prediction of velocity and sediment concentration in the complaints 2 and 3 pipe during both a normal (before burst pipe) and burst pipe event if resuspension velocity is equal to 0.6 m/s.



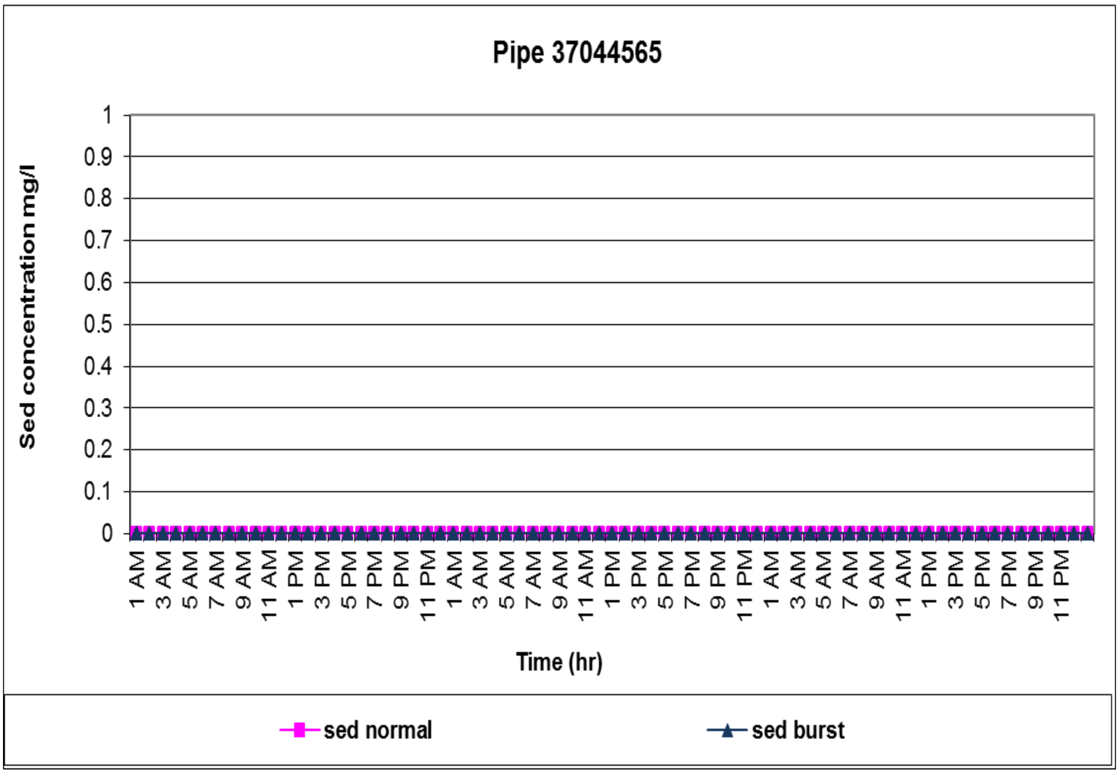
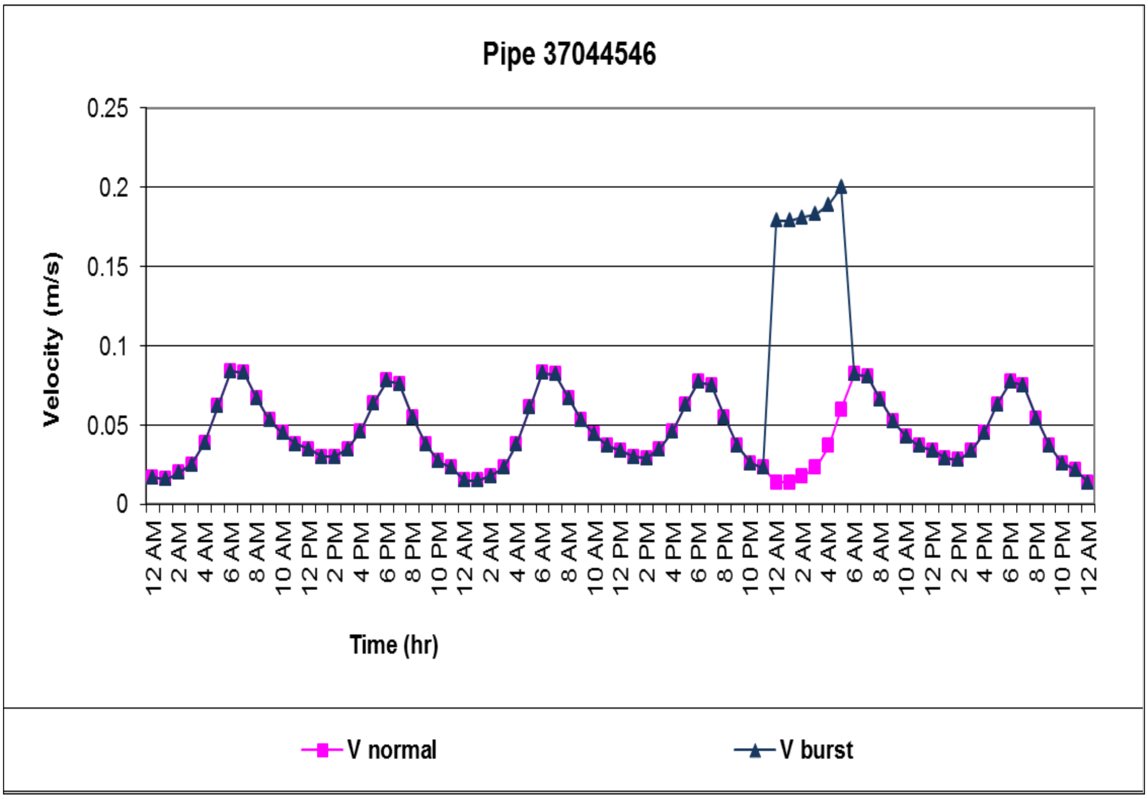


Figure 8.8: The PSM prediction of velocity and sediment concentration in the complaint 4 pipe during both a normal (before burst pipe) and burst pipe event if resuspension velocity is equal to 0.6 m/s.



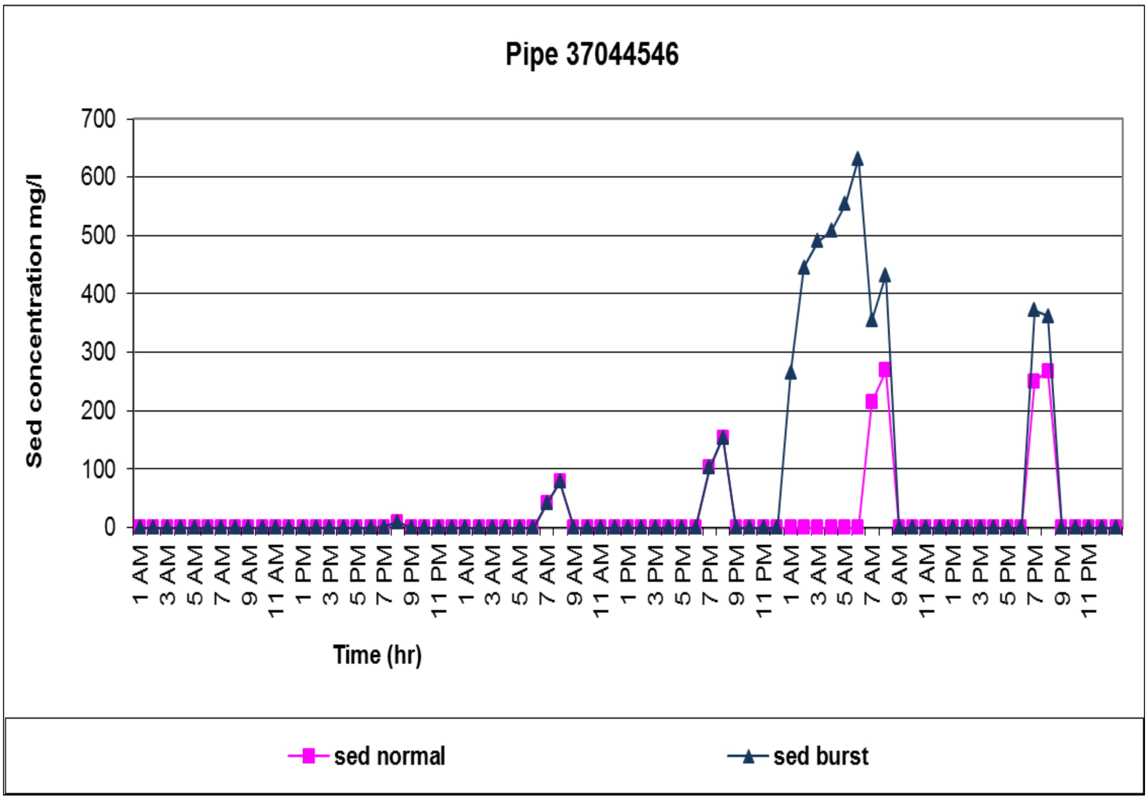
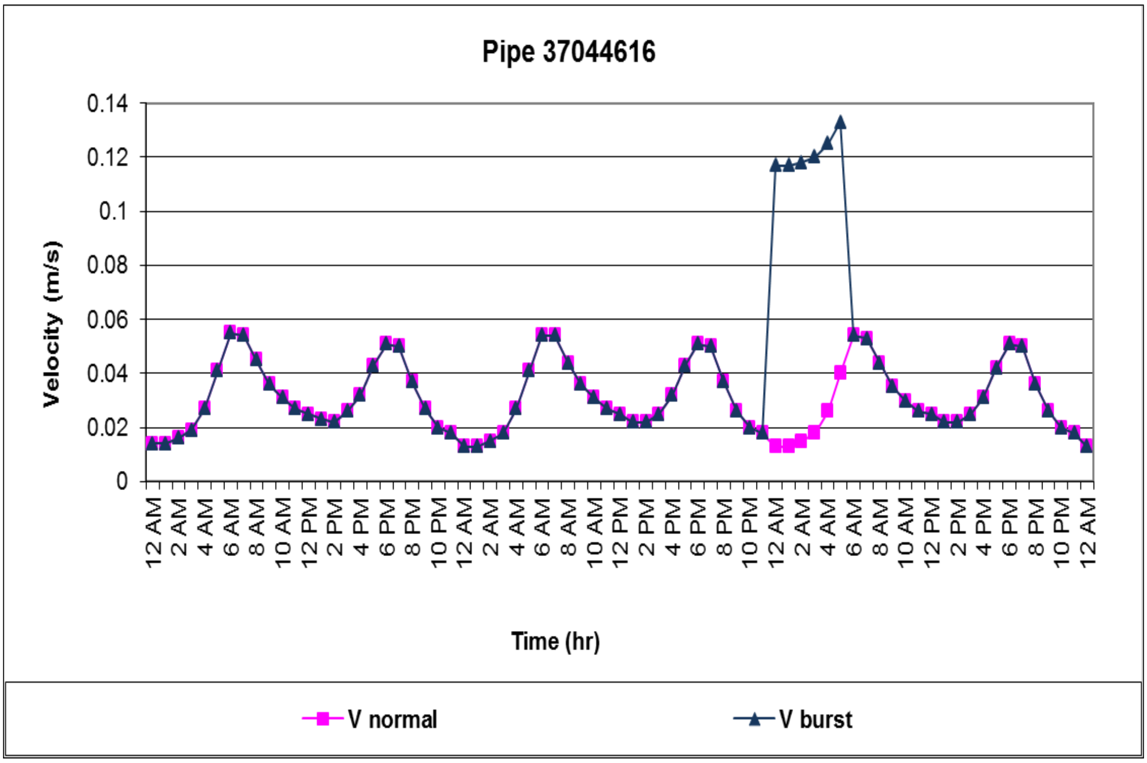


Figure 8.9: The PSM prediction of velocity and sediment concentration in the complaint 5 pipe during both a normal (before burst pipe) and burst pipe event if resuspension velocity is equal to 0.6 m/s.



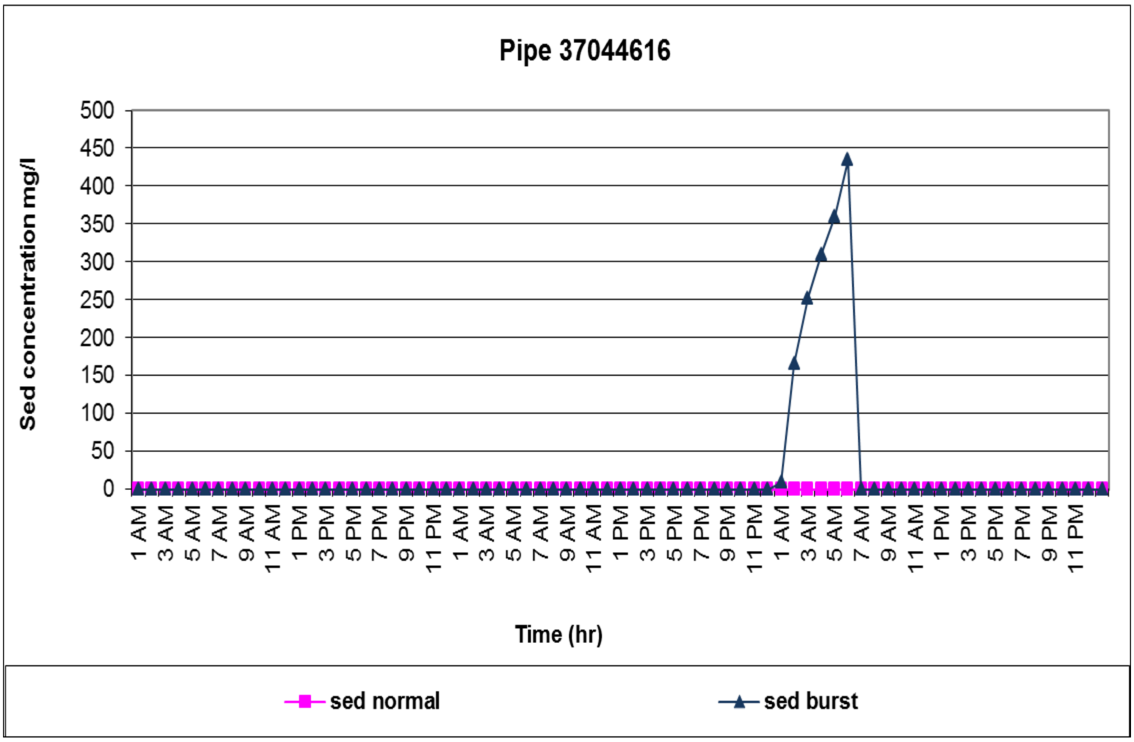
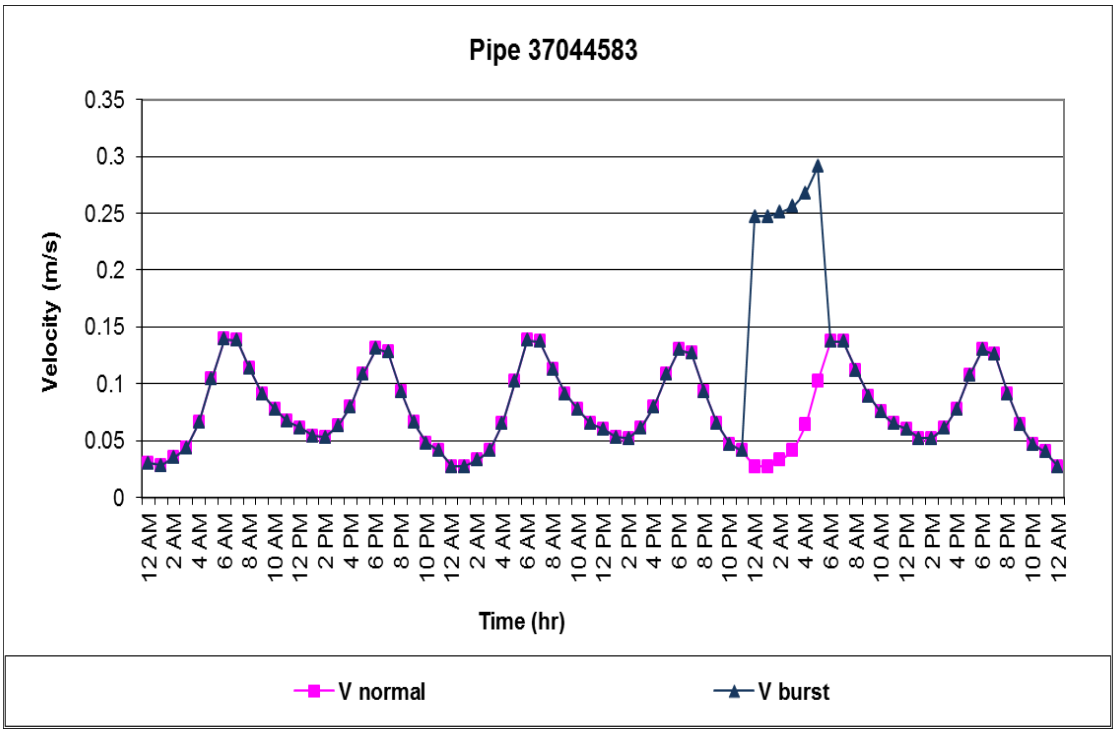


Figure 8.10: The PSM prediction of velocity and sediment concentration in the complaint 6 pipe during both a normal (before burst pipe) and burst pipe event if resuspension velocity is equal to 0.6 m/s.



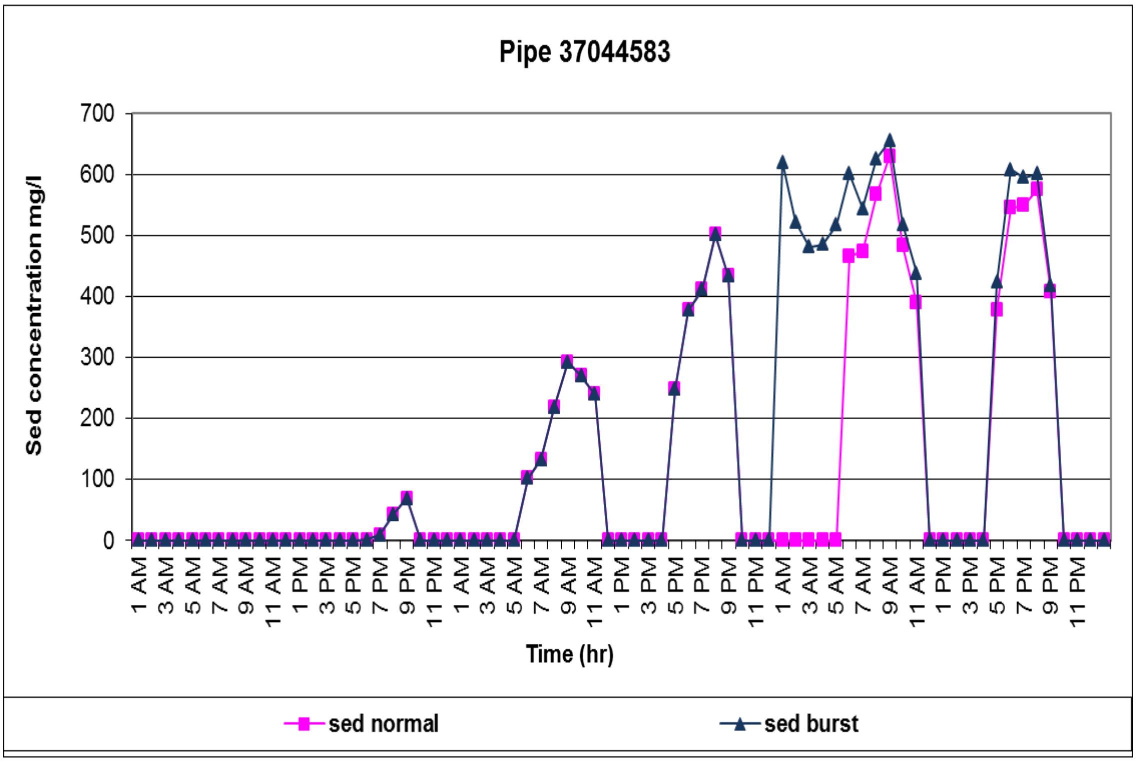


Figure 8.11: The PSM prediction of velocity and sediment concentration in the complaint 7 pipe during both a normal (before burst pipe) and burst pipe event if resuspension velocity is equal to 0.6 m/s.

As expected, figures 8.5 to 8.11 illustrate that the PSM was not able to accurately predict the complaints when a resuspension velocity of 0.6 m/s was utilised. During a burst pipe event, the sediment concentration prediction for pipe “37044565”, complaint 4 was found to be zero. In addition there were complaints even when the velocities in the pipe were 0.16, < 0.11, 0.04, 0.2, and 0.13 m/s. Figures 8.6, 8.7, 8.8, 8.9, and (8.10) show the predicted sediment concentrations were reaching 383, 134, 96, 0, 631 and 434 mg/l respectively. While the sediment concentration prediction in pipe “37044583” pipe of complaint 7 was high at 654, it was near the maximum during normal flow, as shown in Figure 8.11. The sediment concentration increased even before the burst pipe event occurred. As sediments were input into the system pipes before the burst pipe event, pipes were made dirty. Since pipes need not always be dirty, increased sediment concentration and zero complaints are not unexpected. However, it is not acceptable to have zero sediment concentration whilst still receiving complaints. Therefore, it was seen as advisable to attempt a lower resuspension velocity.

The PSM predictions for the sediment concentration for the same hydraulic conditions (velocity profile) as Figures 8.5 to 8.11 are illustrated in figures 8.12 to 8.18 when the PSM is assigned with 0.4 m/s resuspension velocity.

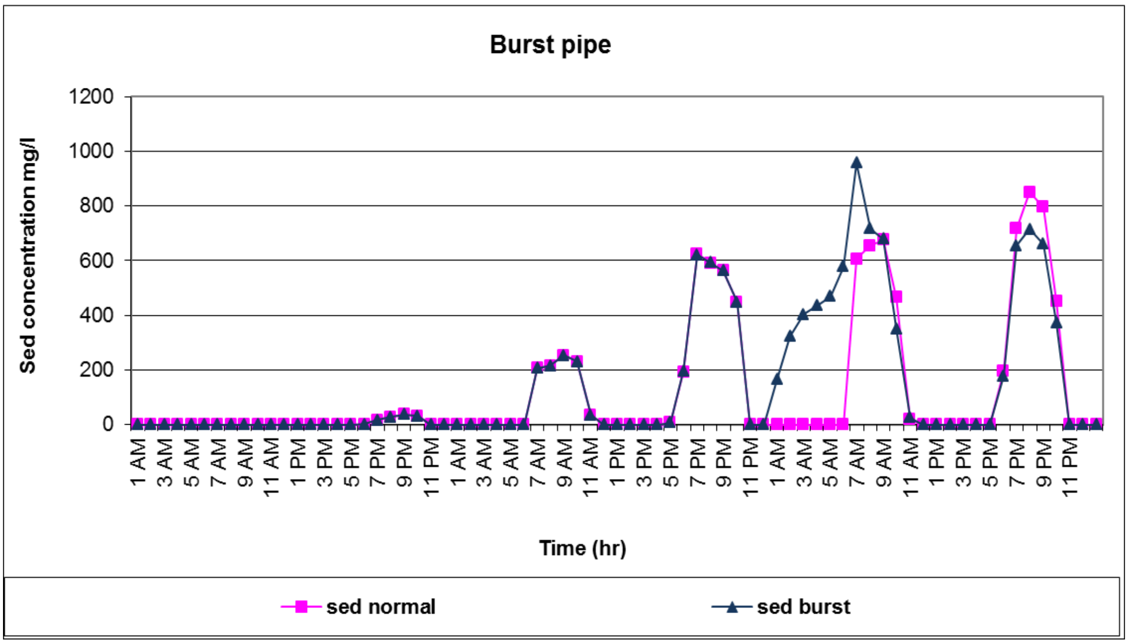


Figure 8.12: The PSM prediction of velocity and sediment concentration in the burst pipe during both a normal (before burst pipe) and burst pipe event if resuspension velocity is equal to 0.4 m/s.

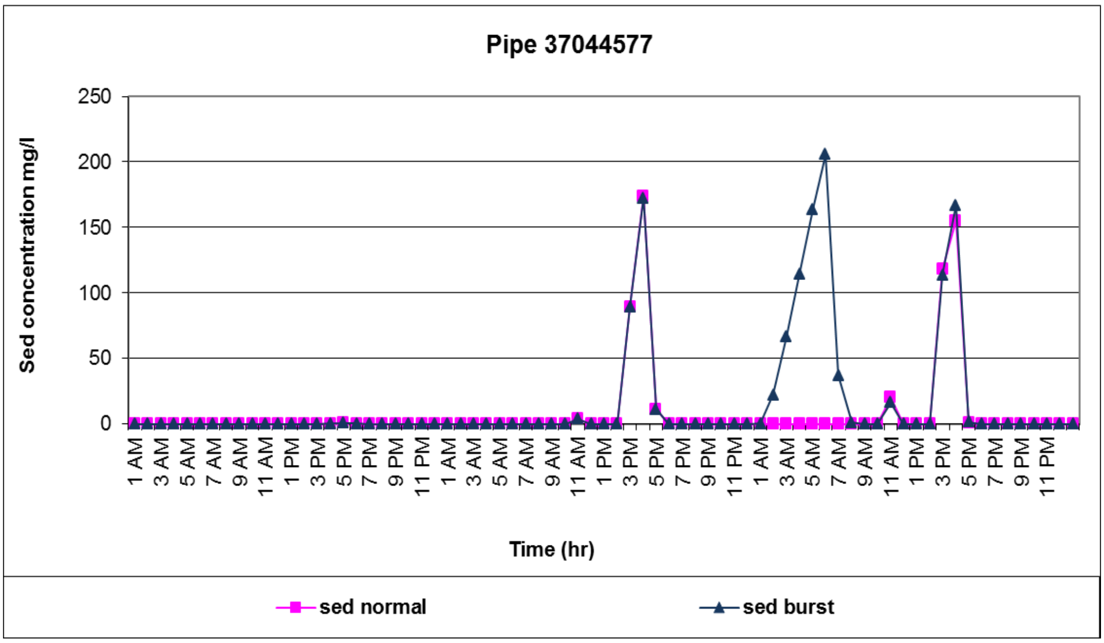


Figure 8.13: The PSM prediction of velocity and sediment concentration in the complaint 1 pipe during both a normal (before burst pipe) and burst pipe event if resuspension velocity is equal to 0.4 m/s.

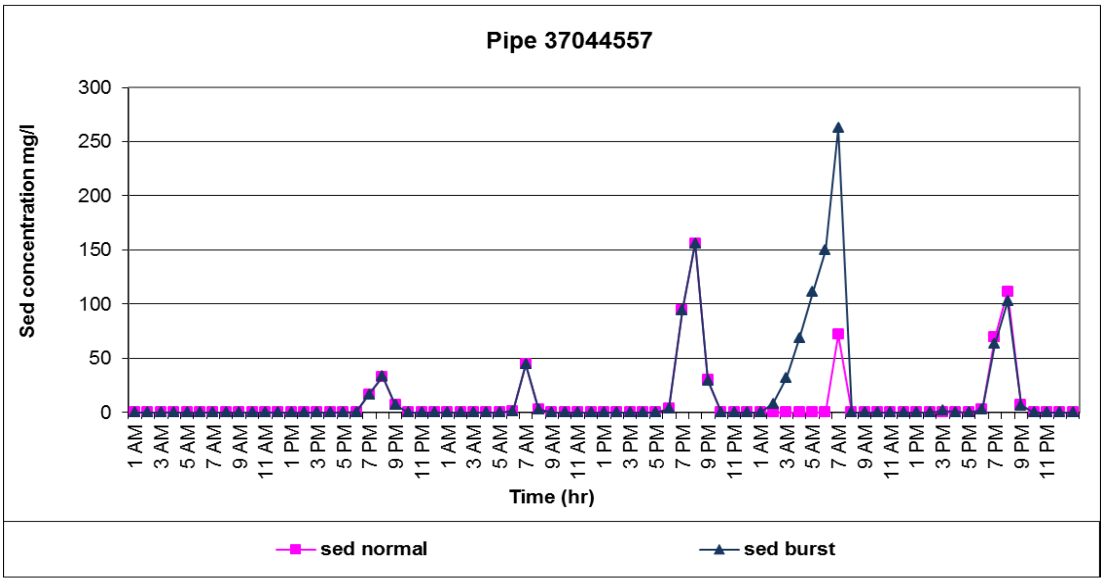


Figure 8.14: The PSM prediction of velocity and sediment concentration in the complaints 2 and 3 pipe during both a normal (before burst pipe) and burst pipe event if resuspension velocity is equal to 0.4 m/s.

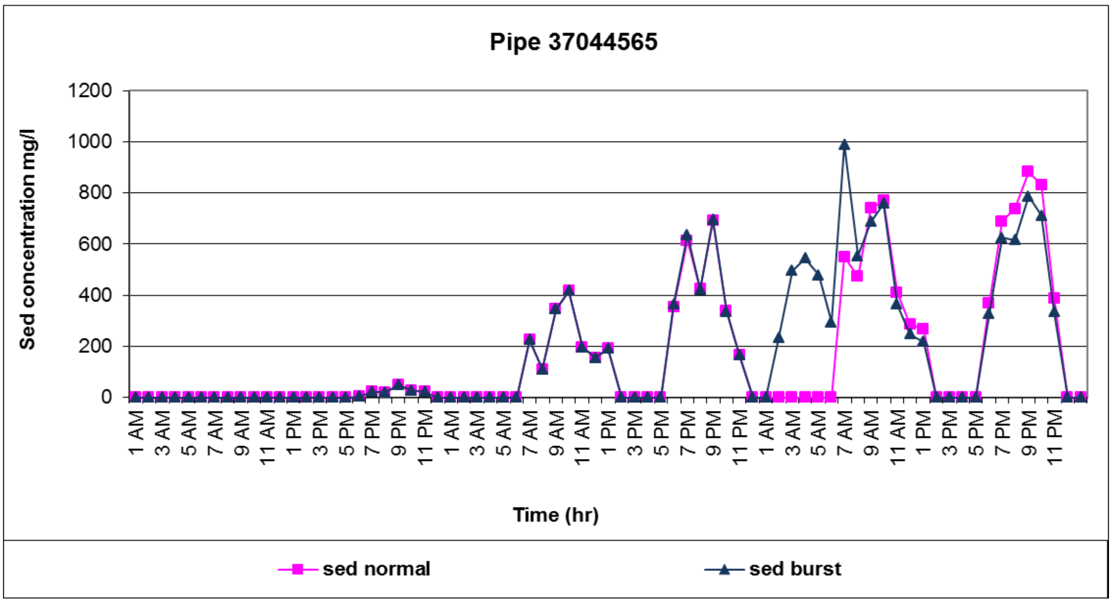


Figure 8.15: The PSM prediction of velocity and sediment concentration in the complaint 4 pipe during both a normal (before burst pipe) and burst pipe event if resuspension velocity is equal to 0.4 m/s.

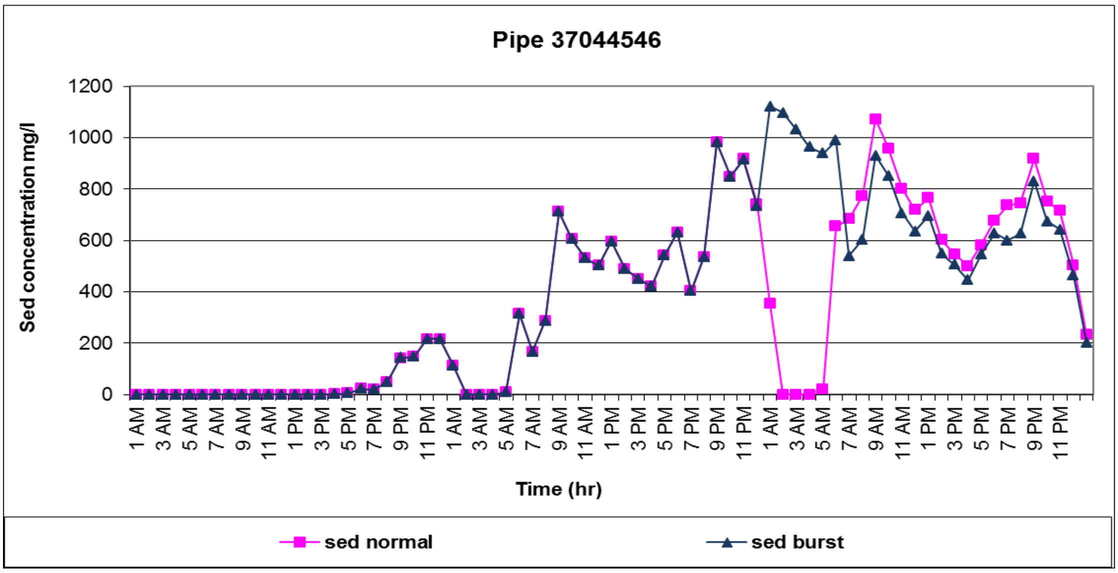


Figure 8.16: The PSM prediction of velocity and sediment concentration in the complaint 5 pipe during both a normal (before burst pipe) and burst pipe event if resuspension velocity is equal to 0.4 m/s.

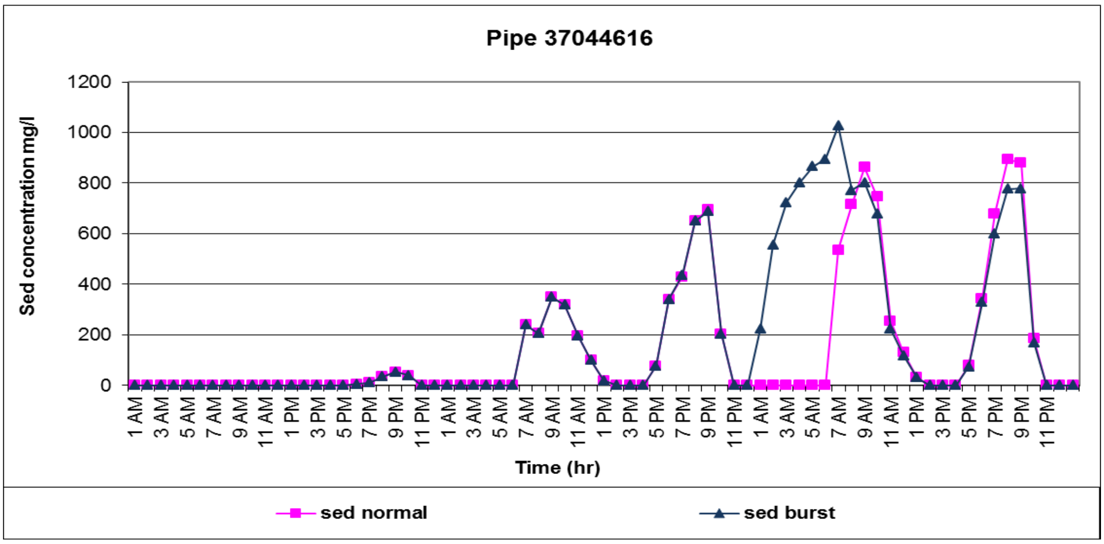


Figure 8.17: The PSM prediction of velocity and sediment concentration in the complaint 6 pipe during both a normal (before burst pipe) and burst pipe event if resuspension velocity is equal to 0.4 m/s.

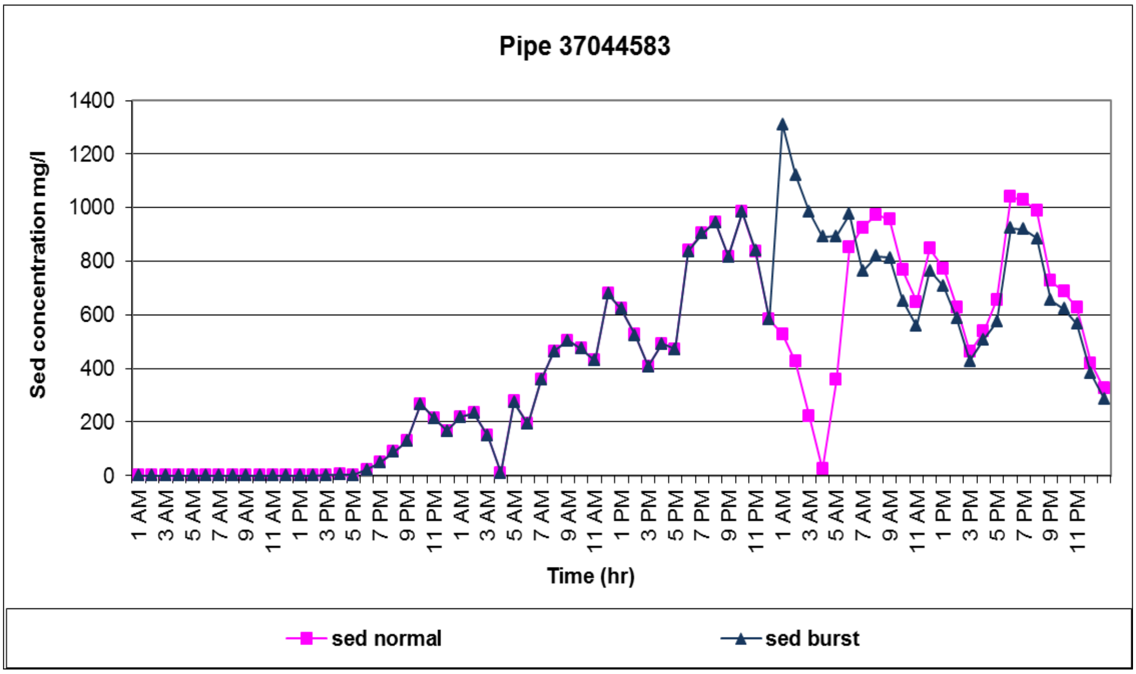


Figure 8.18: The PSM prediction of velocity and sediment concentration in the complaint 7 pipe during both a normal (before burst pipe) and burst pipe event if resuspension velocity is equal to 0.4 m/s.

In this instance, as illustrated in Figures 8.12 to 8.18, the PSM results predicted complaints even during a normal flow, and a burst pipe event always increased the sediment concentration in the water. There were complaints even when the velocities in pipes were 0.16, < 0.11, 0.04, 0.2, and 0.13, Figures 8.6, 8.7, 8.8, 8.9, and 8.10 respectively, and the predicted sediment concentration was near the maximum even during normal flow, as shown in Figures 8.6, 8.8, 8.9, and 8.10. There was no instance when the PSM predicted a zero sediment concentration but complaints were received. Therefore a resuspension velocity of 0.4 m/s performed better than 0.6 m/s.

Finally, the PSM prediction for the sediment concentration is shown in Figures 8.19 to 8.25 when the simulation was run with 0.2 m/s resuspension velocity.

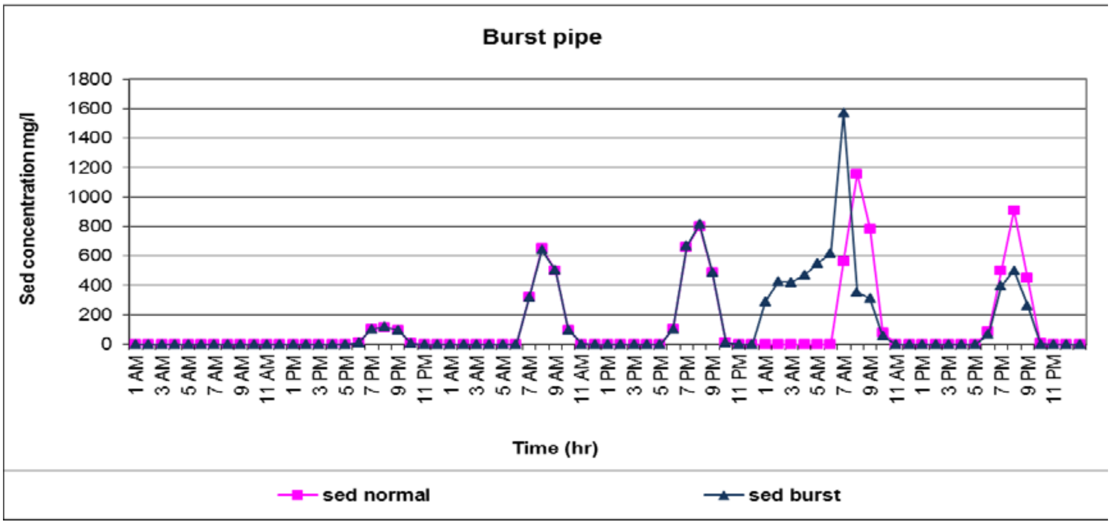


Figure 8.19: The PSM prediction of velocity and sediment concentration in the burst pipe during both a normal (before burst pipe) and burst pipe event if resuspension velocity is equal to 0.2 m/s.

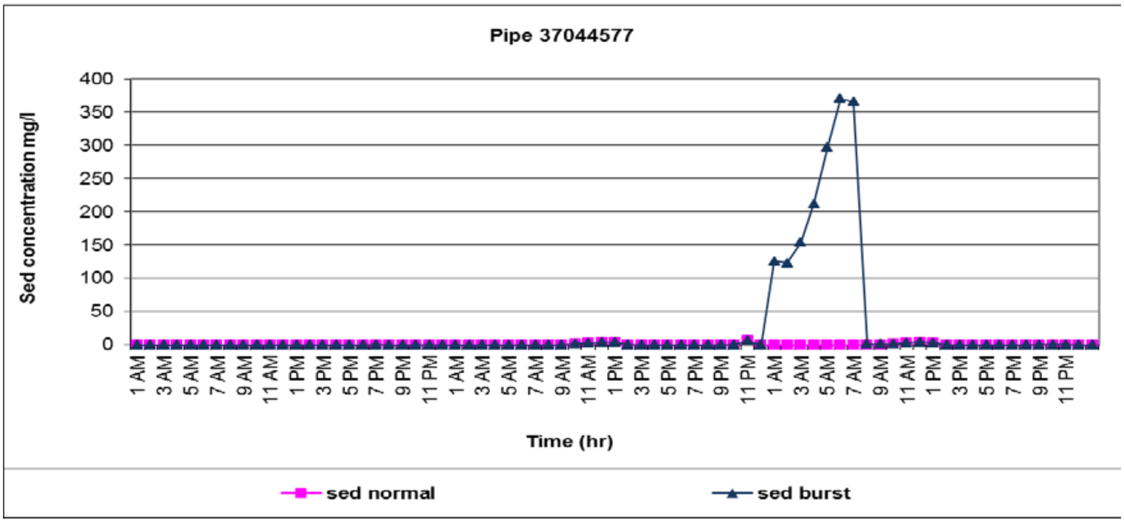


Figure 8.20: The PSM prediction of velocity and sediment concentration in the complaint 1 pipe during both a normal (before burst pipe) and burst pipe event if resuspension velocity is equal to 0.2 m/s.

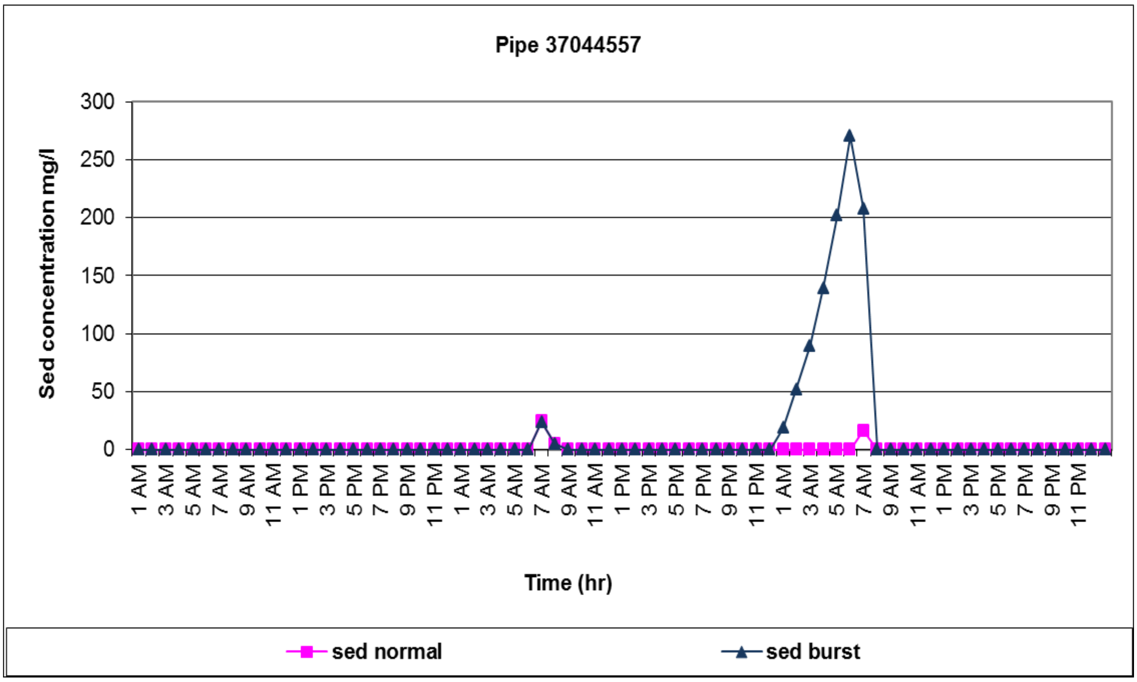


Figure 8.21: The PSM prediction of velocity and sediment concentration in the complaints 2 and 3 pipe during both a normal (before burst pipe) and burst pipe event if resuspension velocity is equal to 0.2 m/s.

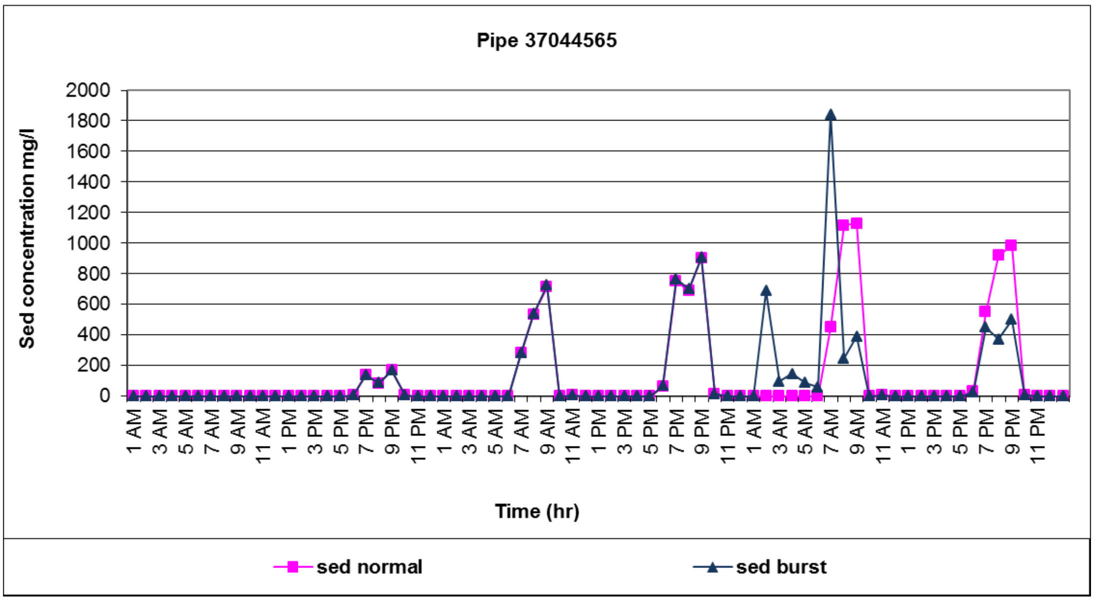


Figure 8.22: The PSM prediction of velocity and sediment concentration in the complaint 4 pipe during both a normal (before burst pipe) and burst pipe event if resuspension velocity is equal to 0.2 m/s.

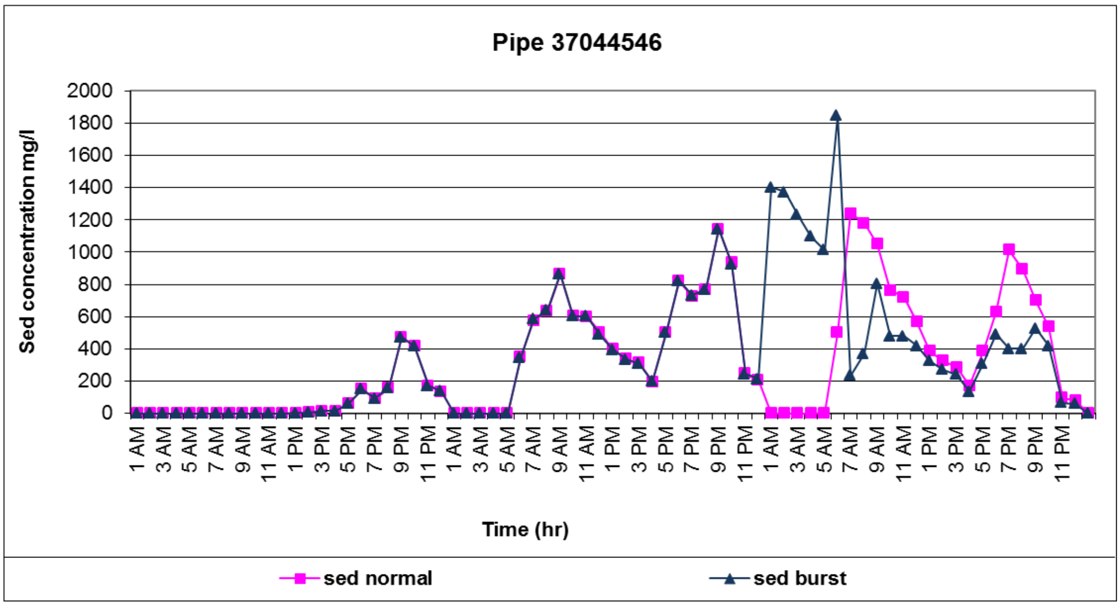


Figure 8.23: The PSM prediction of velocity and sediment concentration in the complaint 5 pipe during both a normal (before burst pipe) and burst pipe event if resuspension velocity is equal to 0.2 m/s.

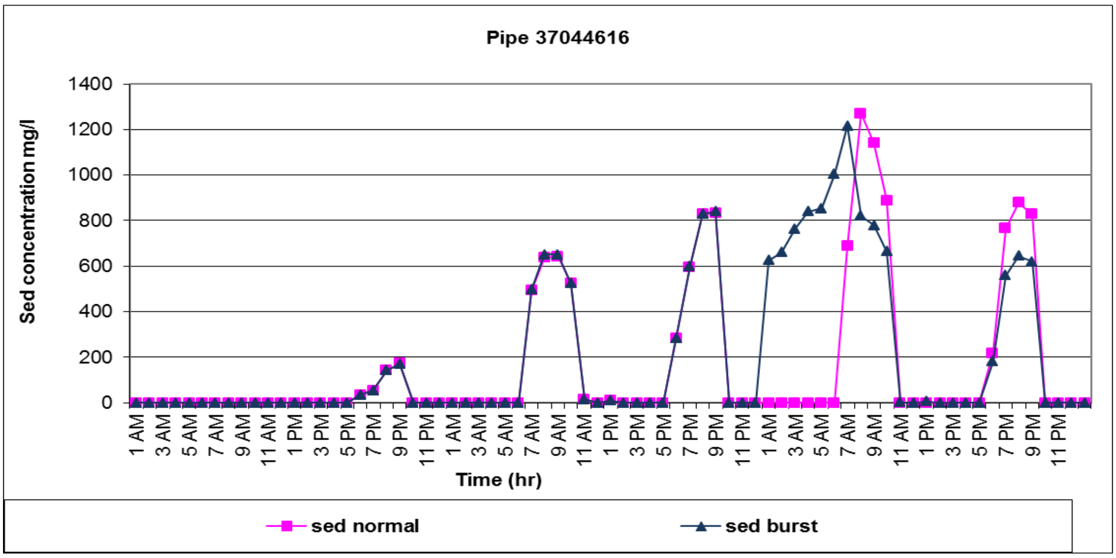


Figure 8.24: The PSM prediction of velocity and sediment concentration in the complaint 6 pipe during both a normal (before burst pipe) and burst pipe event if resuspension velocity is equal to 0.2 m/s.

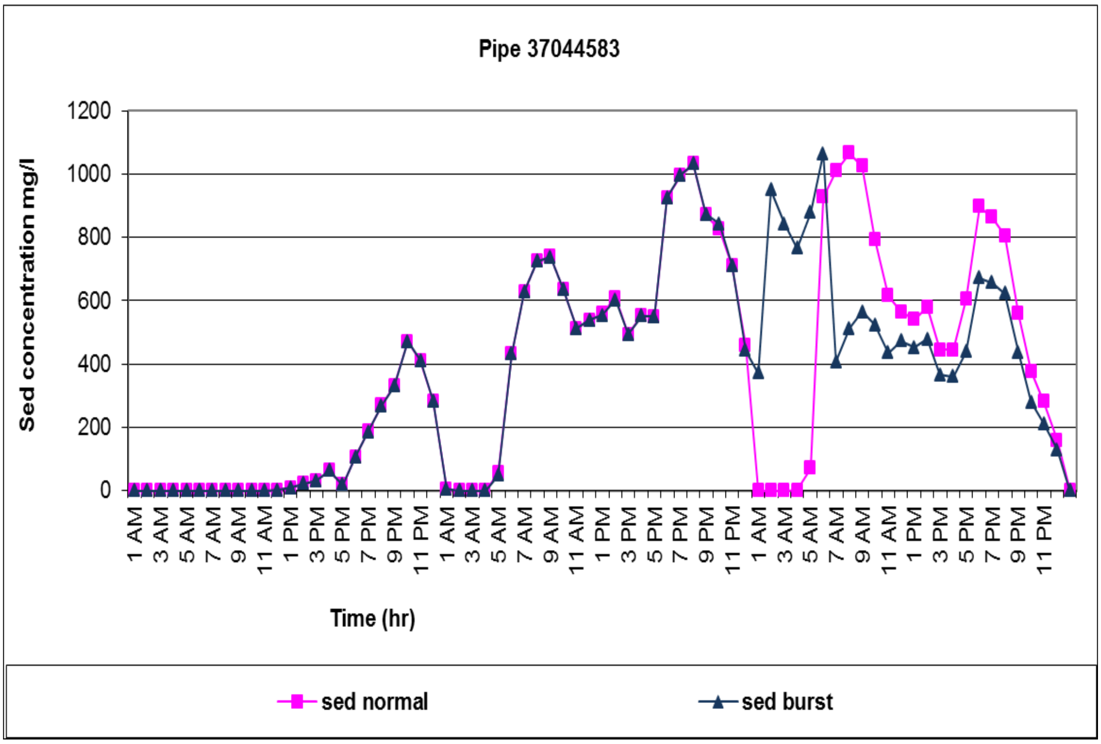


Figure 8.25: The PSM prediction of velocity and sediment concentration in the complaint 7 pipe during both a normal (before burst pipe) and burst pipe event if resuspension velocity is equal to 0.2 m/s.

The prediction of PSM using 0.2 m/s resuspension velocity is not found to be logical. As illustrated in the above figures, the prediction sediment concentration during the burst pipe event was near the maximum during normal flow, as shown in Figures 7.24 and 7.25. The sediment concentrations were too high during normal situations: 1200, 1130, 1240, 1270, and 1065 mg/l, as shown in Figures 7.19, 7.22, 7.23, 7.24, and 7.25.

8.4 Conclusion

As expected, the predicted sediment concentration was high during the burst pipe event, and interestingly it was near the maximum even during normal flow, as shown in many of the figures. These results suggest three important conclusions. Firstly, the resuspension velocity needs to be lower than the commonly used value of 0.6 m/s. Secondly, the sediment concentration in the pipe may not be as high as the value assigned before the burst pipe event. The PSM could be used to understand the potential risks associated with a hydraulic event but not in predicting exactly where complaints will or will not occur.

One of the aspects where prediction could be improved is in understanding the actual velocity profile and sediment transport characteristics in a field situation. Such an understanding would move the PSM's prediction capabilities towards reality. This is undertaken in the next chapter.

CHAPTER 9 FEASIBILITY OF USING EPANET-PSM FOR SEDIMENT TRANSPORT MODELLING

9.1 Introduction

In previous chapters it has been proven that breaking mains events or "burst pipes" are the principal cause of dirty water incidents. This is a significant finding from the results analysis of consumer complaints data (desktop study) which was confirmed by both RPM results and PSM simulation. The PSM results alone however, were not sufficient to predict when and where dirty water complaints would result. Most importantly, three issues were identified. Firstly, the hydraulics in individual pipes are largely unknown, although most simulations assume the same diurnal pattern with a known base demand. Secondly, the characteristics (settlement or resuspension velocities) of the sediment in individual pipes are not known. Thirdly, the sediment concentration in each pipe is not known, nor is the history of the hydraulics in a given pipe. If confidence is to be developed in the predicted values of sediment concentration, some of these unknowns should be more thoroughly understood. Therefore, a fieldwork (FW) study was conducted by manually creating a hydraulic event and monitoring the flow and turbidity as well as the complaints for the surrounding area. A desktop study of customer complaints, in conjunction with the RPM, was used to rank a group of suburbs in Zone M. The dirtiest suburb (D) was chosen to calibrate the EPAnet-PSM. Results from the EPAnet-PSM were subsequently compared with the fieldwork results to understand the feasibility of using the PSM as a tool to predict complaints.

9.2 Fieldwork Method and Materials

To confirm that the EPAnet-PSM correctly predicts relative amounts of sediment and its movement along the pipes of a drinking water distribution system, simulation results needed to be compared with field data. Fieldwork was achieved by manually creating an event and monitoring the flow and turbidity along with complaints for the surrounding area.

9.2.1 Rationale Behind the Selection of All Sites for Fieldwork

The system receiving water from Tank 2 was selected because it contained both suburbs E and D, both of which had recorded the highest number of complaints in the past, as illustrated in Chapter 4; Figures 4.2 and 4.10. This area was also a reasonably a small area to manage and was deemed to have the least impact on customers.

Two locations (L1 and L2), as shown in Figure 9.1 were selected as the major sites from where water was flushed during the fieldwork. L1 was located in suburb E and L2 in suburb D. Both locations had two hydrant points, necessary for reaching the planned flushing flow of 15 L/s.

The RPM investigation for both locations was held before the field trial to decide on the location for fieldwork. It involved conducting RPM tests until a high turbidity (> 10 NTU) was recorded at least twice. The purpose behind this investigation was to confirm which site had more sediment and to check all the surrounding valves.

Figure 9.1: The locations of selected pipes (L1 and L2) for major sites of fieldwork.

From previous RPM works, a sound background of information on the L2 pipe was available. RPM work had been undertaken twice previously on L2 which was the same as site 4aD in that it had rank points of 4 and 6 out of 15 on July 2008 and February 2010, as illustrated in Chapter 5. During these RPM works, one adjacent valve was not functioning, and it always remained closed even when it was manually opened. This fact was confirmed again by conducting an RPM investigation in May 2010. The RPM investigation confirmed that location L1 did not have enough sediment as it did not record high turbidity during the whole of the flushing time with the RPM test (5 minutes before RPM and 15 minutes during RPM). The maximum value of the turbidity was 9.6 NTU which was recorded after 3 minutes, but after increasing the flow to the RPM value, the turbidity quickly decreased. The location of L2 on the other hand, recorded 12 NTU at the first minute of the RPM and 15 NTU during the second minute. The work was therefore stopped to prevent the flushing of the sediment. Due to these results, L2 in suburb D was selected to hold the fieldwork as it contained sufficient sediment to observe the effect of different flow velocity. All other fieldwork sites were selected after the selection of the major site, depending on the PSM results as demonstrated in the next paragraph.

9.2.2 Fieldwork Method

The fieldwork was conducted as follows:

Figure 9.2 illustrates the name and location map of the fieldwork sites. As illustrated in this figure, there were two major sites (near hydrant points Ma1 and Ma2) and two minor sites which were located at least 200 metres from the major sites (Mi1 and Mi2). Three online GE Panametrics PT878 Ultrasonic Liquid Flow meters “Transport® PT878 Flowmeter” were installed as “wrap arounds” to pipes at three sites which included pipe locations between Ma1 and Ma2 (close to Ma1) and the two minor sites. The “Transport® PT878 Portable Liquid Flowmeter” is a complete portable ultrasonic flow metering system with options for connecting to the top of the pipe as a wrap around, so no pipe cutting work is required. The avoidance of cutting prevented any disturbance of the sediment in the pipe. In addition, Magflow type flow meters “AquaMaster™” were installed in both major sites, the connection method has been illustrated in paragraph 5.2.2. Portable turbidity meters were also used in major and minor sites, as illustrated in Figure 9.3. In addition, there were eight sites where turbidity was manually monitored termed St1 to St8. Those eight sites were selected depending on the PSM results (St1 to St8) as shown in Figure 9.4. Some sites were located in an affected area and others were located in an unaffected area. An affected area is defined as the area which will experience higher velocity than is usual during the induced hydraulic disturbance. These eight sites were monitored for turbidity every five minutes. Complaints were also monitored around the surrounding area by requesting the public to contact the Water Corporation with any complaints.

Figure 9.2: The map of fieldwork sites.

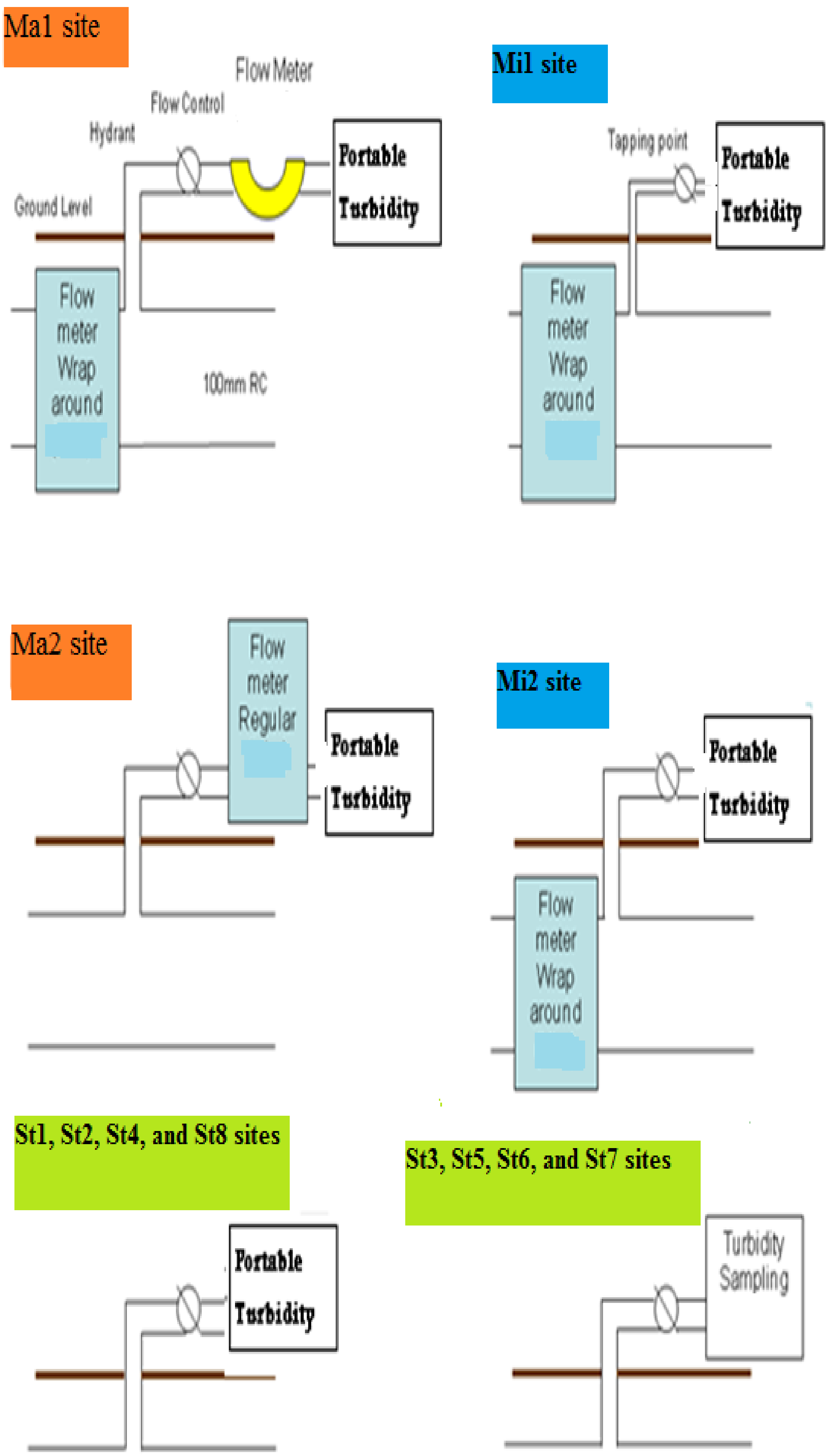


Figure 9.3: Details of instrumentation/monitoring at each fieldwork site.

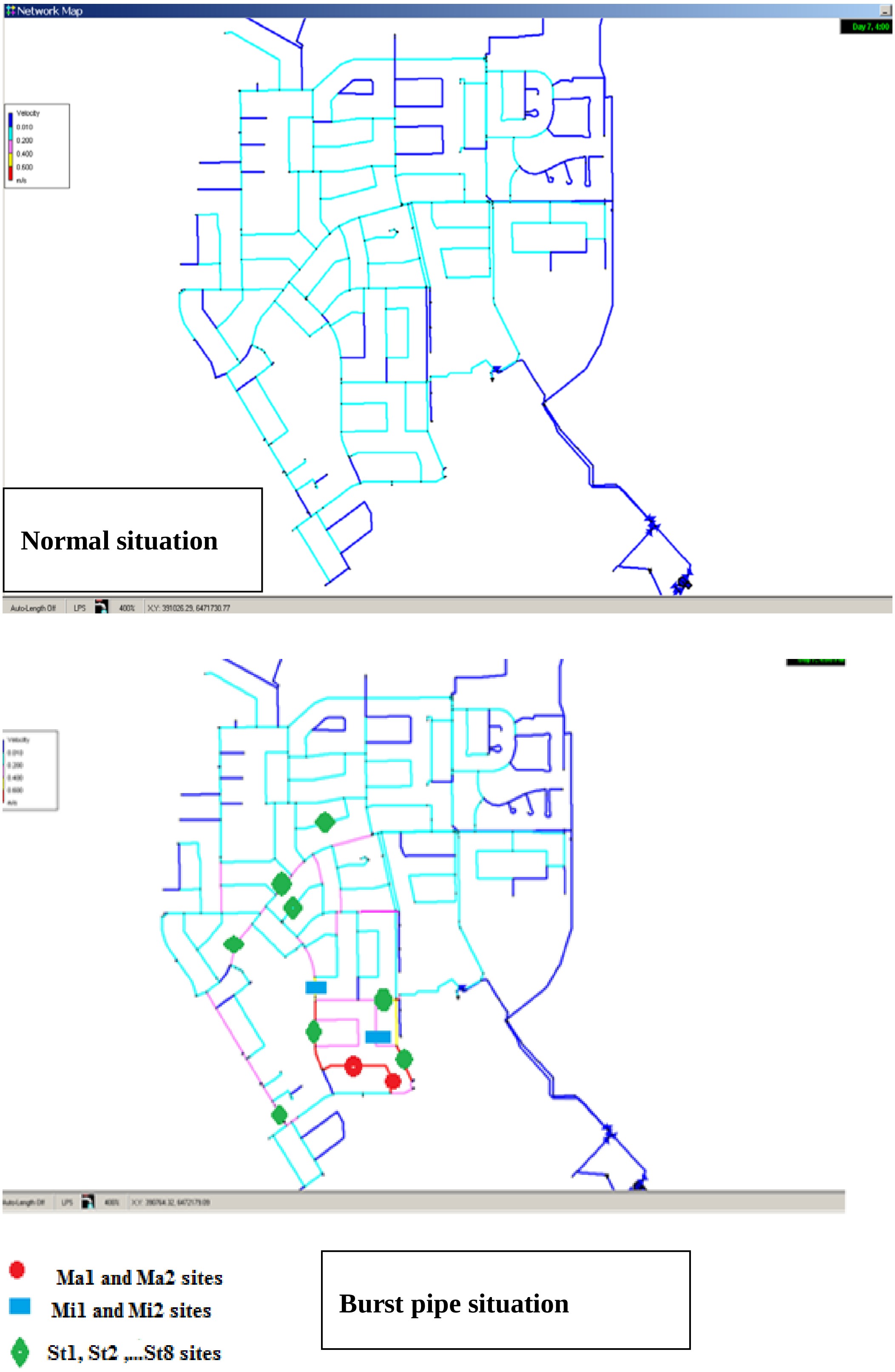


Figure 9.4: EPAnet-PSM velocity during both normal situations and burst pipe time, at suburbs D and E with all selected sites locations.

9.2.3 Details of Selected Sites and Equipment Used for Fieldwork

Table 9.1 illustrates the site locations at suburbs D and E, and the equipment used. It also illustrates the details of works carried out at fieldwork sites. The following work was required to install the equipment: excavation to expose the pipes at sites Ma1, and Mi2; and tapping a point installed and excavation carried out to expose the pipe at site Mi1 as there was no fire hydrant available at site Mi1.

A letter drop was carried out to inform all residents who might be affected by the exercise. This took place twice, prior to the start of fieldwork.

Flow meter instruments were installed on the morning of the same day. The work started at 12:00 PM. Half an hour prior to the start of fieldwork, flow and turbidity were monitored at the Ma1, Ma2, Mi1 and Mi2 sites while the turbidity was monitored at all the rest of the sites to build up a base of information of all pipes. When turbidity at any site, in this case the Mi2 site, was detected to be greater by twice than "what a customer may visibly notice (10 NTU)", the exercise was stopped immediately.

Table 9.1: Fieldwork sites details and equipment used.

Site	**Address**	**Flow Control Required**	**Work Required**	**Flow Meter**	**Turbidity Meter**	**Pipe Details**
Ma1	D	using Mag flow meter (3, 5, 7,max flushing≈8)	Excavation to expose pipe	Mag flow @ hydrant **and** EDS1/ strap-onto pipe	Portable kit @ hydrant	100mm RC

Ma2	D	using Mag flow meter (2, 7L/s)	Hydrant Connected	Mag flow @ hydrant	Portable kit @ hydrant	100m m RC
Mi1	D	As per tapping point tap	Tapping point installed and excavation to expose pipe	EDS2/ strap-onto pipe	Portable kit @ hydrant	100m m RC
Mi2	D		Excavation to expose pipe	EDS3/ strap-onto pipe	Portable kit @ hydrant	100m m RC
St1	D		Hydrant Connected	-	Portable kit @	100m m RC
St2	D		Hydrant Connected	-	Portable kit @	100m m RC
St3	D		Hydrant Connected	-	Hydrant Sampling	100m m RC
St4	D		Hydrant Connected	-	Portable kit @	100m m RC
St5	D		Hydrant Connected	-	Hydrant Sampling	100m m RC
St6	D		Hydrant Connected	-	Hydrant Sampling	100m m RC
St7	E		Hydrant Connected	-	Hydrant Sampling	100m m RC
St8	D		Hydrant Connected	-	Portable kit @	100m m RC

Figure 9.5: Mag flow meter "AquaMaster^{TM}" connected at site Ma1.

Table 9.2: Timeline for Fieldwork as planned.

Time		12:00 - 12:45	12:45 - 01:10	01:10 - 01:55	01:55 - 02:20	02:45 - 02:55	02:55 - 3:55
	site						
Flow (L/s)	Ma1	3	5	7	8	8	8
	Ma2	0	0	0	0	2	7
	Total flow	3	5	7	8	10	15

The selected fire hydrant was connected to a tap with a hose that had a volumetric flow meter. A portable turbidity meter was used to measure the turbidity as shown in Figure 9.3. The turbidity measurements were taken by flushing water at a controlled rate out of a hydrant along the 100 mm main.

Table 9.2 illustrates the period of the controlled flow rate out of fire hydrants at sites Ma1 and Ma2. The first fire hydrant at site Ma1 was opened such that a flow of 3 L/s, 5 L/s, 7 L/s was obtained, and full flushing (≈ 8 L/s) was carried out for the periods shown in Table 9.2. Following this, while keeping the Ma1 fire hydrant fully open, the fire hydrant at Ma2 was opened such that a flow of 2 L/s and 7 L/s was achieved for the period shown in Table 9.2. Turbidity measurements were taken by the portable turbidity meter simultaneously every 5 minutes and monitoring was continued in all of the surrounding area.

9.3 Calibration of Flow Meter Data

As shown in Figure 9.6 the flow is negative when the water flows from Mi1 and it should flow towards Ma1. As the other pipe connected to Ma1 is connected with the valve closed (as also noted earlier during the RPM test), the flushing at Ma1 causes a flow from the EDS1 flow meter (which is placed between Ma1 and Ma2) and from Mi1 (EDS2). When the sum of EDS1 and EDS2 flow data (at Ma1 and Mi1) was totaled, it gave the approximate flushing flow at Ma1, as shown in Figures 9.7 and 9.8, especially until the flushing started from Ma2. This means that the flow meter in-line was accurate.

Figure 9.8 shows that at the end of period of the maximum flushing at site Ma1, the flow reduced to zero in EDS1 at Ma1. This was required in order to move the flow meter that measured the flushing flow at Ma1 to site Ma2. As soon as flushing commenced at Ma2 it was possible that the flow at EDS1 reduced as noted previously. To compensate for that reduction, the flow at Mi2 would need to increase. Therefore, to calculate the flushing flow at Ma1, one needs to calculate it by adding the flow at Ma1 of EDS1 and the flow at Mi1 (EDS2) for the period when the flow condition changed at Ma2.

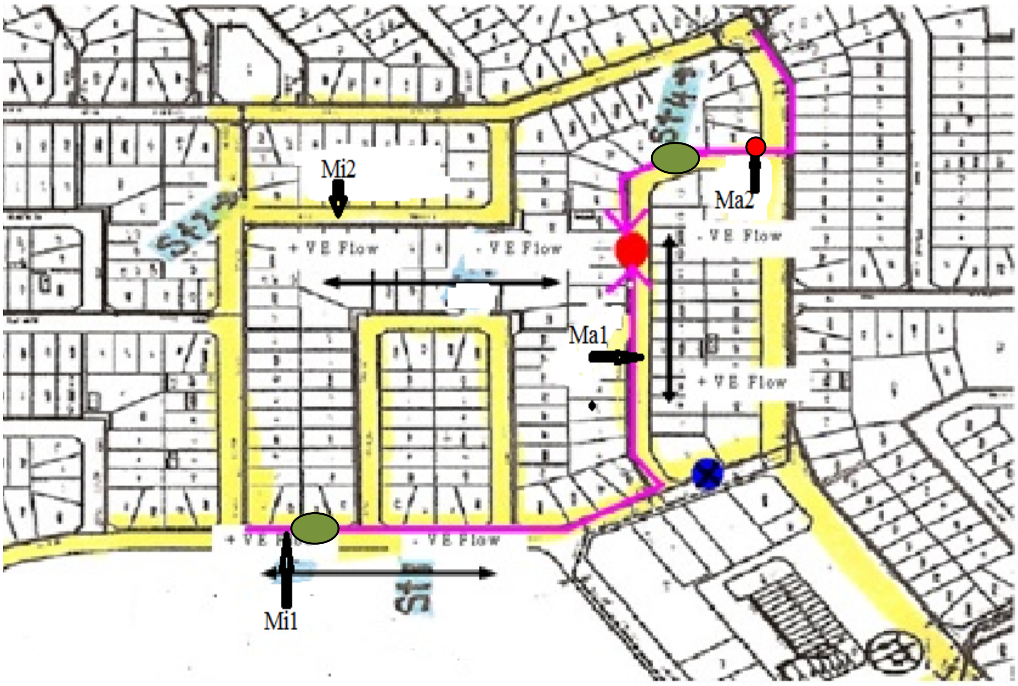


Figure 9.6: Flow direction at Mi1 and Ma1 sites.

EDS flow meter

Closed valve

Flow direction

flushing point

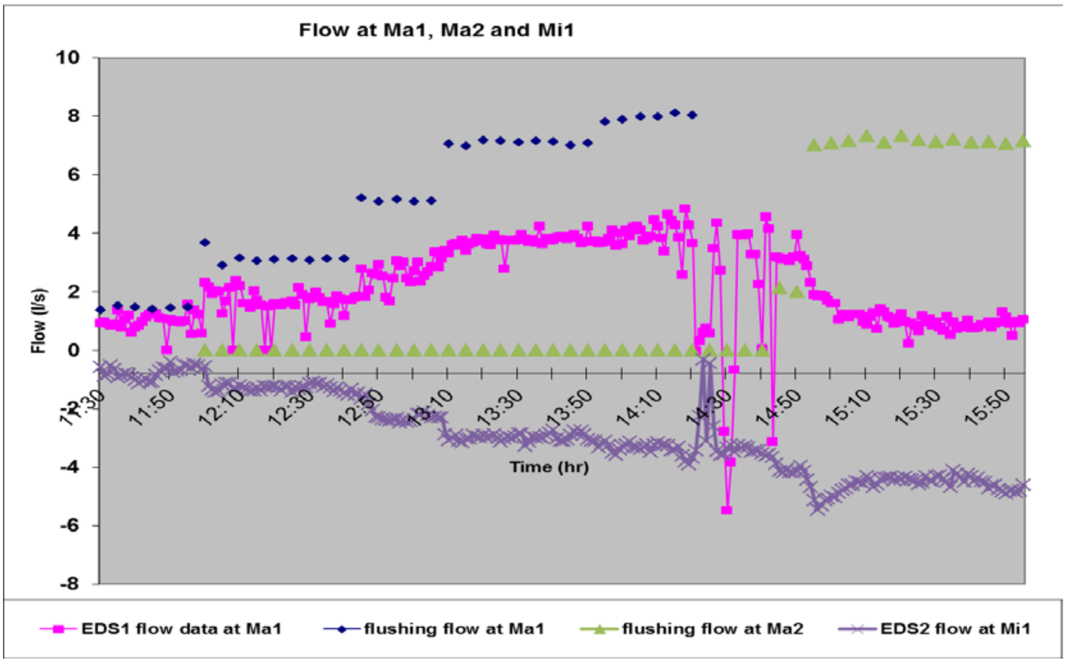


Figure 9.7: Flow data at sites Ma1, Mi1 with flushing value at Ma1 and Ma2.

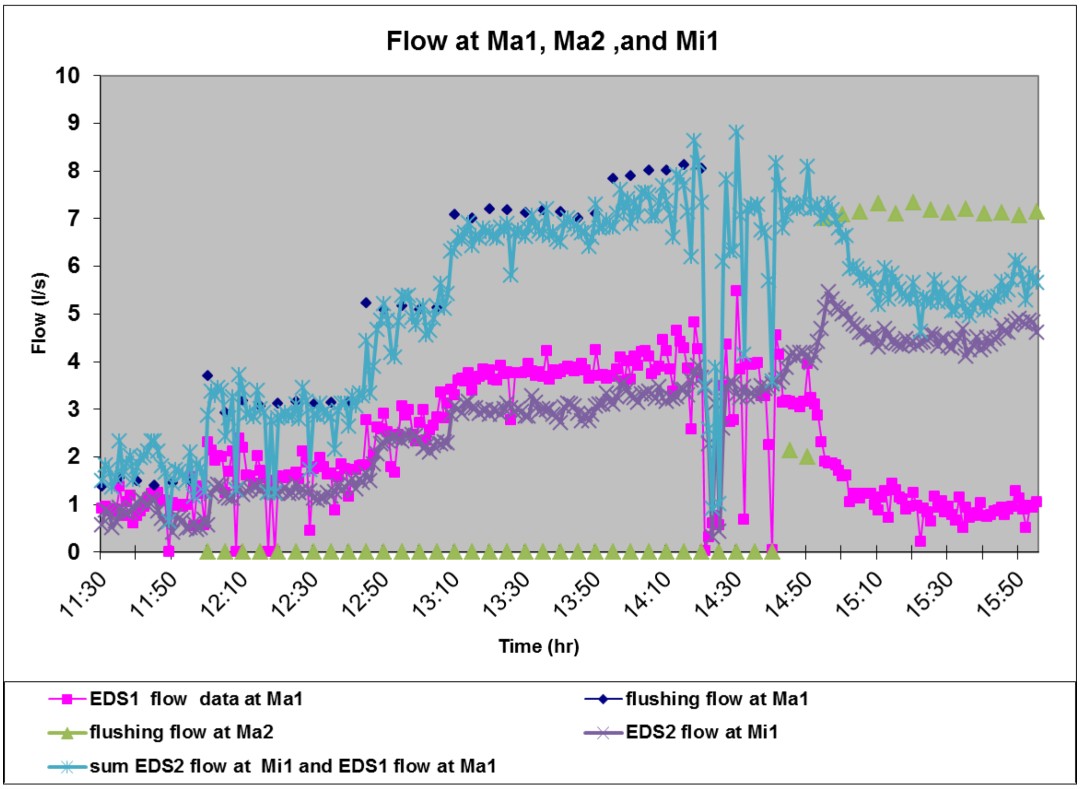


Figure 9.8: Summation of EDS1 flow at Ma1 and EDS2 flow at Mi1 giving approximate flushing value at Ma1.

9.4 Fieldwork Results

Theoretically, discoloured water events (high turbidity) should coincide with high velocities (0.6 m/s or more). Figures 9.9, 9.10 and 9.11 show the flow data as given for EDS1, EDS2 and EDS3 flow meters at Ma1, Mi1, and Mi2 sites respectively, overlaid with the respective turbidity results.

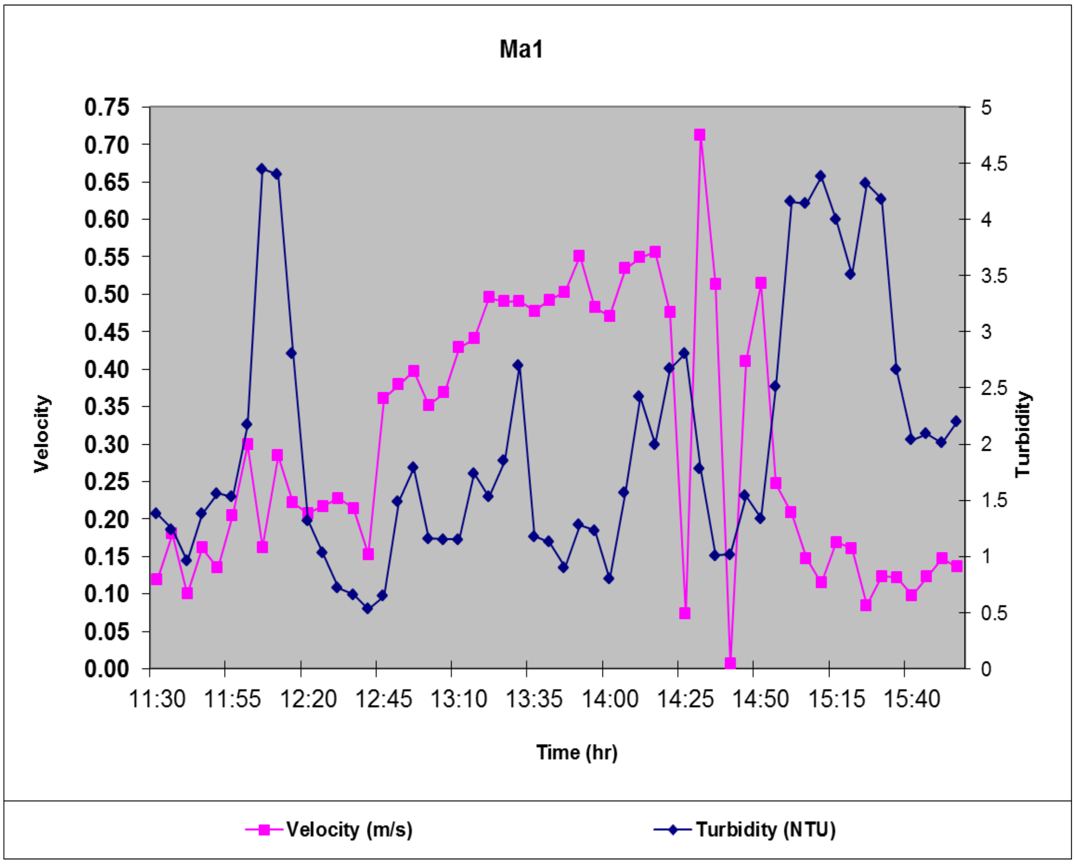


Figure 9.9: Flow rate and turbidity results at site Ma1.

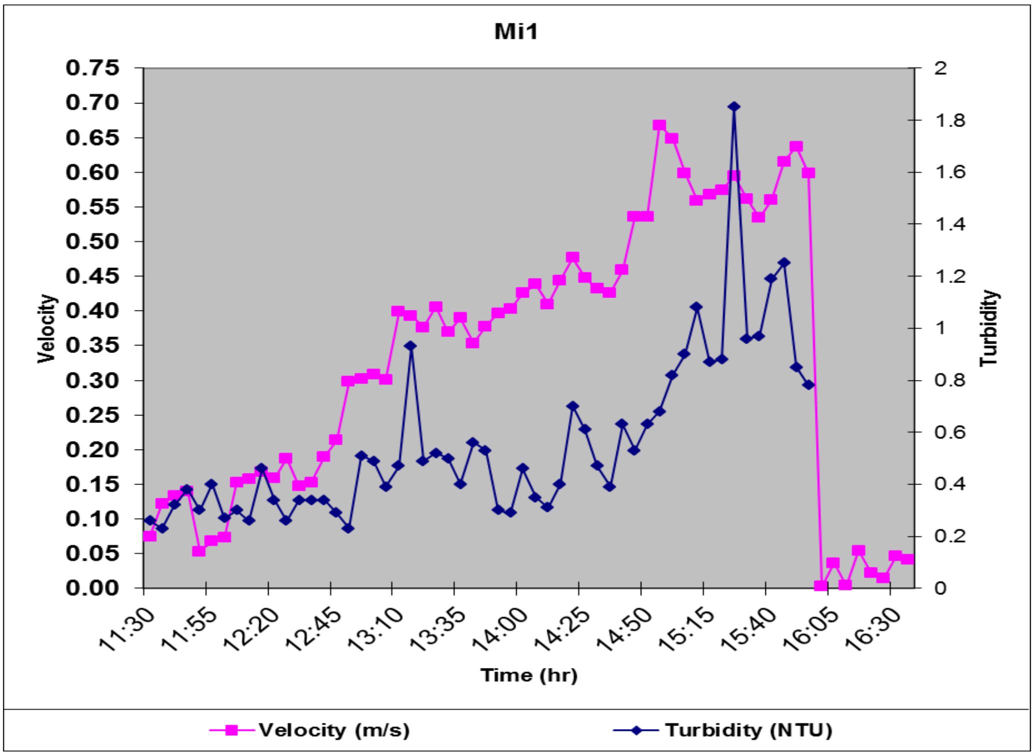


Figure 9.10: Flow rate and turbidity results at site Mi1.

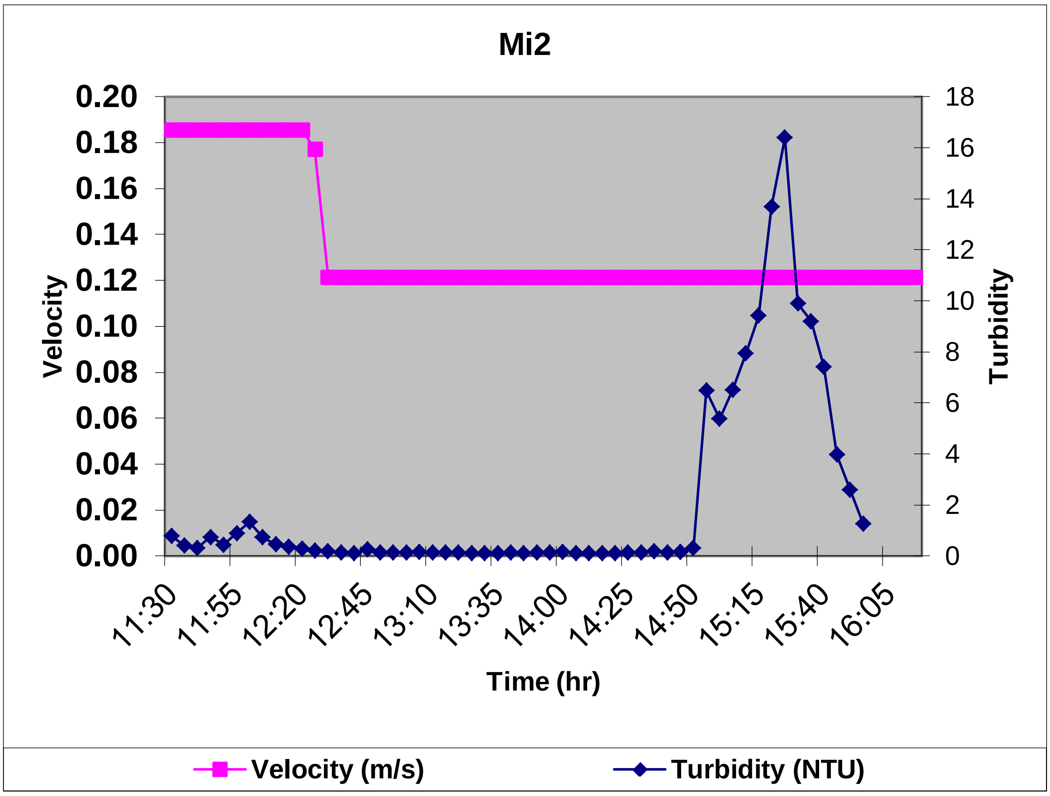


Figure 9.11: Flow rate and turbidity results at site Mi2.

It is clear from the overall view of Figures 9.9 to 9.11 that the pattern of turbidity follows that of the velocity for Ma1 and Mi1 sites, but it was different at the Mi2 site. A deeper look at the results of the Ma1 site shows that the highest turbidity of 4.45 NTU was recorded at a velocity of 0.16 m/s at 12:05 hrs and the recorded turbidity was 1.78 NTU at 0.7 m/s at 14:30 hrs. Despite an increase in velocity to about 0.7 m/s, the recorded turbidity was lower than that at 0.16 m/s. The same trend could be noted at the Mi1 site. As the velocity gradually increased, the highest turbidity of 0.93 NTU was recorded at 0.39 m/s at 13:15 hrs and when the velocity reached 0.65 m/s at 15:00 hrs, the turbidity recorded was 0.82 NTU.

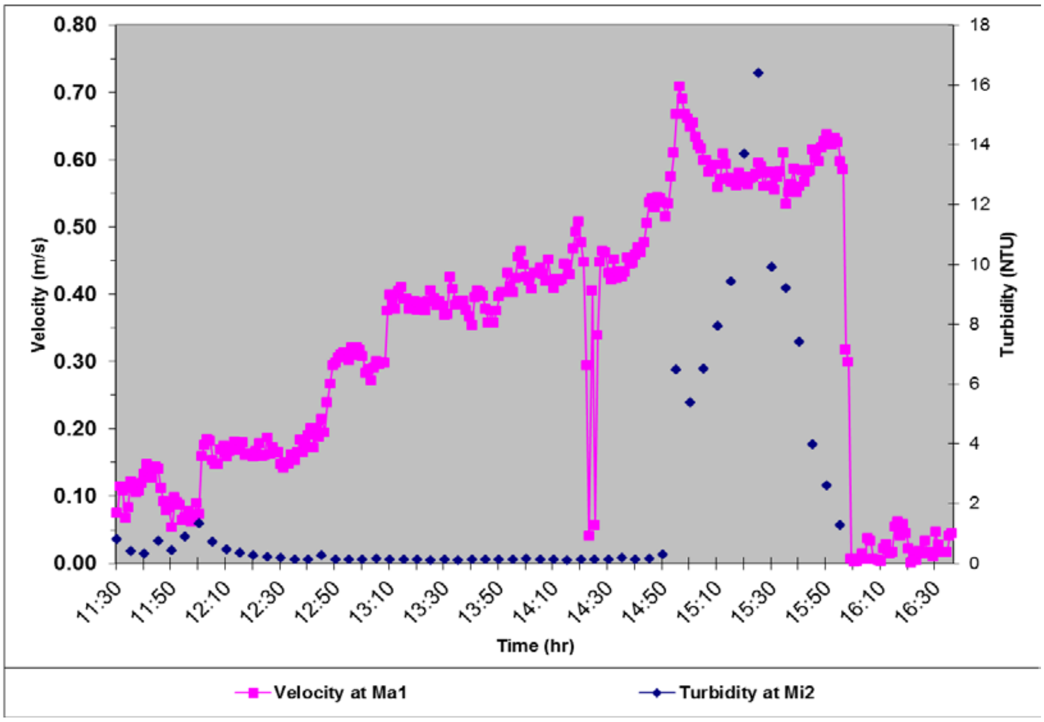


Figure 9.12: Mi2 turbidity with Ma1 velocity.

Many researchers have studied the relationship between velocity and sediment. Friedman et al., 2002 observed that velocities more than 1 fps (0.3 m/s), are not sufficient to remove sediments or provide any scouring action. Vreeburg and Boxall, 2007 suggested that at a velocity of 0.14

m/s, the turbophoretic force exceeded the gravitational force resulting in a uniform supply of material to the pipe surface, i.e., particles are transported from the bulk fluid to less turbid regions near the wall where they can be trapped in cohesive layers. Jayaratne et al., 2004 conducted tests on a 100 mm clear PVC pipe and showed that at velocities between 0.07-0.25 m/s the sediment started to resuspend while between 0.25-0.6 m/s they moved completely. However, this observation was based on a laboratory experiment. The results of the Mi2 site are contradictory to past literature or theory which assumed that it was not possible to record high turbidity at a low velocity. However, in this research, site Mi2 recorded high turbidity (16.4 NTU) at a low velocity of 0.12 m/s which continued from 12:25 to 16:25 hrs, but it recorded high turbidity simultaneously with the high flushing that took place at Ma1 and Ma2 and recorded maximum turbidity at 15:15 hrs, as shown in Figure 9.12.

9.5 Comparison between Fieldwork Results and EPAnet-PSM Predictions.

To confirm the ability of the EPAnet-PSM to predict sediment accumulation/movement patterns in water distribution networks, simulation results were required to validate the field data.

The EPAnet-PSM was run over one week (168hrs). Zone M hydraulic patterns were pre-programmed into the model at 5 minute intervals. In the “time options”, the “hydraulic time step” and “pattern time step” were both set to 0:05 to reflect the way the patterns had been programmed. Both the “quality time step” and “reporting time step” were entered as 0:05.

As illustrated before in paragraph 8.2.1 it was not possible to enter an initial sediment concentration for a particular pipe. Initial sediment concentration before the burst pipe event was overcome by having two parallel but identical reservoirs instead of Reservoir 2; which supplied water to Tank 2; as illustrated in Figure 9.13. One reservoir contained a zero “source sediment quality” and the other contained 1000 mg/l. The reservoir with a high sediment concentration was set to supply water for two days. The supply reservoir was then switched to the second reservoir with zero sediment concentration for the rest of the simulation time. However, the problem was not solved by the use of two reservoirs (one reservoir was clean and other was dirty). This was due to the sediment moving from the reservoir to Tank 2 at the time the pumps were working. Therefore the sediment reached only parts of suburb D but not suburb E, as illustrated in Figure 9.14, with 0.4m/s resuspension velocity (the same problem was observed at 0.6 and 0.2 m/s). It therefore indicates that there was insufficient sediment in the pipes prior to the pipe burst. Many other solutions have been applied in an attempt to solve this problem but the same results were obtained during the simulation with EPAnet-PSM for the first three solutions. The fourth solution gave a successful run but the EPAnet-PSM program could not show the results, as illustrated in Figure 9.15. The attempted alternative solutions were:

- Increase the time of the dirty reservoir to supply water for 5 days and the clean one to supply water for the remainder of the simulation time (2 days).
- Increase the source sediment quality to 100000 mg/l for the dirty reservoir.
- Increase both the time and the quantity of sediment (both above solution used together).

- Increase the EPAnet-PSM run time period over two weeks (336 hrs) instead of one week (168 hrs).

Finally, EPAnet-PSM was run for a time period of over one week (168 hrs). Using one reservoir (Reservoir 2), the “source sediment quality” was nominally entered as 1000 mg/l for two days. This was achieved by administering 1000 mg/l of sediment pattern for two days and then zero for the rest of the time of the simulation, as illustrated in Figure 9.16. Even though the sediment pattern was kept at 1000 mg/l for just two days, the reservoir continued to supply dirty water to the system, as illustrated in Figure 9.17. In this situation, the sediment reached both suburbs D and E. The results of this simulation will be discuss in detail in the following sections.

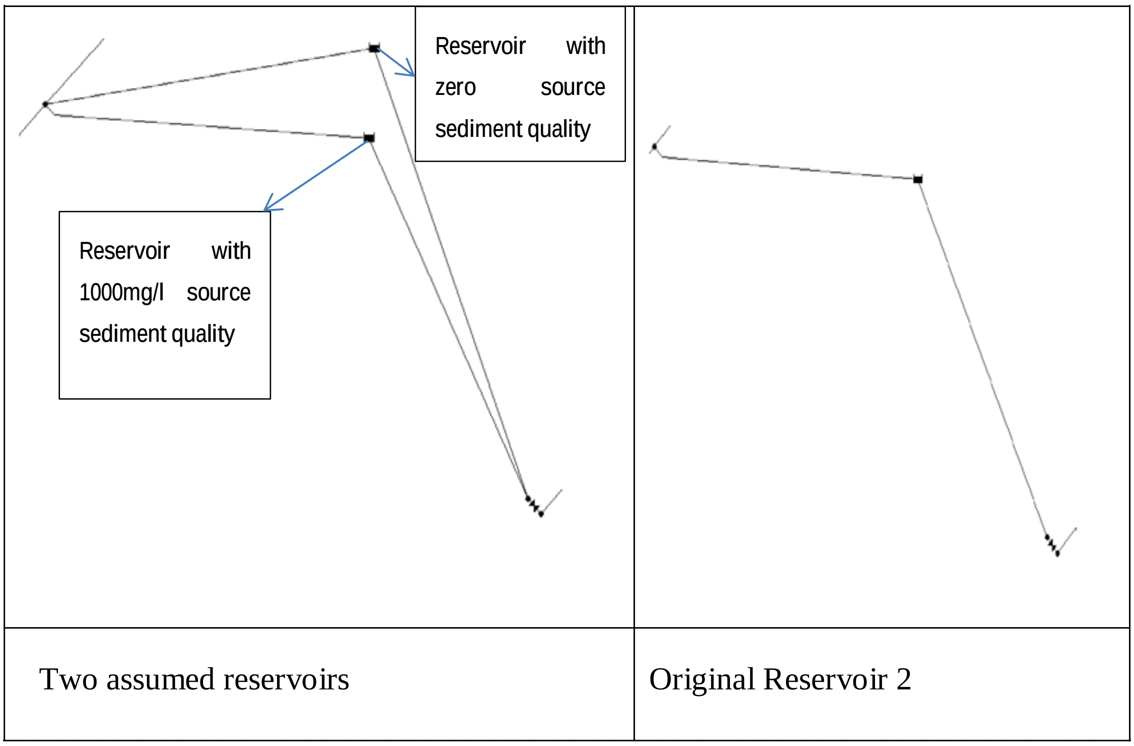


Figure 9.13: Two assumed reservoirs instead of Reservoir 2 to solve the problem of initial sediment in the pipes.

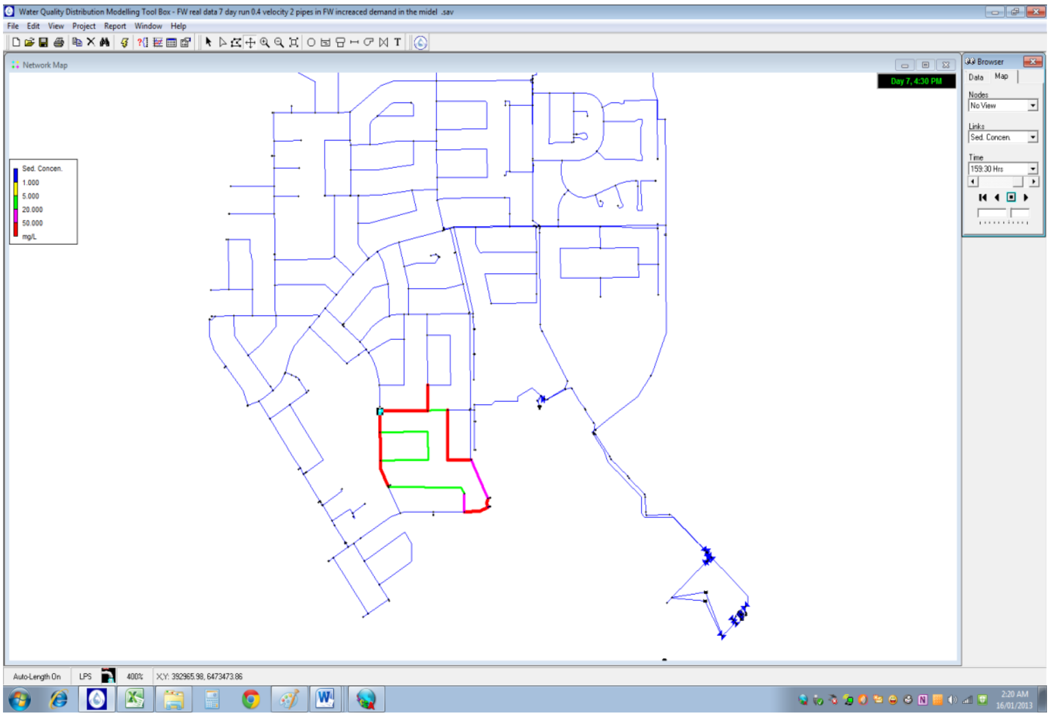


Figure 9.14: EPAnet-PSM prediction for sediment in pipes before burst pipe with 0.4 m/s resuspension velocity.

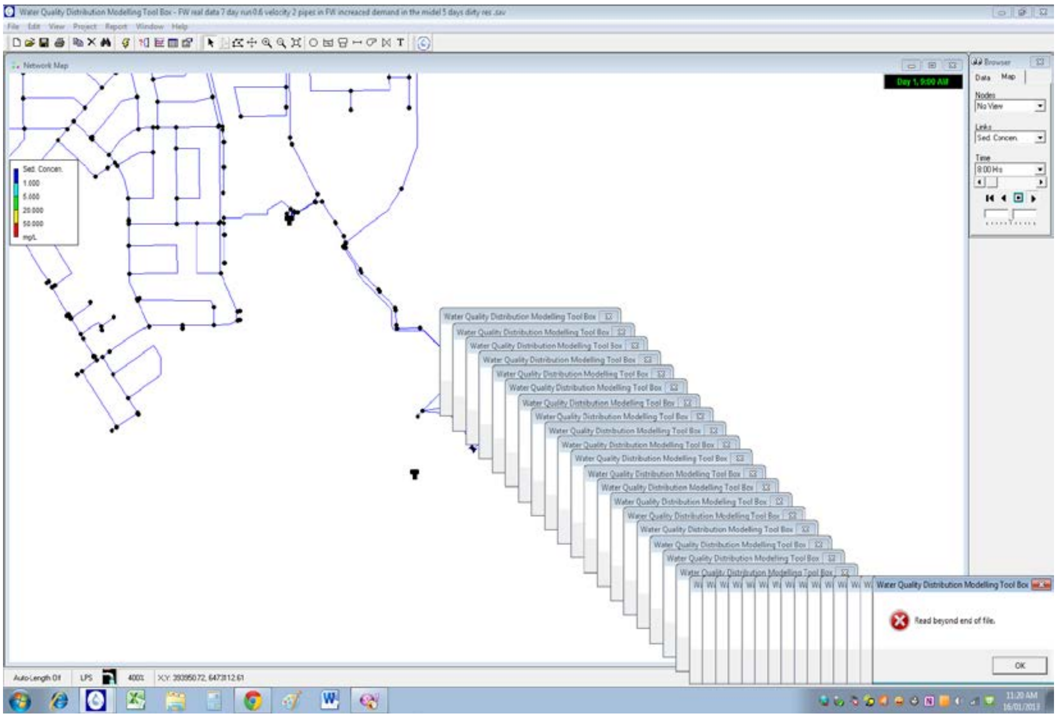


Figure 9.15: EPAnet-PSM problem when run time period is over two weeks (336 hrs).

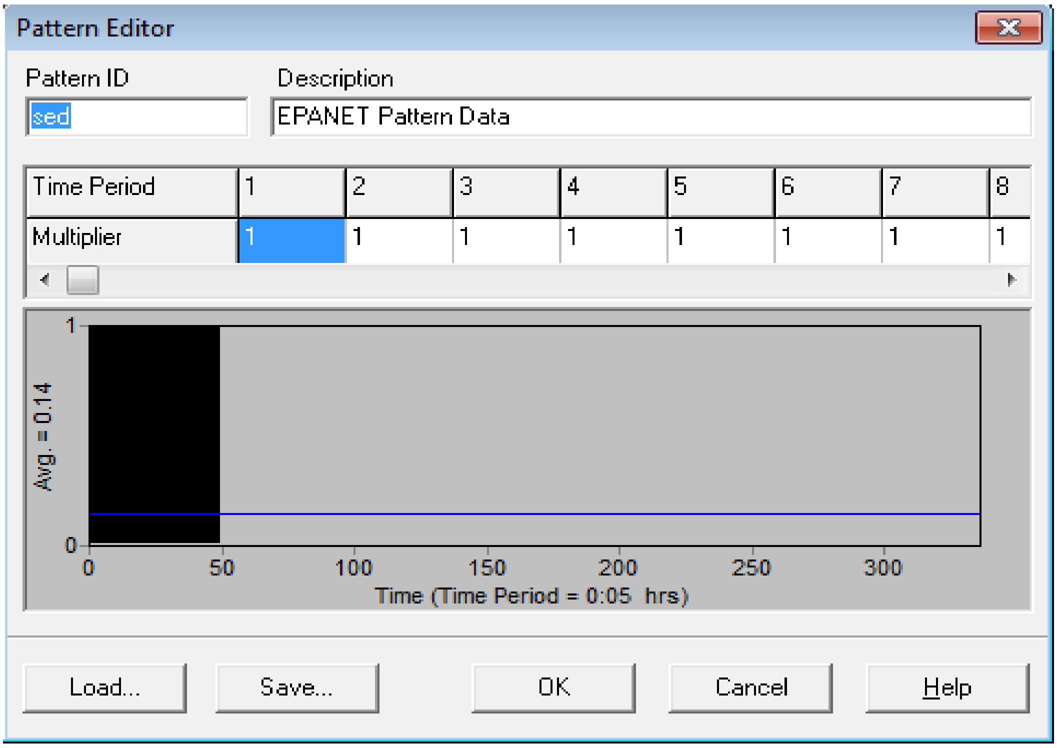


Figure 9.16: EPAnet-PSM graph of sediment pattern to Reservoir 2.

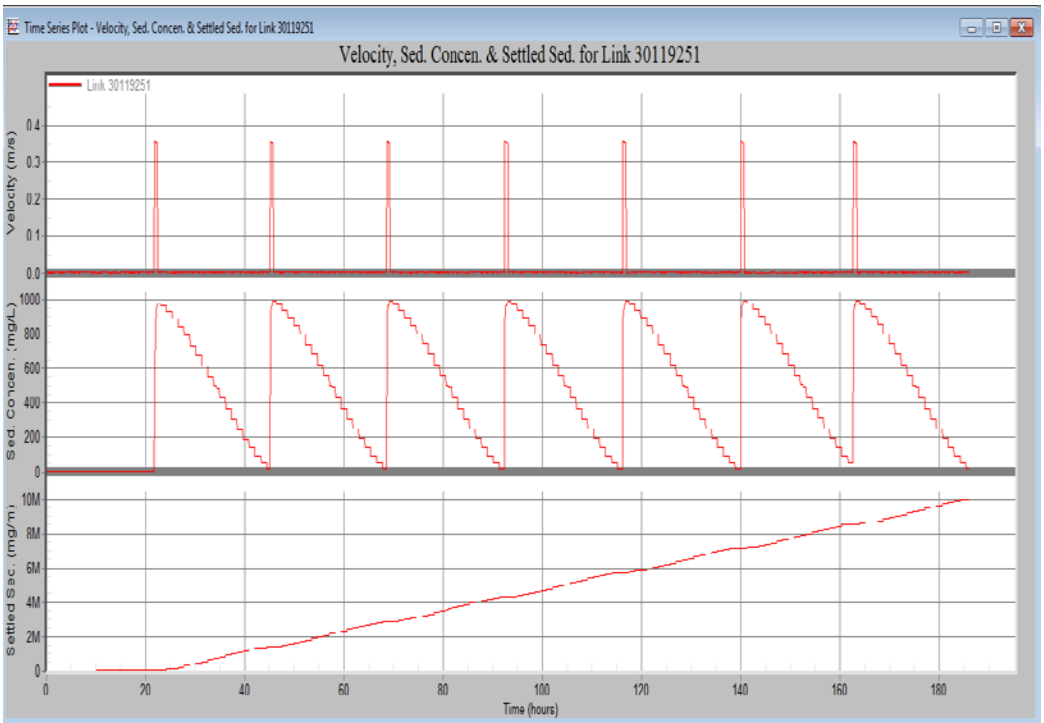


Figure 9.17: EPAnet-PSM prediction for sediment concentration, velocity and settled sediment with 0.4 m/s resuspension velocity in the pipe next to the reservoir when using sediment pattern for two days in Reservoir 2.

9.5.1 EPAnet-PSM Predictions When Sediment Pattern Used for two Days in Reservoir 2

Using the sediment pattern for two days in Reservoir 2 was the only alternative solution which gave an initial sediment concentration for all networks in suburb D and E. However, this was obviously not the same as would occur in a real situation because the sediment was continuously supplied to network systems at high concentrations.

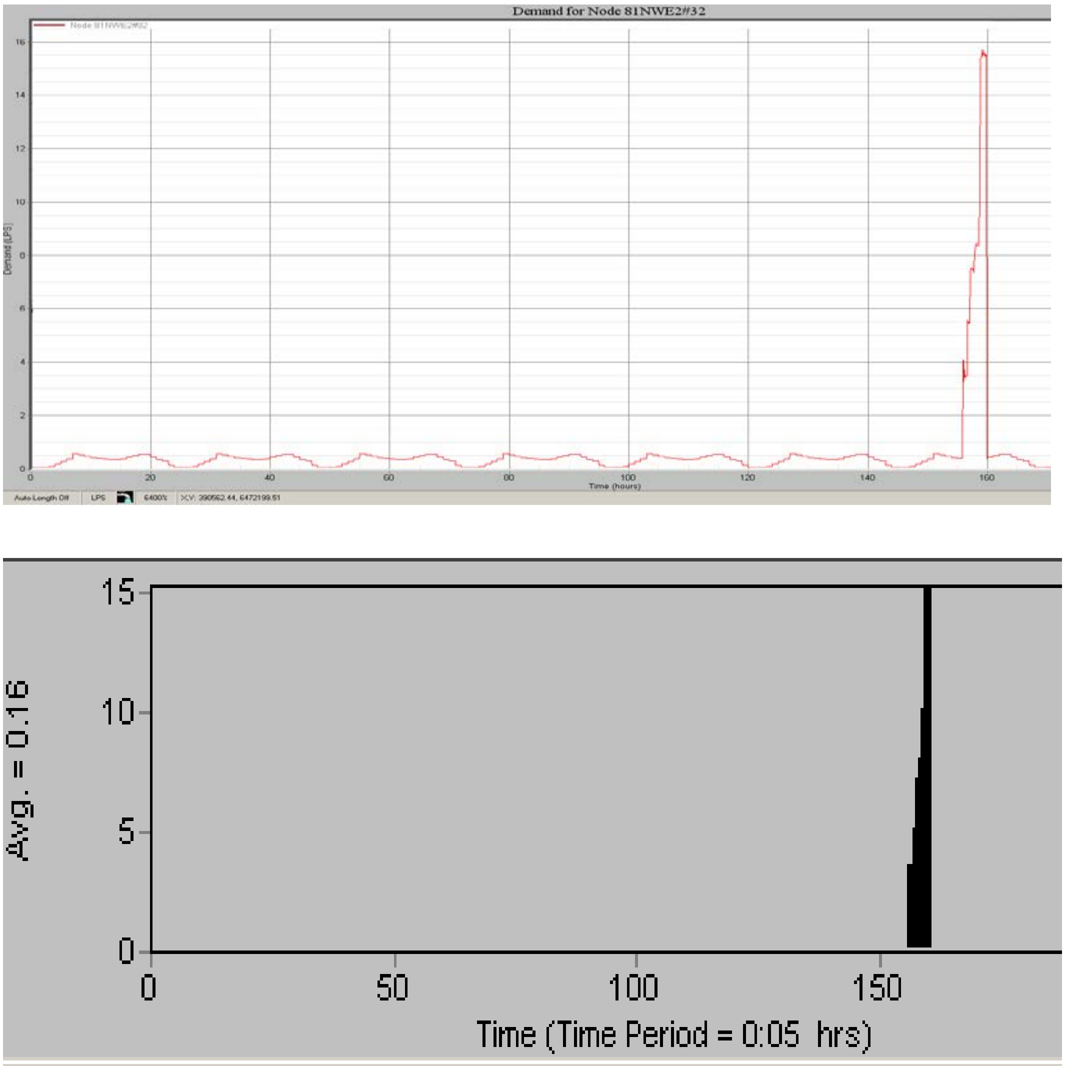


Figure 9.18: EPAnet-PSM graph of downstream node demand.

Following industry practice, the burst pattern was entered as an increase in demand in the downstream node with the same values of flushing as in the fieldwork, as shown in Figure 9.18. The burst pipe action was started at the beginning of 156 hrs of simulation run time. As expected and illustrated previously in Figure 9.4 there were differences between the EPAnet-PSM predicted velocity during both the normal and burst pipe situations in suburbs D and E.It is clear from this figure that the velocity during a normal situation was less than 0.2 m/s. However, when profiles of sediment concentration were studied, it was found that the profile changed depending on the adopted resuspension velocity such as 0.2, 0.4 and 0.6 m/s.

By firstly analysing the overall results of a velocity, moving sediment concentration and matching this with the affected locations during fieldwork, a basic understanding of the affected area could be developed. With 0.6 m/s resuspension velocity, the affected area was as illustrated in Figures 9.19 and 9.20. The velocity profile is given in Figure 9.4. When 0.6 m/s as a resuspension velocity was used, it was noticed instantly from viewing those figures and moving sediment in EPAnet-PSM that there was no relation between the sediment concentration (turbidity) and the high demand achieved in the fieldwork. This was due to the PSM prediction that at the beginning of every day, after day 5 at 1AM, the affected area shown in Figure 9.19 appeared and continued for 2 hours and the affected area extended day by day after day 5. However, the velocity in pipe Mi2 did not exceed 0.25 m/s, hence sediment movement could not be noted. This phenomenon has a relation with the working time of pumps, as illustrated in Figure 9.21. At EPAnet-PSM simulation time equivalent to 12 PM on day 7, or during fieldwork, the PSM predicted the absence of sediment in the pipes, and the prediction continued during the whole of the fieldwork simulation time. It is possible that at the time of flushing at Ma2, this would have caused the pump to start and cause sediment concentration to increase at Mi2 similar to that which was noticed at 1AM on the 5th, 6th and 7th days. Therefore, any prediction of sediment transport should be treated with caution.

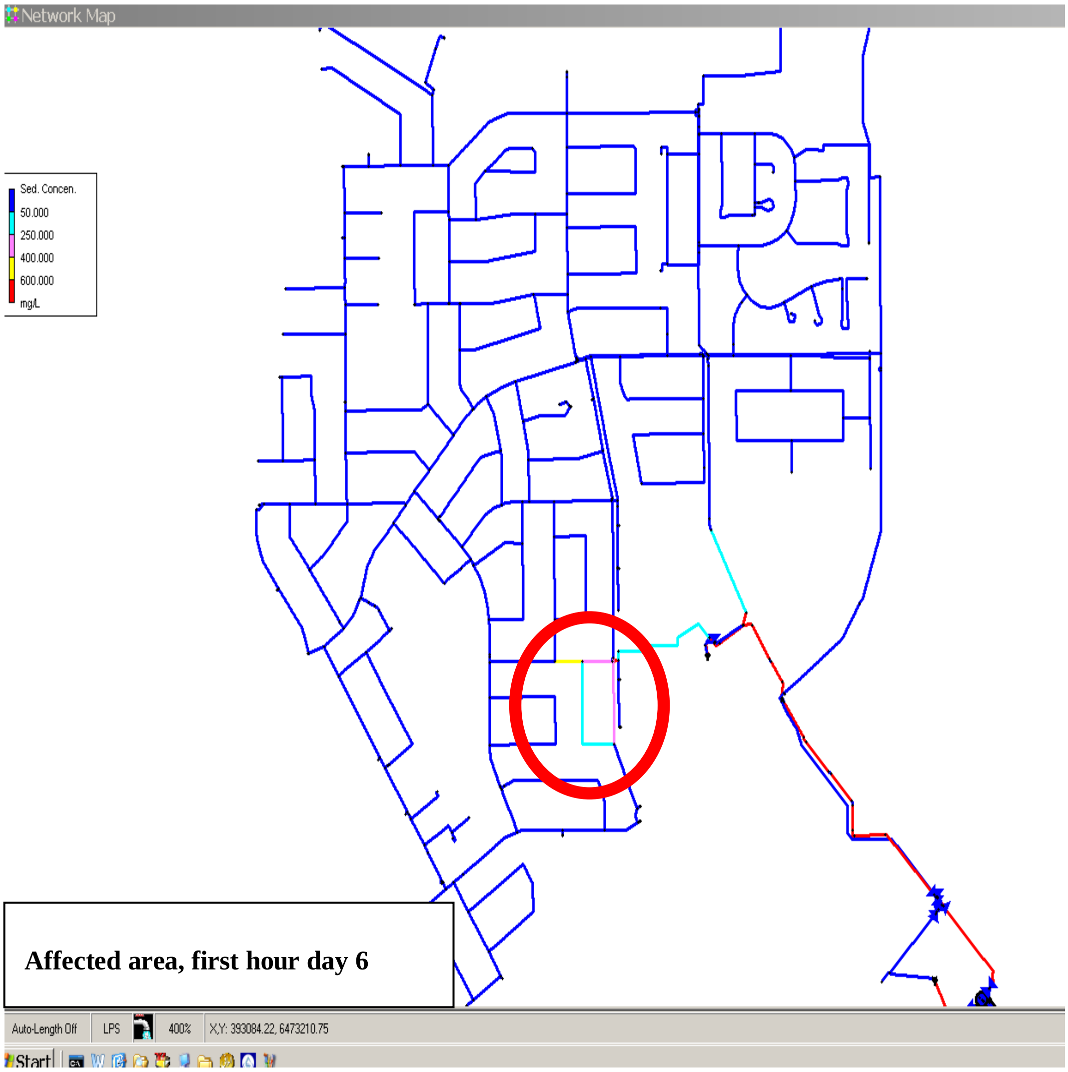


Figure 9.19: EPAnet-PSM sediment concentration results with 0.6 m/s resuspension velocity during first hour on days 6 and 7 of normal situation, at suburbs D and E.

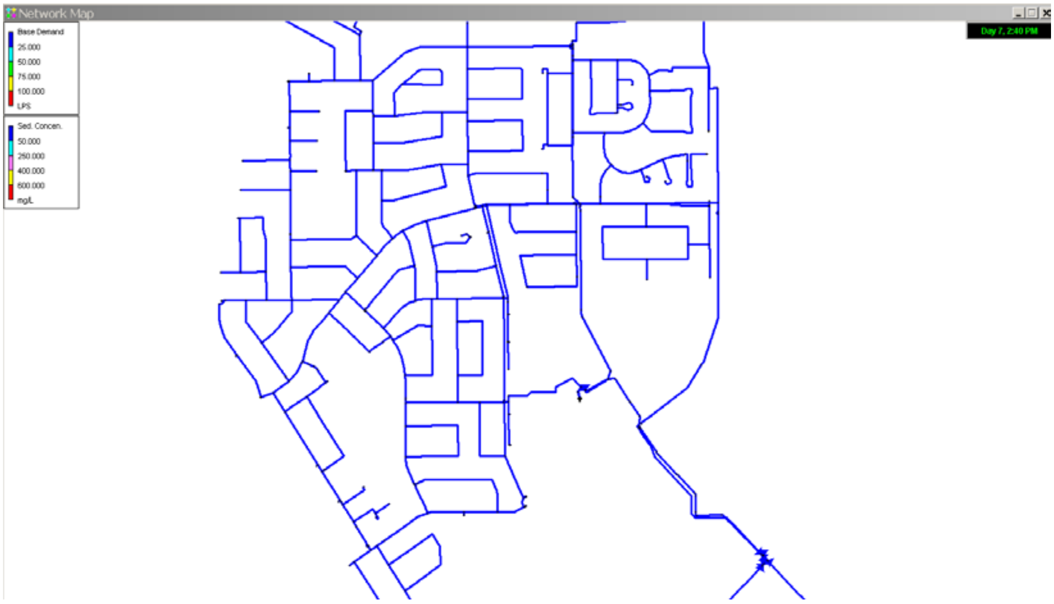


Figure 9.20: EPAnet-PSM sediment concentration results with 0.6 m/s resuspension velocity during fieldwork simulation time; day 7, at suburbs D and E.

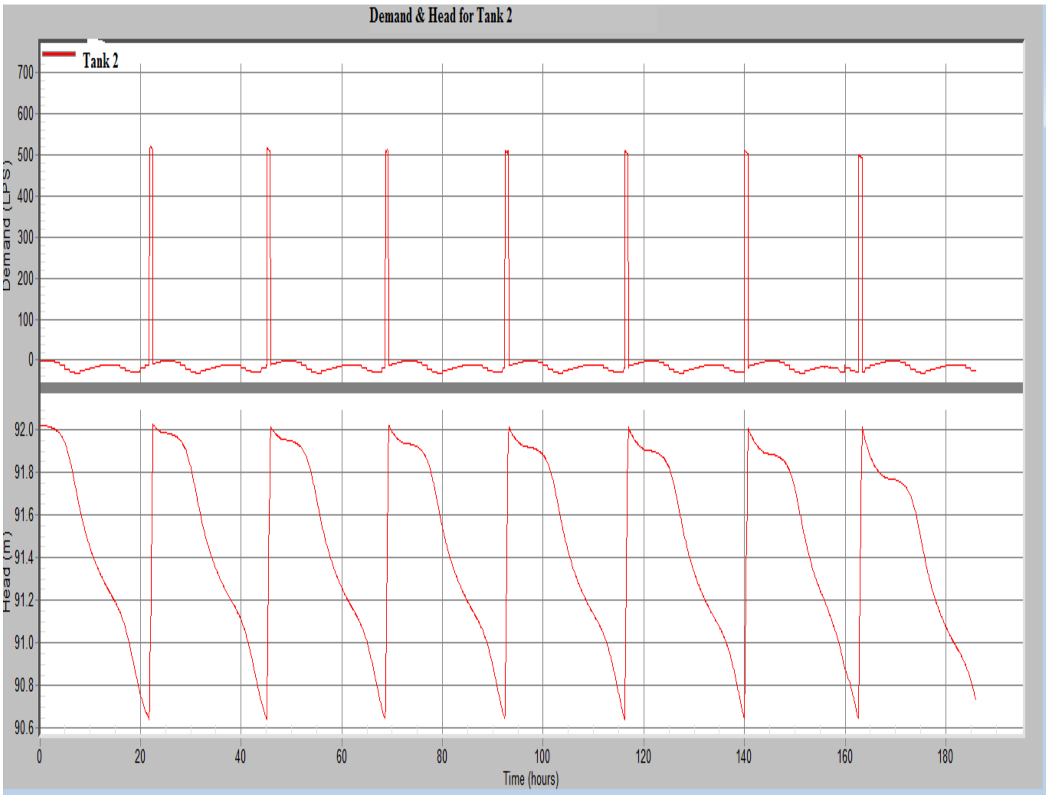


Figure 9.21: EPAnet-PSM demand and head of Tank 2.

The results were different when the EPAnet-PSM was run with 0.4 m/s resuspension velocity, as illustrated in Figure 9.22. The first affected area was Mi2 at 3:50 PM when the demand reached more than 15 l/s at flush points. This matched with real fieldwork results. The results with 0.2 m/s resuspension velocity also matched with the real fieldwork, as shown in Figure 9.23. Therefore, analysis has been conducted in detail by comparing the EPAnet-PSM prediction, using 0.2 m/s and 0.4 m/s resuspension velocity, with fieldwork results.

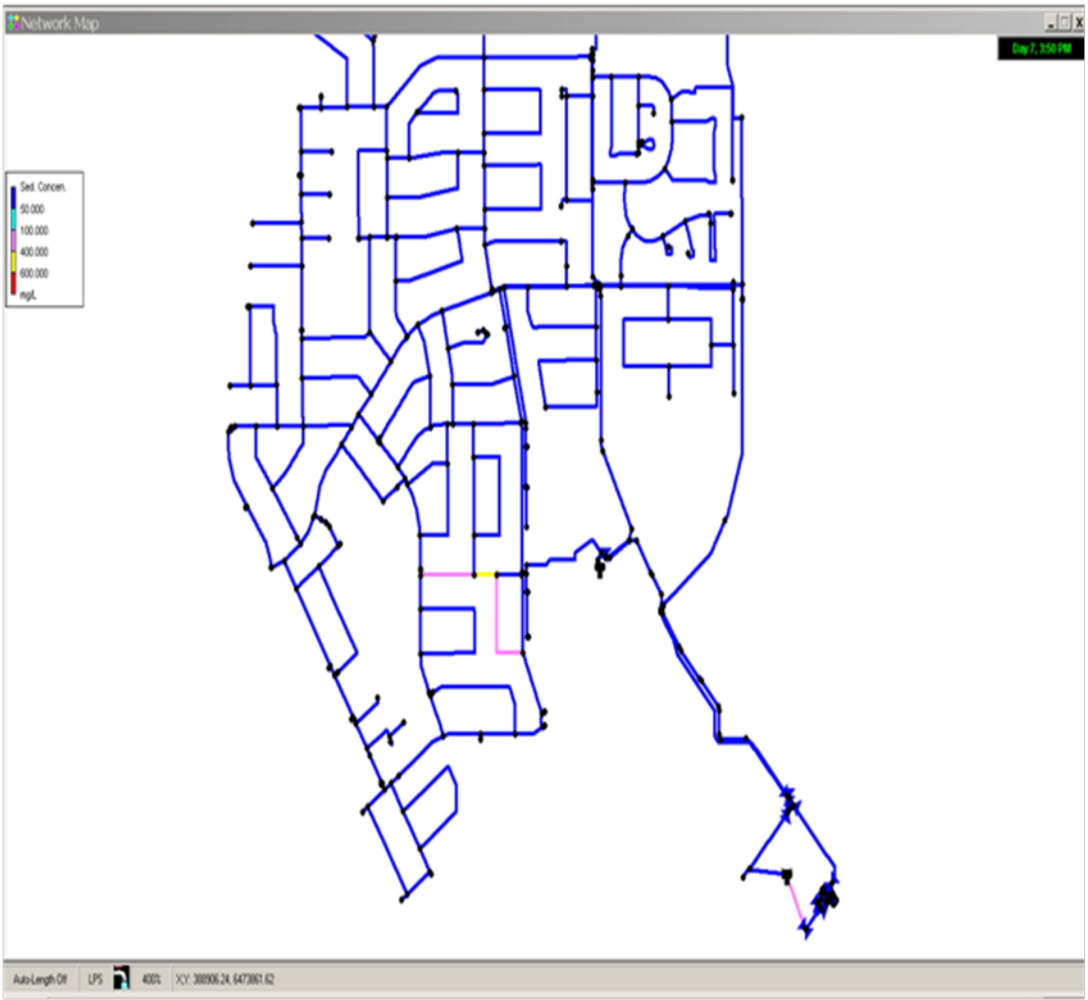


Figure 9.22: EPAnet-PSM settling sediment results with 0.4 m/s resuspension velocity during fieldwork simulation time; day 7, at suburbs D and E.

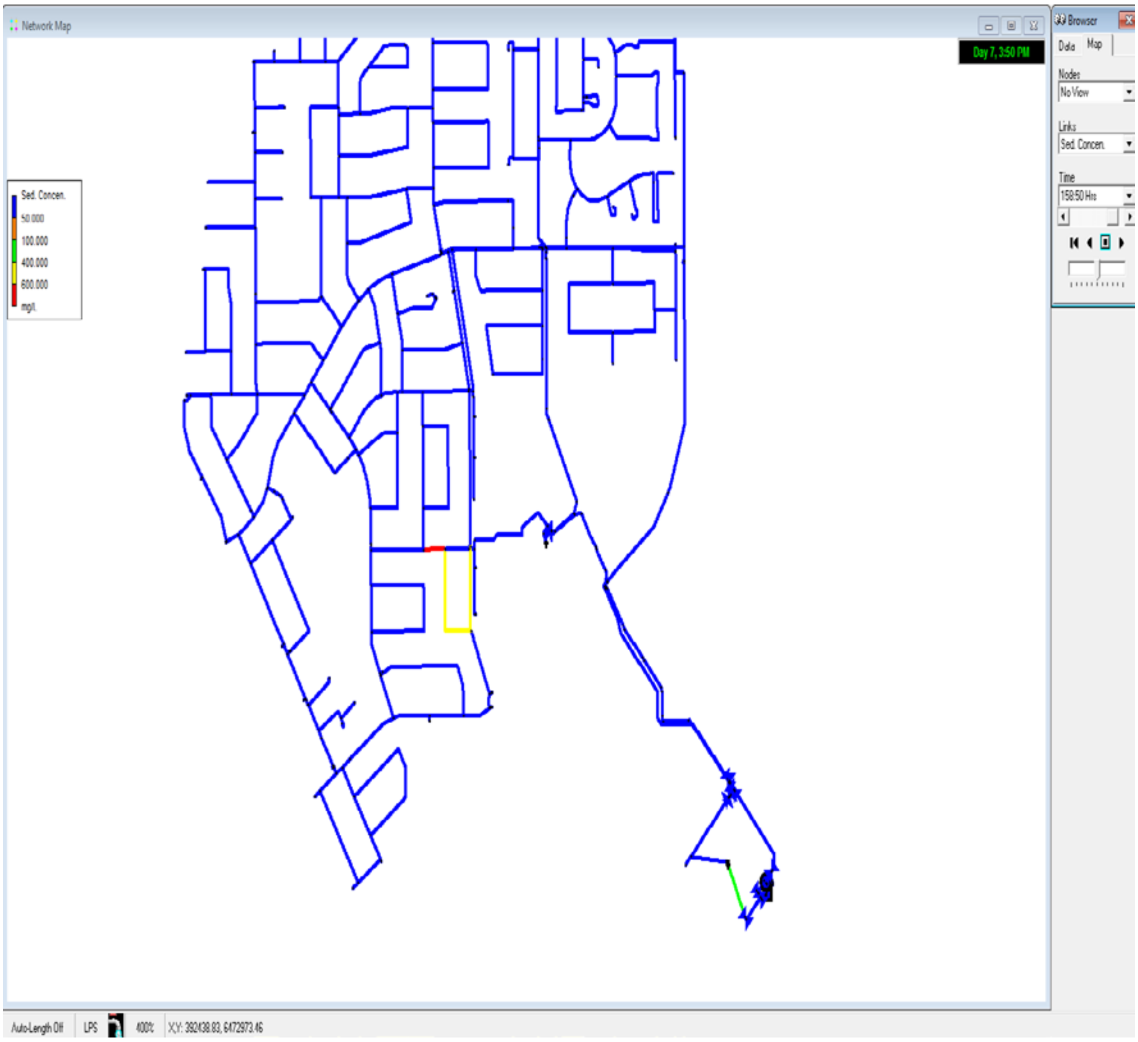


Figure 9.23: EPAnet-PSM settling sediment results with 0.2 m/s resuspension velocity during fieldwork simulation time; day 7, at suburbs D and E.

9.5.2 Comparison between EPAnet-PSM Prediction Velocity and Fieldwork "Measured" Velocity.

Velocity measured in fieldwork should be compared with the EPAnet-PSM predicted velocity before commencing any other comparisons for other predictions like sediment concentration with turbidity. Figures 9.24 to 9.26 illustrate the comparison of velocities at Ma1, Mi1 and Mi2 respectively.

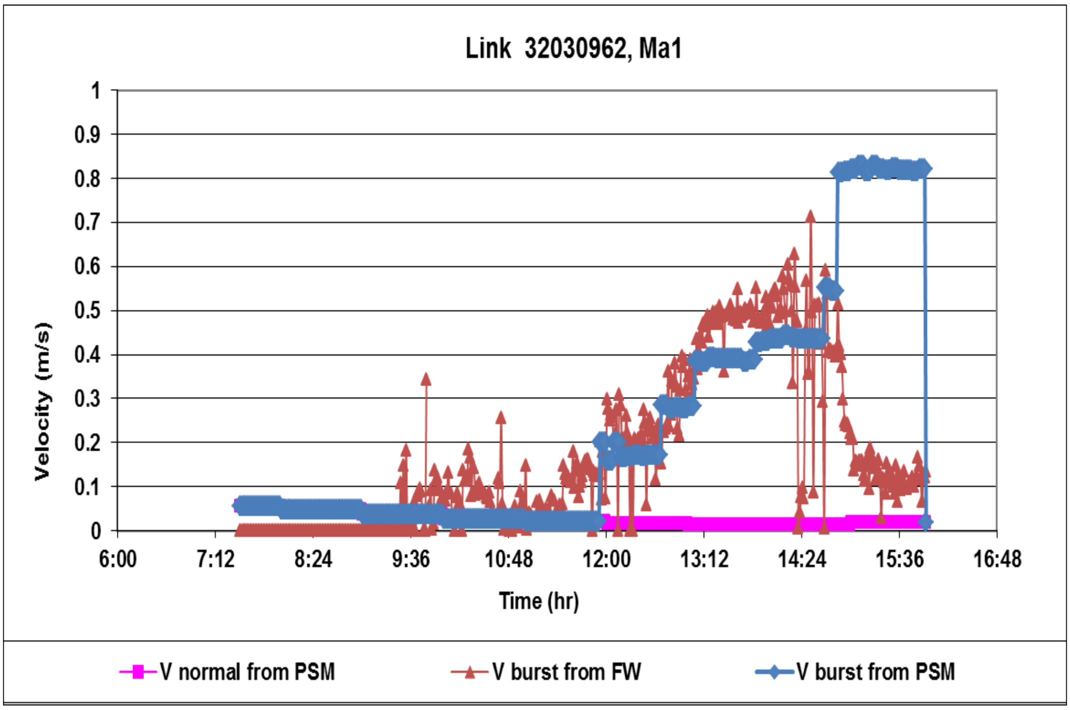


Figure 9.24: EPAnet-PSM prediction for the velocity in the Ma1 and Ma2 pipe in both normal and burst pipe situations compared with Ma1 fieldwork velocity results.

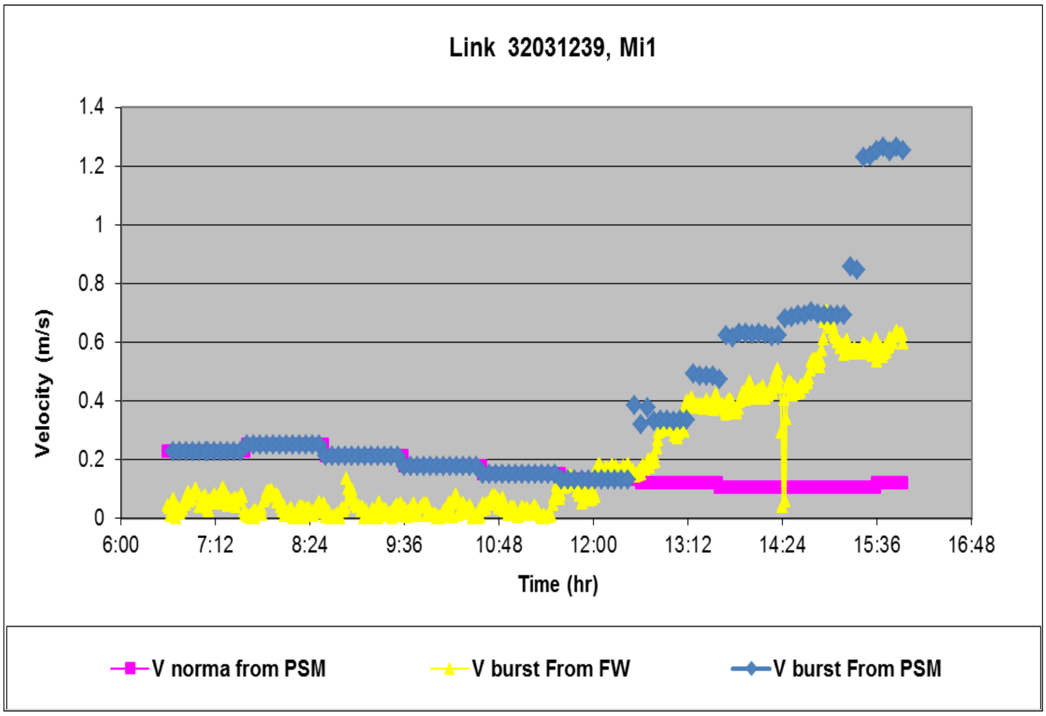


Figure 9.25: EPAnet-PSM prediction for the velocity in the Mi1 pipe in both normal and burst pipe situations compared with fieldwork velocity results.

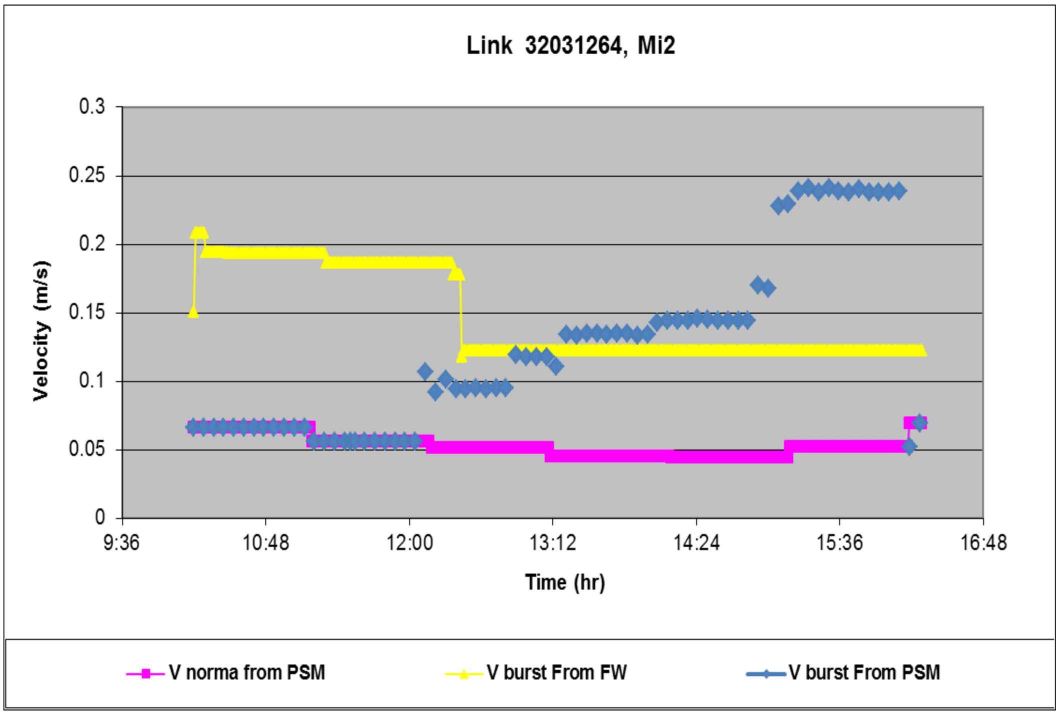
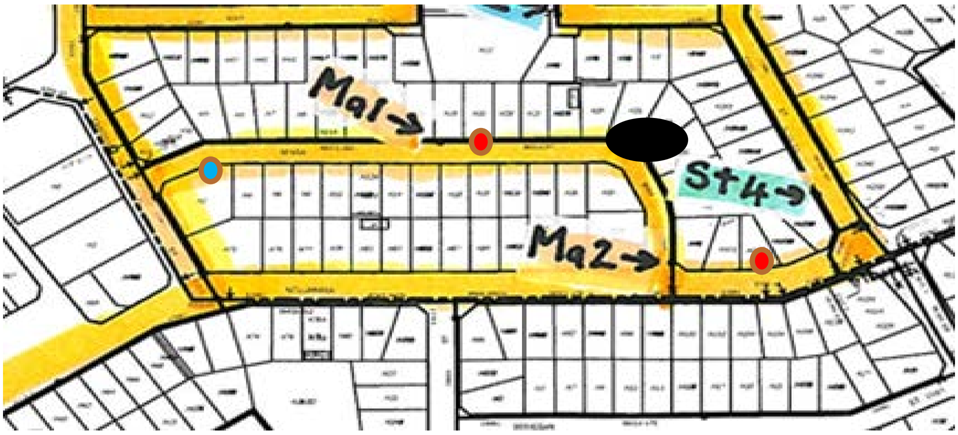


Figure 9.26: EPAnet-PSM prediction for the velocity in the Mi2 pipe in both normal and burst pipe situations compared with fieldwork velocity results.

It is clear from Figure 9.24 that there are differences between the EPAnet-PSM predicted velocities compared with the fieldwork burst pipe situation velocities, starting from 14:50 hrs (the time at which the flushing from Ma2 started) until the end of fieldwork. This was due to the fieldwork flushing being carried out at two points (Ma1 and Ma2). The flow meter was installed in the pipe between them, but in the PSM the demand was increased in the downstream node, as illustrated in Figures 9.27 and 9.6. Although this is the industry practice, another two PSM runs were also undertaken by creating one or two nodes at the middle of pipe 32030962 (Ma1 and Ma2 pipe). The creation of one or two nodes was in order to recreate the real situation as much possible, but the results did not improve (a sample of the results is illustrated in appendix C).



Downstream node

Flushing two points, Ma1 and Ma2.

Flow meter at link 32030962

Figure 9.27: Location of flow meter in relation to major sites.

It clear from Figures 9.25 and 9.26 that the velocities pattern does not match at all. A hydraulic model is a simplified version of what occurs in the real situation. A lot of assumptions are made. For example, in a real network there are some control operational valves which are closed or partially open but those valves are not present in the hydraulic model. When this is not implemented, the model will not match the real situation. Therefore, the flows predicted by EPAnet-PSM (normal flow) are different from those calculated in the fieldwork before the burst flushing occurred. This may be because the fieldwork was held from 11AM to 4PM during the high demand period. The key aspects of this model are the hydraulic data used for the model. When these data are not accurate, an accurate prediction cannot be expected. If the hydraulics in the PSM networks are completely different to the real situation then so is the distribution of sediment. Despite the shortcomings some PSM runs were undertaken and the results are presented in Appendix C.

With all the difficulties in assigning sediment concentrations at the beginning of a run and the many issues that required rectifying, as illustrated in paragraph 7.3, the author has decided not to present any sediment concentration predictions. Also noted in an earlier chapter, is an incongruous calibration of prediction with both the burst pipe and complaints data. Hence the results collectively led to a conclusion that the PSM as it stands now could be used to understand the potential risks associated with a hydraulic event, but not in predicting exactly where complaints will or will not occur. The program requires modification that will take all problems into consideration and another investigation then undertaken to test the reliability of EPAnet-PSM. For this reliability test, the collected data could be used.

9.6 Conclusion

The key aspect of this chapter has been to understand the feasibility of using the PSM model to predict dirty water incidents. The field trial and consequent simulation revealed many issues with the PSM.

The first issue is related to correctly representing the detailed conditions that define the water flow in the real distribution network in local areas. The PSM overlays or calculates the sediment using the output (velocity) of the EPAnet model. To accurately validate the model, the velocity profile should match with that observed in the field. To reasonably predict the velocity the hydraulic data entered should be reasonably correct. The input data to the hydraulic model is not always exact as not a great deal of exact information is usually available regarding pipes in the system. When this data is not accurate, an accurate prediction cannot be expected. If the hydraulics in the networks are completely different to the real situation, the velocity and thus the distribution of sediment will be very different. It is therefore advisable to gain an understanding of the issues related to representing the hydraulic model as a reflection of the real world scenario.

The second issue is related to how sediment is characterised or entered. In the development of the PSM program, a great deal of laboratory research has been performed to identify the type of sediment and different velocities that determine the sediment's behaviour. The determination of these velocities is very important. For effective modelling results, the determination of these sediment characteristics has to be effected by fieldwork not by laboratory work. Therefore, more investigation into resuspension velocity is necessary in the real system.

The third issue is related to observed sediment resuspension at velocities far below those suggested in the literature. In the literature a velocity of 0.6 m/s is given as the right resuspension velocity. However, in all cases the sediment was found to be moving at 0.1-0.2 m/s. It should also be noted that if a pipe does not experience a velocity as high as 0.2 m/s, then the sediment will start to resuspend if 0.2 m/s is experienced. Likewise, if a pipe frequently experiences a higher velocity such as 0.5 m/s, a velocity of 0.5 m/s not sufficient to resuspend the material. Therefore there should be flexibility to enter the resuspension velocity depending on the pipe history. Investigation is required into the effect of pipe history on the required velocity to resuspension (normal velocity) velocity. It may also be advisable to look at the type of sediment and type of pipe (through flow or dead-end or loop pipe). This will be investigated in further fieldwork as illustrated in the following chapters.

The fourth important issue is related to flexibility in EPAnet-PSM to entering the initial sediment into the pipes even before the hydraulic modelling starts. This facility is not currently available.

CHAPTER 10 REAL RESUSPENSION VELOCITY

10.1 Introduction

One of the aims of this research was to validate a computer model (Particle Sediment Model-PSM) designed to predict sedimentation patterns in the pipes of drinking water distribution and reticulation networks. The results generated by the model were compared with field data to ensure the model could predict sediment behaviour in drinking water supply networks. Previous investigations suggested the use of 0.6 m/s as the resuspension velocity (Jayaratne et al., 2004) was not correct. As illustrated in Chapter 9, the highest turbidity during the fieldwork trial was recorded with a velocity of 0.18 m/s not 0.6 m/s. Similarly, the use of 0.2 or 0.4 m/s as a resuspension velocity provided a more reasonable prediction. In fact, if lower resuspension velocities were attempted, this would have given similar results. Therefore, the obvious conclusion from previous investigations with field trials and PSM predictions was that the resuspension velocity was less than 0.6 m/s. However, the exact value to be adopted is not known. The value of the resuspension velocity from a real system requires more investigation. The field trial also indicated that the pipe connected to the Mi2 site behaved in an unusual manner (Figure 9.11), i.e. higher turbidity was recorded when a velocity of just 0.18 m/s was observed. Therefore, additional fieldwork was conducted for five sites to increase the velocity (additional velocity) gradually from 0.1 to 0.7 m/s followed by a full flushing to understand the behaviour of sediment in the pipeline. Due to the excessive expense of measuring the in-line flow, only the induced flow out of each pipe was measured. It was thought that this measurement was sufficient to prove that even a small change in flow is sufficient to induce sediment transport.

10.2 Resuspension Velocity Fieldwork

10.2.1 Method and Equipment

To find the real resuspension velocity, further fieldwork for five sites (two with dead-ends, loop, through pipes and the Mi2 site) was undertaken. The additional velocity was gradually increased from 0.1 to 0.7 m/s followed by a full flushing at the end of fieldwork at each site. During the whole work, unidirectional flow was maintained.

Similar to RPM work and previous field trials, AquaMaster™ - the electronic flow meter - was used for flow measurement. The same procedure of connection the flow meter, as explained in paragraph 5.2.1, was followed. The same portable HACH2100 Turbidimeter was also used to measure the turbidity. The fieldwork was undertaken over two days in October 2011.

10.2.2 Selection of Sites

The details of the selected sites are given in Table 10.1. Figures 10.1 to 10.5 show the location of the sites on a map. The legends of Figures 10.1 to 10.5 are illustrated in Table 10.2. The selected sites were 1aH, 3aE, 4aD, 8aE and Mi2. The sites were selected from previous RPM sites illustrated in Chapter 5 as two with dead-ends, one through pipe, one loop pipe and the Mi2 site of previous fieldwork, which recorded the highest turbidity during PSM calibration fieldwork, with a velocity as low as 0.18 m/s. All selected sites were located in suburb D and E, except a site which was selected in suburb H as an alternative site. It should be emphasised that a comprehensive background on selected sites was available from a previous desktop study and RPM study, as illustrated in Chapters 4 and 5.

Table 10.1: Information on the five selected sites.

Site No.	suburb	Water resource	Last cleaned	Notes	Fig. No.	Unidirectional length (m)
1a.	H	Tank 1	Not cleaned	Closed valve at the end, near reservoir	(10-1)	324.2
3a.	E	Tank 2	Not cleaned	through pipe	(10-2)	307.2
4a.	D	Tank 2	Not cleaned	Loop point or dead-end*	(10-3)	376
8a.	E	Tank 2	Not cleaned	Closed valve at end, near reservoir	(10-4)	367.2
Mi2	D	Tank 2	Not cleaned	Loop point	(10-5)	307

*There was a non-functional ("closed") valve during fieldwork, which was not

Table 10.2: Legend for all figures 10.1 to 10.5.

	Flushing point
	Unidirectional flow route
	Valve already/previously closed
	Closed valve during fieldwork

Figure 10.1: Site 1aH, dead-end pipe; unidirectional flow length = 324.2 m; Tank 1 supplies the water.

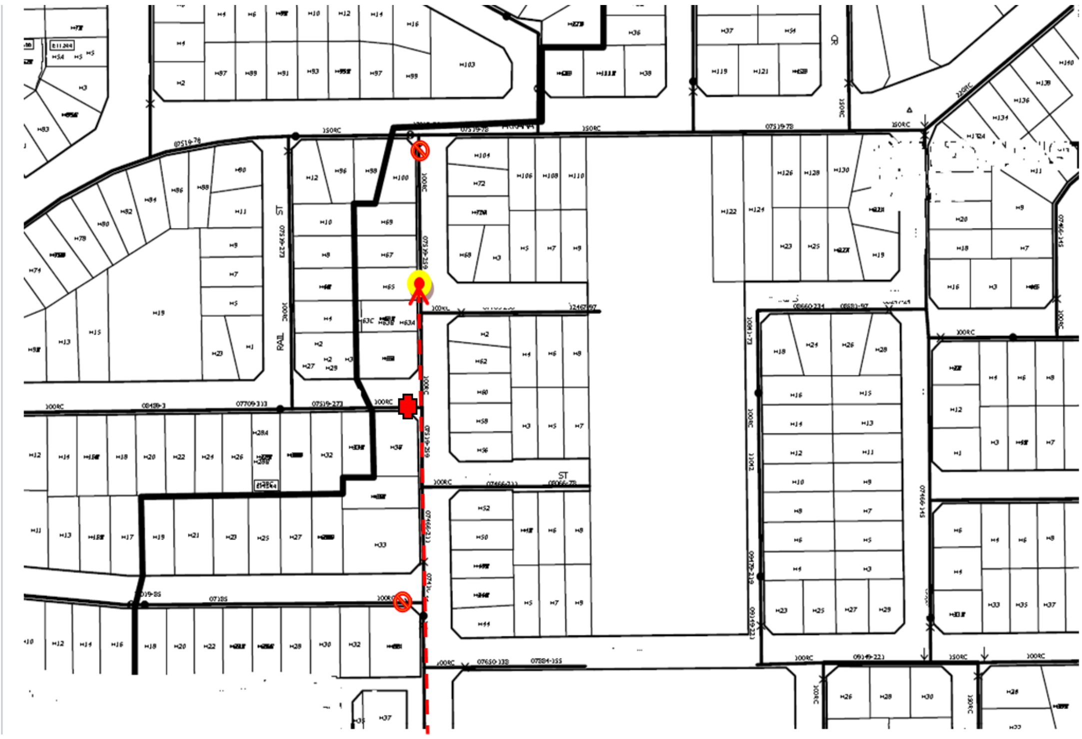


Figure 10.2: Site 3aE, through pipe; unidirectional flow length = 307.2 m; Tank 2 supplies the water.

Figure 10.3: Site 4aD, loop pipe or dead-end, unidirectional flow length = 376 m; Tank 2 supplies the water. Note the closed valve was not working during fieldwork.

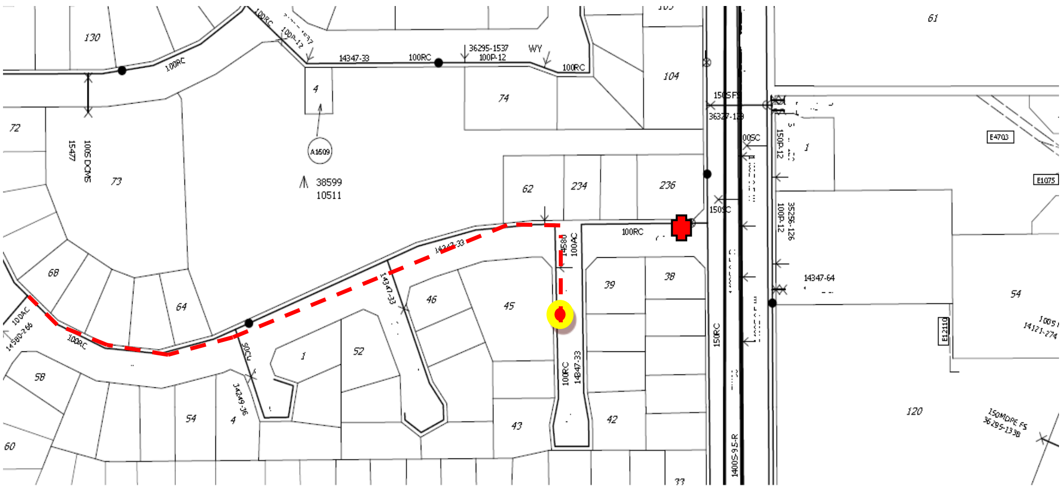


Figure 10.4: Site 8aE, dead-end, unidirectional flow length = 367.2 m; Tank 2 supplies the water.

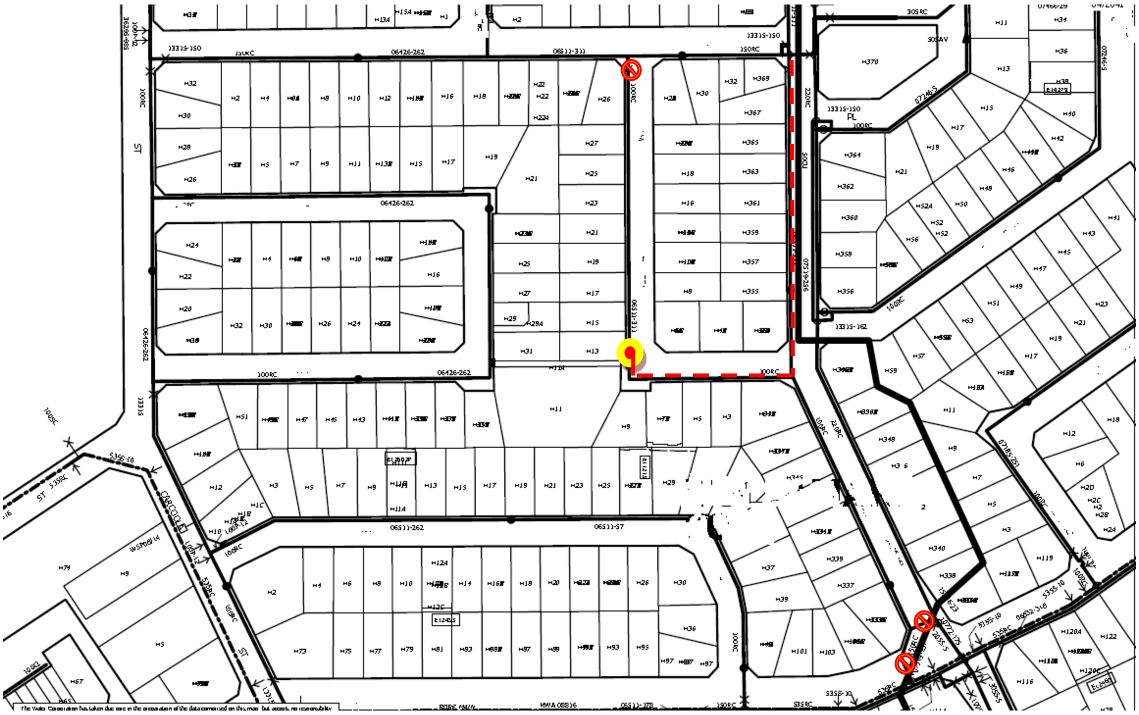


Figure 10.5: Site Mi2, loop pipe, unidirectional flow length = 307 m; Tank 2 supplies the water.

The fieldwork method was applied as follows:

The turbidity measurements were taken at the hydrant where flushing at a controlled rate was carried out. The hydrant was located on a 100 mm main. For this, the valves further down the 100 mm main had to be completely shut off so that no other pipes contributed to the flow, or to ensure unidirectional flushing. The end point of the unidirectional length was a branch or a larger diameter pipe, so velocities experienced in the unidirectional pipe would not be experienced in other pipes supplying water to the targeted pipes.

At each street, after closing off relevant valves, the selected hydrant was connected to a tap with a hose that had a volumetric flow meter attached at one end. Samples were regularly collected and turbidity was measured using a portable turbidity meter.

Table 10.3: Time of flushing for each velocity.

Site no.		1aH	3aE and Mi2	4aD	8aE
Unidirectional length		**324.2**	**307.2**	**376**	**367.2**
Additional velocity (m/s)	**Additional flow (L/s)**	**Time (min.)**			
0.1	**0.79**	**54.0**	**51.2**	**62.7**	**61.2**
0.2	**1.57**	**27.0**	**25.6**	**31.3**	**30.6**
0.3	**2.36**	**18.0**	**17.1**	**20.9**	**20.4**
0.4	**3.14**	**13.5**	**12.8**	**15.7**	**15.3**
0.5	**3.93**	**10.8**	**10.2**	**12.5**	**12.2**
0.6	**4.71**	**9.0**	**8.5**	**10.4**	**10.2**
0.7	**5.50**	**7.7**	**7.3**	**9.0**	**8.7**
Flushing	**8.00 or more**	**5.3**	**5.0**	**8**	**6.0**

Following Table 10.3 as a guide, the hydrant was opened until the flow meter was showing 0.79 ,1.57…..,5.5 L/s, and complete flushing was undertaken to achieve additional velocities of 0.1, 0.2…..0.7 m/s and full flushing velocity at the end (respectively). The duration (time) at each site was a function of the unidirectional length and flow velocity. It was calculated by the following formulae: time (min) = unidirectional flow length (m)/velocity (m/s)/60. Turbidity readings were simultaneously taken by the portable turbidity meter every minute. This procedure was followed for all five sites. The flushing times were taken as being to the nearest minute as was practical. Depending on the available pressure and pipe type, the maximum flushing flow was less than 5 L/s in some sites, while in other sites it was greater than 8 L/s.

10.3 Results and Discussion

The results are illustrated in Figures 10.6 to 10.10. In general, the new results give a sound explanation of the previous fieldwork results in Chapter 9, i.e., the maximum turbidity was recorded with a lower velocity than at a higher velocity. Further explanation regarding each site is given below.

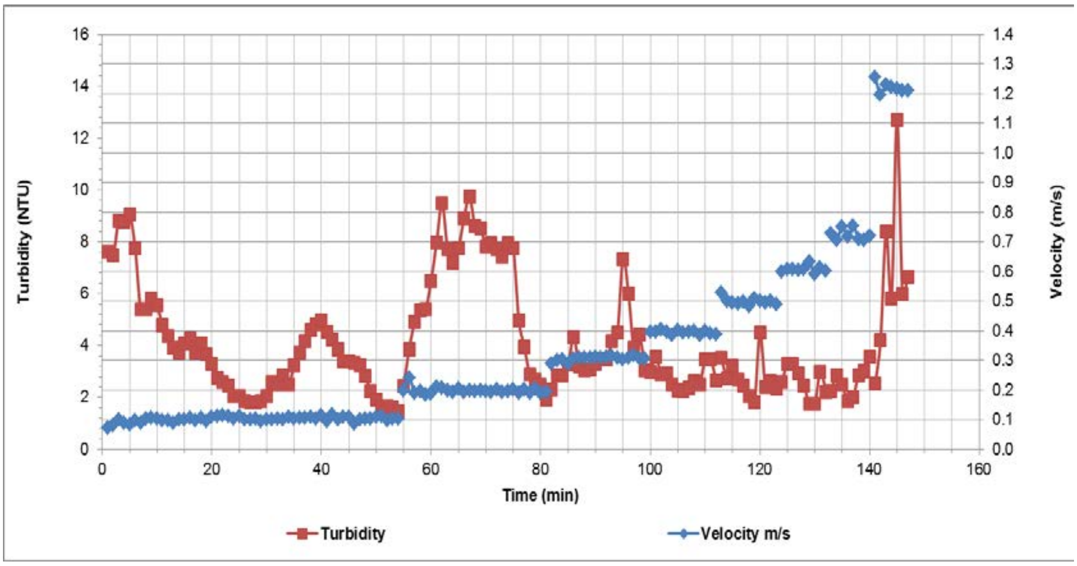


Figure 10.6: Site 1aH; dead-end pipe; turbidity and additional velocity results.

During the above fieldwork at site 1aH, the maximum turbidity values of 8.8, 9.7 and 12.7 NTU were recorded with velocities of 0.1, 0.2 and 1.22 m/s respectively, as illustrated in Figure 10.6. The turbidity shape at 0.1 and 0.2 m/s resembles an inverted parabola, i.e., the turbidity gradually decreased after peaking. It should also be noted that the turbidity observed was high when the velocity was 1.22 m/s. This was probably due to the higher velocity (more than 0.2 m/s) reached in the other pipes which were connected at the other end of unidirectional pipe.

When this occurs, the water flowing to the hydrant may actually bring dirty water into the area being flushed (Friedman et al., 2002).

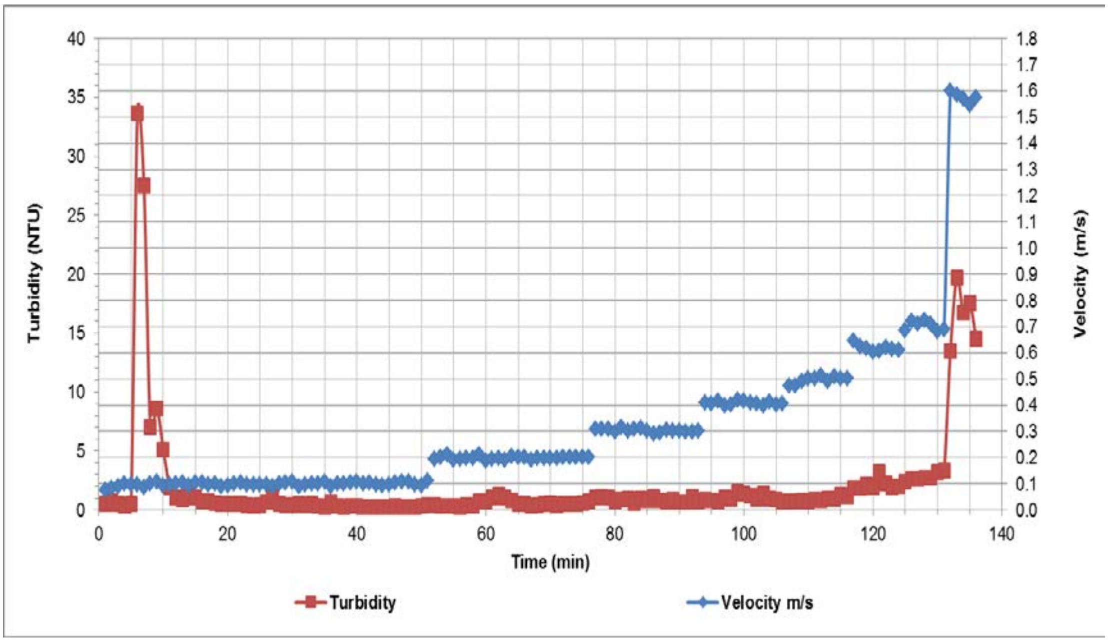


Figure 10.7: Site 3aE; through pipe; turbidity and additional velocity results.

The behaviour observed at a lower additional velocity (<0.2 m/s) resembles that observed in most fieldwork sites. The behaviour observed with full flushing explains why the Water Corporation records many complaints when they adopt the flushing policy following the receipt of a complaint. This is possibly because flushing moved the sediment from other pipes as in burst pipe events. It should also be noted that many RPM and flushing activities were undertaken at these sites by this project team during the research period from 2009 to 2011. This explains why the values of turbidity were low even when the pipe had a dead-end.

The results for site 3aE, given in Figure 10.7, showed very different behaviour. The values of turbidity for the whole time were <4 NTU, except for the maximum turbidity values of 33.6 and 19.7 NTU, recorded with velocities of 0.1 and 1.58 m/s. This was a flow through pipe, hence there was less chance for sediment accumulation. This fact is further reinforced since the area under the turbidity curve was very narrow. The possible cause for the sediment could be from smaller particles arising from pipe erosion or a small pocket of sediment.

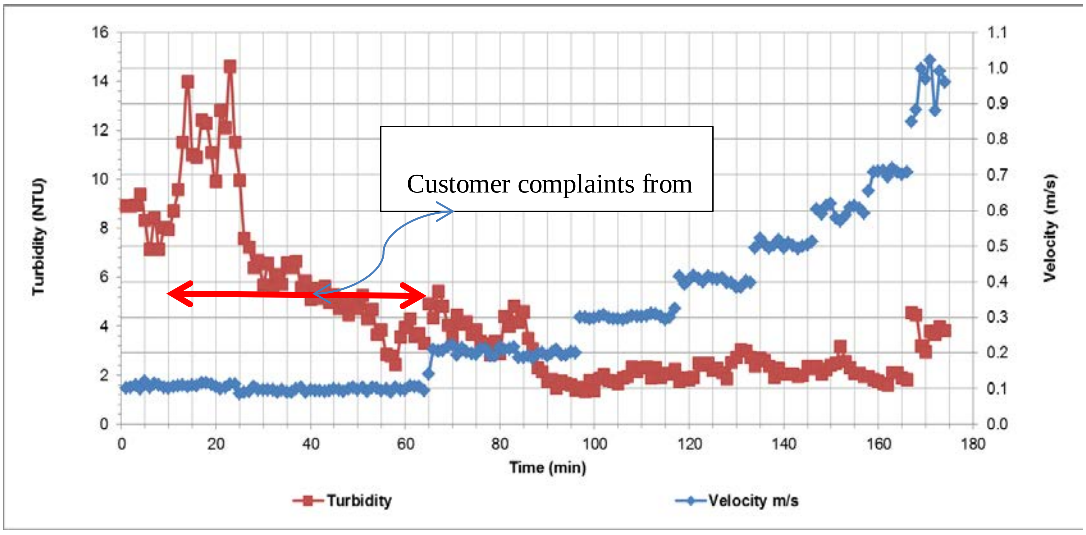


Figure 10.8: Site 4aD; loop pipe or dead-end; turbidity and additional velocity results.

During the fieldwork at site 4aD (Figure 10.8), there was high turbidity and customer complaints from surrounding properties even with an additional velocity of 0.1 m/s. All maximum values of turbidity were recorded with this low additional velocity, as illustrated in Figure 10.8. This particular site usually records a great deal of complaints as there are many multi-storey and duplex buildings in the area, and this eventually leads to considerable flushing activity by the Water Corporation. This explains why the maximum turbidity value was low even when the pipe had a dead-end (12.7, 9.7 NTU and 14.6, 14 NTU for 1aH and 4aD respectively). The dead-end usually registers much higher turbidity when disturbed.

Site 8aE had the same result as 1aH, as illustrated in Figure 10.9, hence no explanation is given.

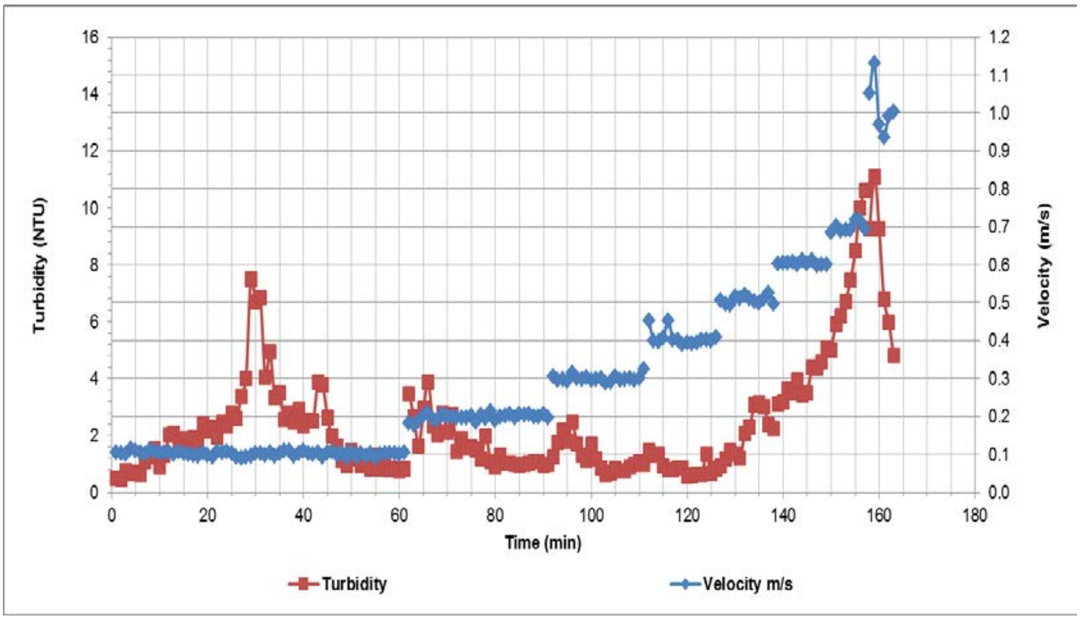


Figure 10.9: Site 8aE; dead-end; turbidity and additional velocity results.

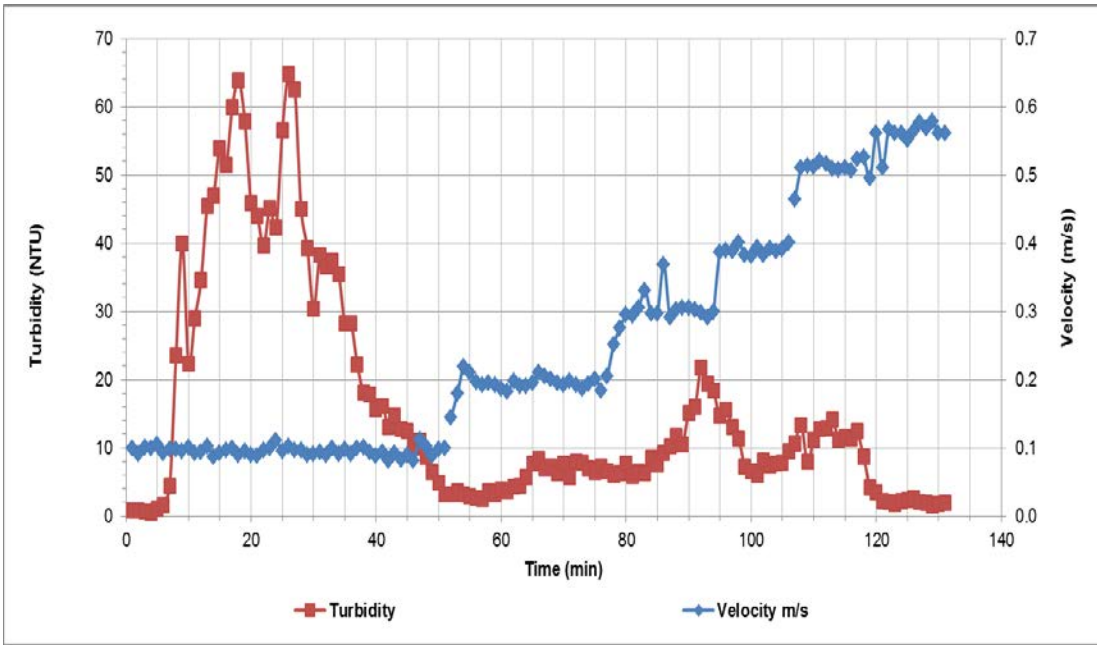


Figure 10.10: Site Mi2, loop pipe, turbidity and additional velocity results.

More interesting results arose from Mi2 site (Figure 10.10), which recorded high turbidity during an additional velocity of 0.1 m/s and these are in agreement with the results of previous fieldwork in Chapter 9. The critical review of existing literature is important and that is done in the next section.

10.4 New View to Literature Results

The fieldwork results showed that high turbidity was possible with a lower value of velocity. As explained earlier, the existing literature requires re-evaluation.

Polychronopolous et al., (2003) from their desktop study for South East Water in Melbourne stated;

"*There was an absence of any correlation between customer complaints and water velocity which was unexpected*".

The results of the fieldwork actually indicated that many parameters were to be considered in understanding whether turbidity was caused by hydraulic events. A pipe usually undergoes fluctuation in velocity or flow rate, diurnally, weekly and seasonally. This means the sediment in the pipe is conditioned to such variation in flow or velocity. It would be hard to dislodge the settled sediment from the pipe, if a normal flow is experienced. In local pipes (~ 100 mm diameter), velocity is low and usually ranges between 0.02 -0.1 m/s. The sediment in the wall is conditioned to this velocity, i.e., A velocity higher than the maximum of all the velocity usually experienced is required to displace the sediment. If the maximum velocity experienced in a pipe under normal circumstances as normal velocity is (Vn), then it is possible to induce movement of the sediment if the velocity in the pipe exceeds Vn.. To take this aspect into account, an examination of the ratio of (V_b/V_n) is proposed; (V_b) is the burst velocity, the velocity experienced at the pipe during the burst and V_n is the maximum normal velocity. If the ratio exceeds 1.0, then there is a likelihood of sediment movement. However, it should be noted that there should be some sediment present. The amount of sediment in the pipe will determine how much sediment will resuspend, and therefore the magnitude of turbidity. The amount of sediment depends again on previous history, such as previous dirty water incidents, or flushing of the pipe. Therefore, any sign of increasing turbidity should be treated as the impact from hydraulic events, and any flow that induces velocity more than the conditioned velocity is capable of inducing the dirty water incident. With this view in mind the literature data was analysed.

Based on the data from Polychronopolous et al., 2003 (Table 10.4), a sound correlation between dirty water incidents (peak turbidity) and V_b /V_n (velocity with maximum turbidity/maximum normal velocity) at each pipe could be obtained as illustrated in Figure 10.11. Similar to that which was expected, any increase in velocity above the V_n caused the dirty water incidents. Again, it is notable that there is no requirement for the velocity to reach as high as 0.6 m/s in order to cause dirty water incidents. The number of complaints was not correlated as the complaints data was not complete, i.e., the exposed population was not provided as the total complaints would not help in understanding the impact of turbidity on complaints, as noted earlier in Chapter 4.

Table 10.4: Polychronopolous et al., 2003 desktop study data for South East Water in Melbourne.

Name	Maximum normal velocity V_n (m/s)	Velocity for maximum Turbidity V_b(m/s)	V_b/V_n	no. of complaints	peak Turbidity (NTU)
Carisbrook	0.05	0.191	3.82	0	18
Grasmere	0.1	0.127	1.27	0	87
Rubens	0.05	0.127	2.54	3	28
Chagall	0.1	0.127	1.27	1	429
Clerehan	0.1	0.191	1.91	2	18
Later	0.05	0.127	2.54	0	50
parkhill	0.05	0.255	5.1	4	122
Finley	0.05	0.382	7.64	3	510
Ulah	0.05	0.255	5.1	0	160

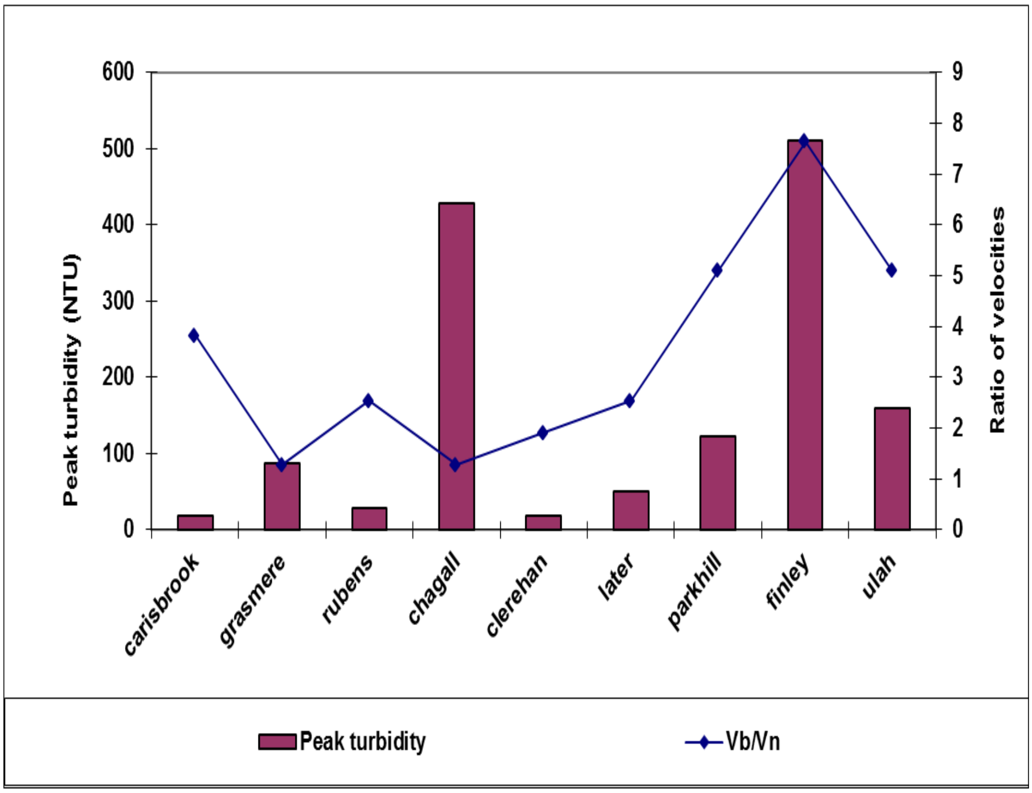


Figure 10.11: Correlation between peak turbidity and (V_b/V_n); "V_n" maximum normal velocity and "V_b" velocity at maximum turbidity; for Polychronopolous et al., 2003 data.

The results clearly show that the effect of pipe history on the required velocity to resuspend the sediment and type of pipe (through flow or dead-end or loop pipe) require more consideration.

10.5 Discussion of Fieldwork of Validation of PSM

Figures 10.12, 10.13 and 10.14 were the result of the application of the new theory of the effect of the maximum normal velocity on the required resuspension velocity to the fieldwork data, illustrated in section 10.4.

Because site Mi2 was located at a loop street there was a possibility that a greater amount of turbid material in this region had not been flushed for some time and for these sites of stagnant flow, a velocity of between 0.1- 0.2 m/s was enough to mobilise the sediment.

As a hydraulic model is a simplified version of what is actual, a lot of assumptions are made. For example, in reality, in a network, there are some control operational valves which are closed or partially open but those valves were not entered in the hydraulic model. When this was not implemented, the model could not completely match the real situation. Therefore the flows predicted by PSM (normal flow) are different from those calculated in the field, before burst flushing occurred. In addition, it should be noted that the demand at the nodes is nominally defined and the pattern is predetermined for all pipes. Although the pattern could be true if an average flow is considered, it cannot be true in local areas where there can be larger variation. Therefore, further work is needed to match the flow in every branch of the pipe.

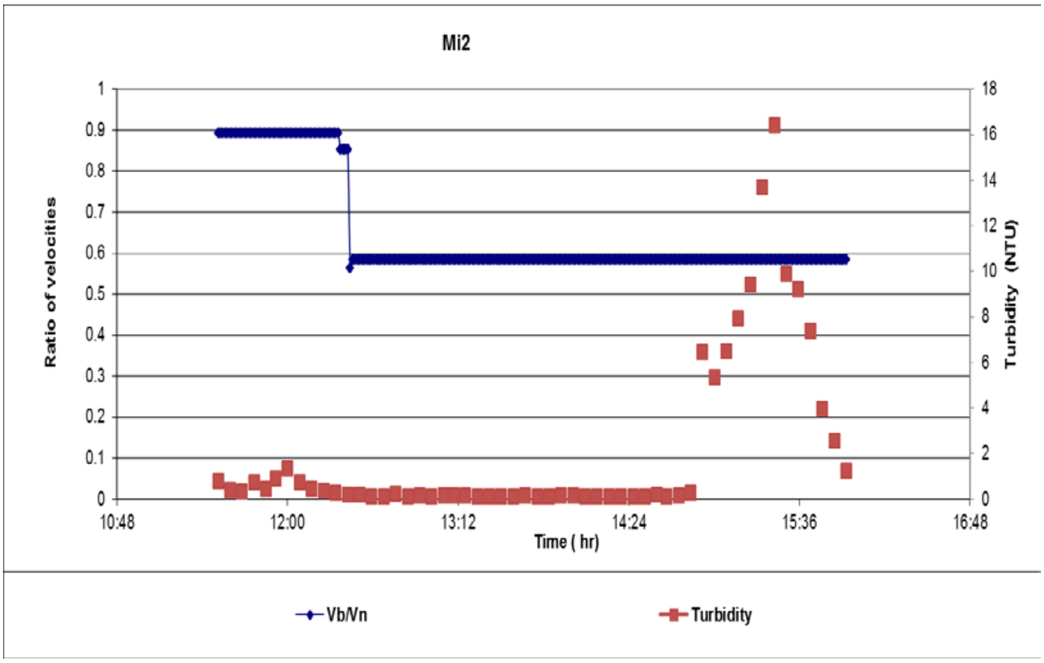


Figure 10.12: Real data of velocity $_{burst}$/velocity $_{normal}$ (V_b/V_n) and turbidity for Mi2 site.

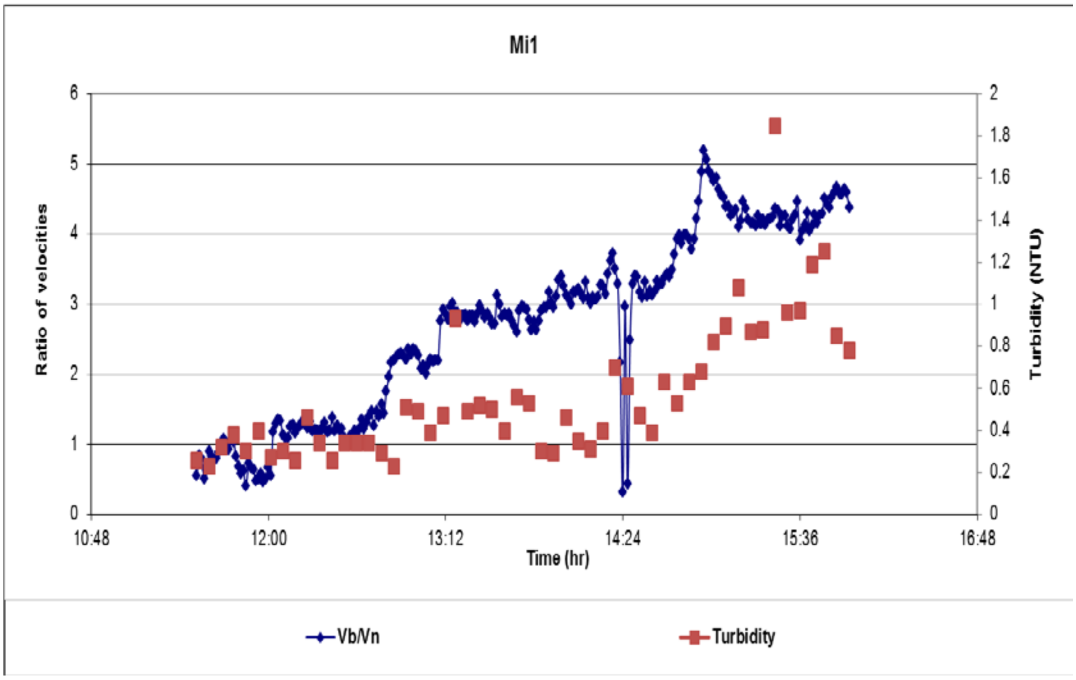


Figure 10.13: Real data of velocity $_{burst}$/velocity $_{normal}$ (V_b/V_n) and turbidity for Mi1 site.

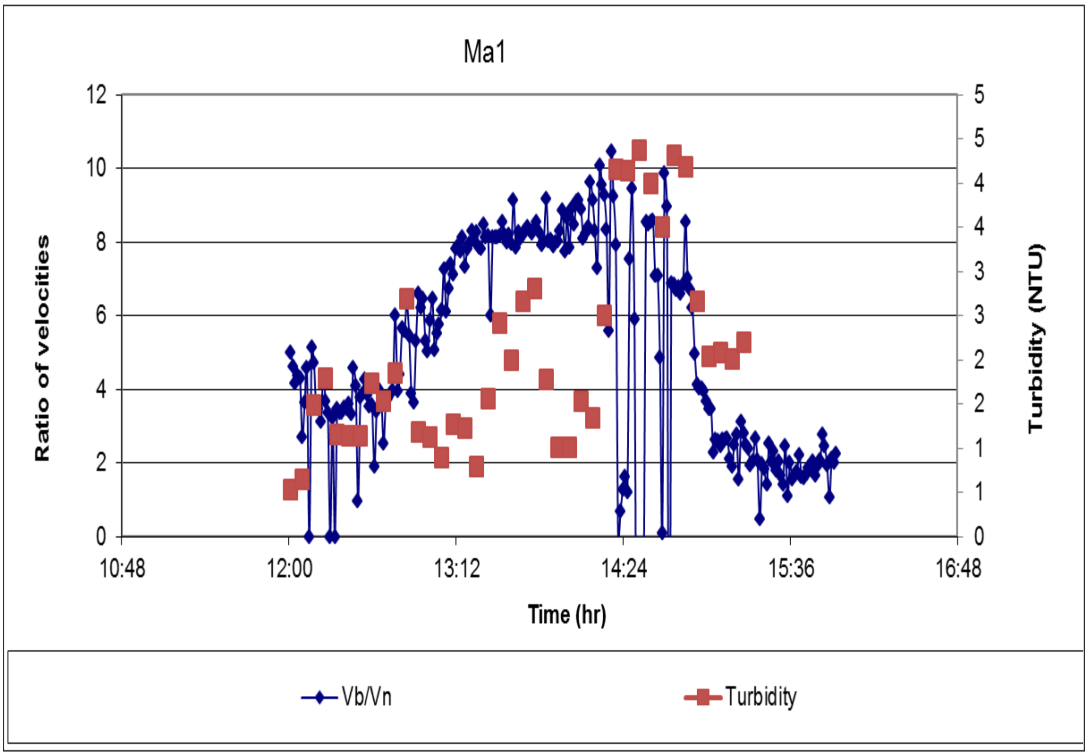


Figure 10.14: Real data of velocity $_{burst}$/velocity $_{normal}$ (V_b/V_n) and turbidity for Ma1 site.

As illustrated in Figures 10.13 and 10.14 a new theory was confirmed about the required mobilisation velocity of accumulated particles within distribution networks, as this depends historically on the highest velocity the pipe is exposed to prior to the burst main incident, and the velocity the pipe experiences during the discoloured water event rather than the absolute velocity. However, the results of site Mi2; Figure 10.12; show the maximum turbidity recorded with the ratio equal to 0.6 followed by a ratio equal to 0.9. During the period when the pipe experienced 0.9, it never showed any signs of sediment (turbidity). As the velocity experienced was low but continued over a long period of time (about 4 hrs) in the pipe, the only explanation could be the movement of particles from another pipe as much higher velocities were induced in other pipes due to a simultaneously higher flushing flow in other sites. However, this behaviour is still not as expected and therefore, more investigation is required.

10.6 Conclusion

It is logical that if a pipe continuously experiences higher velocity there cannot be sediment that could resuspend at this particular velocity and a velocity higher than the velocity it normally experiences is required. However, it should be noted that the value of turbidity a pipe experiences is a function of sediment in the pipe. It has been proven in this work and in the previous chapter that resuspension velocity is not a fixed quantity but varies depending on the situation.

High turbidity was recorded at site Mi2 with the ratio of velocities equal to 0.6. This means that the pipe has experienced much higher velocities previously (and as a usual occurrence), hence its recent behaviour is deemed unusual, although one explanation that could be offered is that the the sediment has been transported from another pipe.

CHAPTER 11 NEW CLEANING STRATEGY

11.1 Current Cleaning Strategy

In most countries, water utilities including the Water Corporation, clean pipes either regularly (preventative) or depending on the number of customer complaints (reactive).

In the reactive approach, an emergency response is adopted first, i.e., upon receiving a complaint, personnel are sent out to the location where the complaint is made and the nearest hydrant is flushed for a short period of time without closing any valves. This is the conventional flushing method in which pipes are flushed at 10 to 15 L/s for 5 to 15 minutes without closing any valves. During the flushing period, the utility personnel keep in contact with the resident to make sure that their water has become completely clear. If water at the customer tap is not clear then the flushing at the hydrant is continued until it has. Due to the uncontrolled nature of the cleaning, our fieldwork in Chapter 10 indicated that many unwanted additional complaints could be induced. If more complaints are made, then this is a risk area for complaints and financial losses as millions of dollars are annually spent on cleaning all pipes in those identified areas. By the time water utilities decide to clean a system in a preventative manner, many complaints have already been made and this seriously affects the water utilities customer relationships. The conclusions from previous chapters also indicated that the more complaints are made, the cleaner the pipe becomes. Hence it is a wasteful exercise to adopt preventative maintenance after a number of complaints are made. Due to cost implications, no water utilities undertake a purely preventative approach where pipes are cleaned at regular intervals irrespective of the number of complaints received by the water utilities. Conclusions from previous chapters indicate that a preventative approach would reduce the sediment and hence the impact of hydraulic events on the number of complaints. However, the period during which cleaning would remain effective in the studied system is less than one and a half years. Therefore, to spend money efficiently, the area to be cleaned should be carefully selected and the least expensive cleaning strategy implemented.

An understanding of the location and deposition patterns of discoloured water in drinking water networks would improve the ability to target preventative maintenance. Such an improvement would therefore lead to cost savings by more targeted proactive cleaning of water mains. Additionally, it would increase customer satisfaction and water utility compliance with the turbidity standards in both Perth and National Guidelines requirements.

11.2 An Extended RPM as a Cleaning Strategy

To achieve an understanding of the location and deposition patterns of discoloured water in drinking water networks, a regular RPM covering the whole network could be adopted. It would give an indicator of the situation of pipes regarding sediment. By extending the RPM, cleaning of the pipes could be achieved by a controlled unidirectional flow for the required time without wasting water or money unnecessarily. By applying this method the cost of air-scouring could be avoided and the number of emergency flushing locations could be substantially reduced, as no turbulence would be caused in unwanted areas causing many unwanted complaints. An extended RPM could also be used as a possible replacement for the full flushing used for mains cleaning. This means that water losses during mains cleaning could be reduced by about two thirds. The RPM could be adjusted depending on unidirectional length, rather than restricted to fifteen minutes duration. Thus, the flushing period needs to be calculated based on the pipe length for unidirectional controlled RPM flushing.

11.3 Estimating the Ability of Controlled RPM as a Cleaning Strategy

To verify the ability of the controlled RPM to clean sediment accumulation in water mains, both the RPM controlled method and the full flush method were simulated along with the PSM in the same street. Based on the previous PSM runs in Chapter 9, the adopted resuspension velocity was equal to 0.4 m/s. The objective was to find which method gives an optimal removal of settled sediment.

In order to remove sediment from the pipe wall using controlled RPM, a high velocity of 0.4 m/s needed to be achieved by closing the specific valves which allowed the water to be directed in one way through the pipe that was planned to be flushed. Since water is flowing in one direction and through the directed path, only the pipe that was planned to be flushed would be cleaned and the settled sediment would be directly flushed out through the fire hydrant, thus not contaminating the water in other connected pipes nearby. This study is dedicated to finding out which flushing method is the most effective using software (PSM) analysis.

Generally in the PSM, increasing the demand at a node near the location of a fire hydrant (located using the Litespatial program) represents the opening of a fire hydrant to flush pipes. When carrying out conventional flushing, the demand used at the selected node was set to an additional 10 L/s while in the controlled RPM, the demand was set to an additional 3 L/s.

In this study, in order to fairly compare both flushing methods, unidirectional RPM flushing was firstly carried out. Unidirectional RPM flushing required some valves closed and a hydrant being opened to create a one-way flow for the period calculated based on the unidirectional pipe length for the selected pipe {i.e. time (min) = unidirectional flow length (m) /velocity (m/s)/60}. The unidirectional length was determined from Litespatial program.

Conventional flushing was then carried out using the 10 L/s demand and 10 minute flushing period, without closing any valves. If there was no removal in settled sediment while undertaking conventional flushing, the flushing period was increased by 5 or more minutes to see if that was sufficient to remove the settled sediment.

The comparison of results between both flushing methods, the conventional and unidirectional controlled RPM for the loop link network was analysed, and the overall understanding of the results are discussed in detail in the following section. The parameters that are used to compare against the effective flushing method are settled sediment concentrations (mg/m) using the results from the PSM software.

11.4 Selected Street Location and Method

In this project, many through and loop pipe networks were analysed, but the analysis for the dead-end pipes has not been considered in this report as the majority of the dead-end pipes in the whole of the pipe network do not have a fire hydrant located at the far end of the pipe link (this was checked using Litespatial program). It is recommended that fire hydrants be installed at the far end of this type of pipe network to allow effective flushing to be carried out. The results of one scenario, the loop pipe network are chosen as an example of results for discussion. The loop pipe location with all available valves and fire hydrants is illustrated in Figure 11.1.

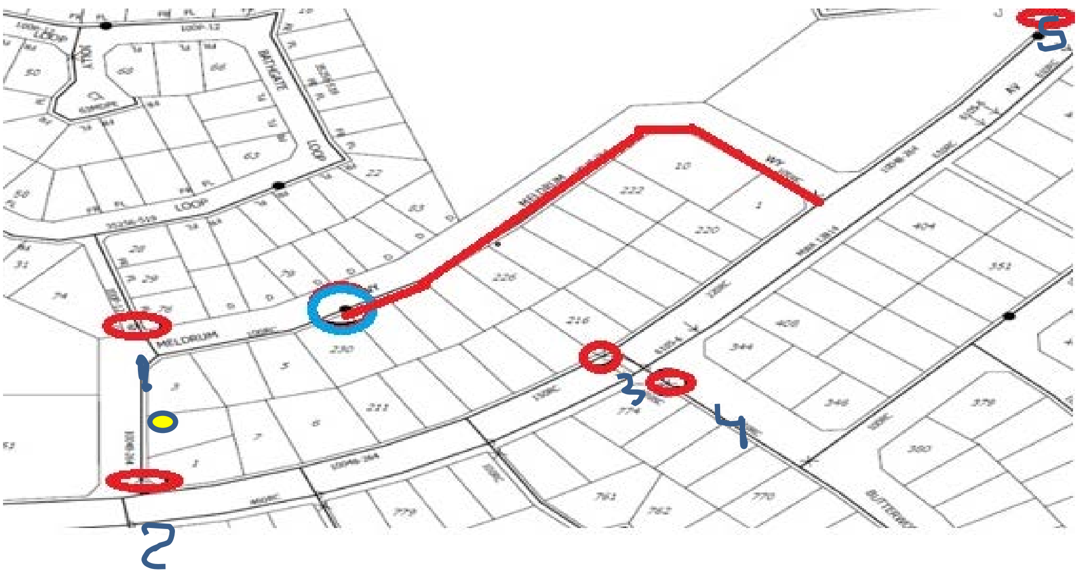


Figure 11.1: The circle shows fire hydrants and valves.

	Fire hydrant
	Closed valves
	Unidirectional flow at link in PSM; 39043534
	node Downstream in PSM; **817** NWF1#39

In this particular loop network, there are two possible pathways to create unidirectional flow. After analysing the results from both pathways, the pathway that gave the best results was chosen in terms of the length of the pipe it would clean and the lack of complaints. The results are displayed below. A thin red line is drawn on top of the pipe network to show the direction of the water flow created by closing the valves and the opening of a fire hydrant is marked by blue circles in Figure 11.1. The available valves are marked by red circles. Using the unidirectional controlled RPM flushing method, three options were available depend on which valves were closed to create a one-way flow. The flushing period was determined based on the length of the unidirectional flow pipe {i.e. time (min) = unidirectional flow length (m)/velocity (m/s)/60}. The unidirectional length was determined from the Litespatial program as equal to 323.5 m for the loop part which is shown in Figure 11.1 as unidirectional flow, if three valves, 1, 2 and 5 were closed. The unidirectional length will be 550.7 m, if the closed valves were 1, 2, 3, and 4. It will be 445 m, if the closed valves were 1, 2, 4, and 5. Thus with 0.4 m/s, the flushing time was (323.5/0.4)/60 = 13.5 mins, (550.7/0.4)/60 = 23 mins, or (445/0.4)/60 = 18.5 mins. In the PSM software, the pattern step is set at 5 minute intervals. For example, flushing can only be carried out for 5, 10, or 15 minutes and so on. So in this case, 13.5, 23 and 18.5 minutes can be input as 15, 25 and 20 minutes in PSM respectively. Because the quantities of settling sediment were very small in two pipes connected to loop pipes, flushing for 15 minutes was chosen for both controlled RPM and conventional flushing, especially for comparison purposes.

In the PSM software, closing valves is done by closing the pipe/link; each pipe line and connection has its own ID which can be used to locate it. The command control in the PSM software allows for any link to be closed for a specific time. This command control was used to close certain valves when unidirectional and controlled RPM type flushing was carried out. The command control in PSM was used to close certain links (pipes) to cause the water to flow in the desired path. Flushing was done by increasing the demand at a downstream node. In this particular case, in order to carry out flushing, the demand at node 817NWF1#39 was increased as 3 L/s. A run period of 336 hours was chosen. This time period was chosen so it would give enough time for the sediment to settle on the pipe wall, thus the model reflects the real situation. When carrying out flushing, the flushing period is chosen to begin at 80:00 hrs to give enough time for all the sediment (particles) to settle down in the pipe. Similar to previous cases, two reservoirs were adopted: one was clean and the other was dirty, as illustrated previously in Chapter 7.

11.5 Results and Discussion

In the PSM program, three runs were undertaken; all of them starting with the same sediment concentration (mg/L). The first run was of the origin situation to allow a comparison between the two cleaning methods. The second run was carried out by increasing the demand at node 817NWF1#39 to 3 L/s from 79:55 - 80:10 for 15 minutes with unidirectional flow (three valves were closed; valves 1, 2 and 5). The last run was executed with another situation where no valves were closed. In the case of node 817NWF1#39, demand was increased to 10 L/s from 79:55 - 80:10 for 15 minutes, similar to the Water Corporation's emergency flushing procedure. The time series results from the PSM of the affected pipes are illustrated in Figures 11.2 to 11.6. It is clear from Figure 11.2 that link 39043534 (planned-to-clean) eventuated in being flushed using a controlled RPM while it would still be unclean with the conventional flushing method; as noted earlier in Chapter 10 it can take considerable time for a pipe to become clean. The same results of cleanliness could be seen in Figures 11.3 and 11.4 for links 39043542 and 39043544. In contrast, unintended links 39043538 and 39043507 eventuated in being flushed with conventional flushing; a high quantity of settling sediment was evident with controlled RPM.

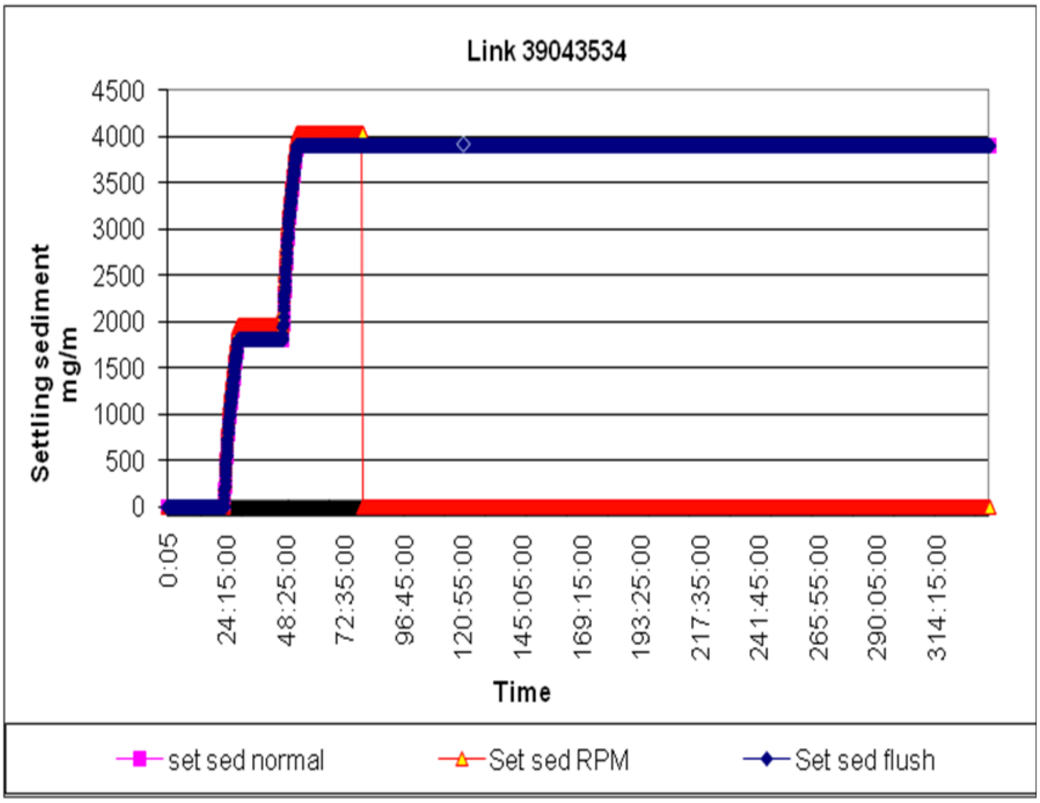


Figure 11.2: The PSM results of Link 39043534; the "planned-to-clean" pipe.

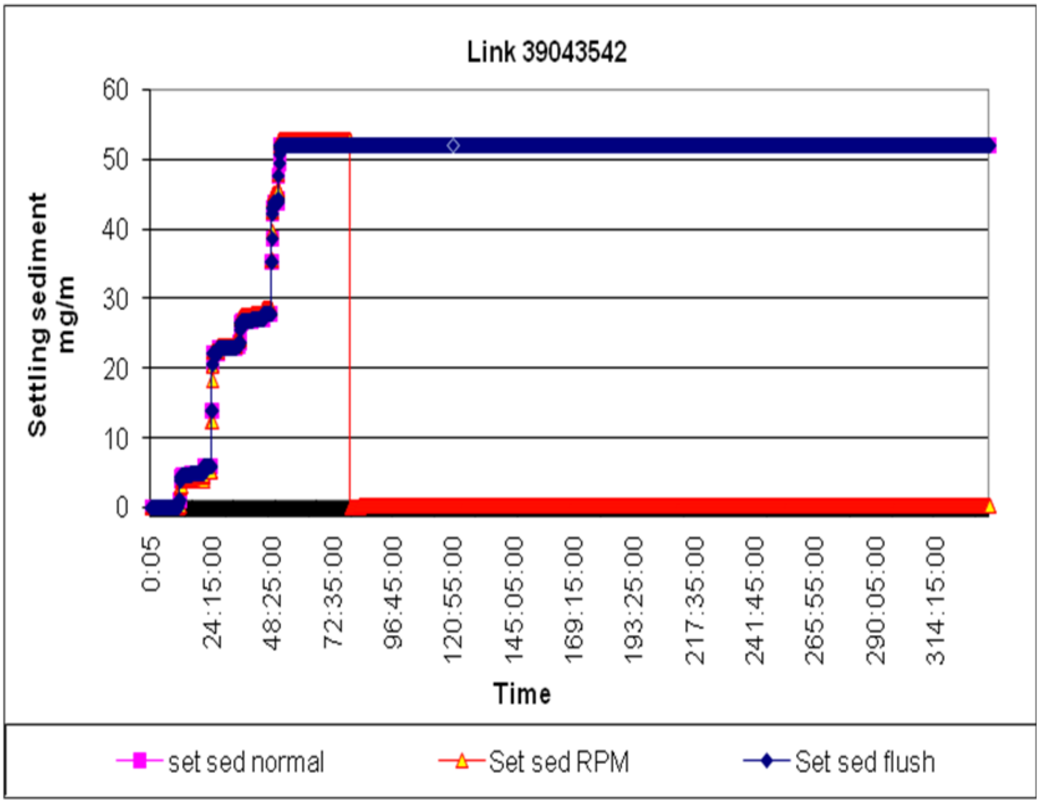


Figure 11.3: The PSM results of Link 39043542.

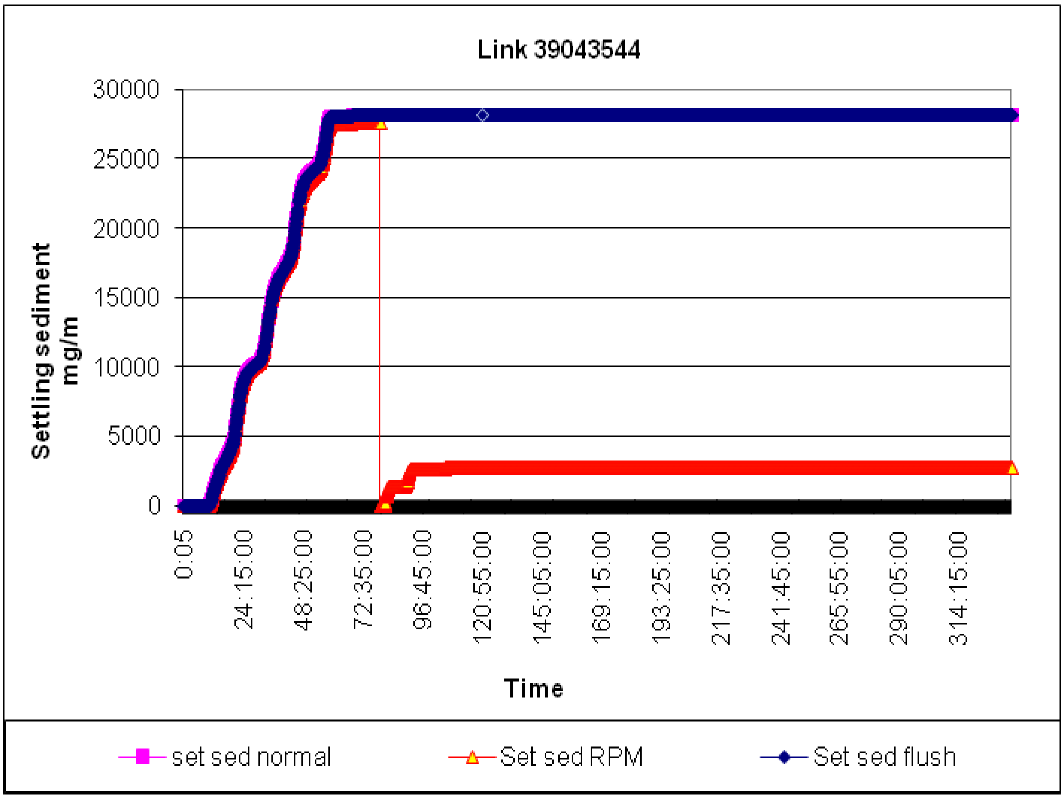


Figure 11.4: The PSM results of Link 39043544.

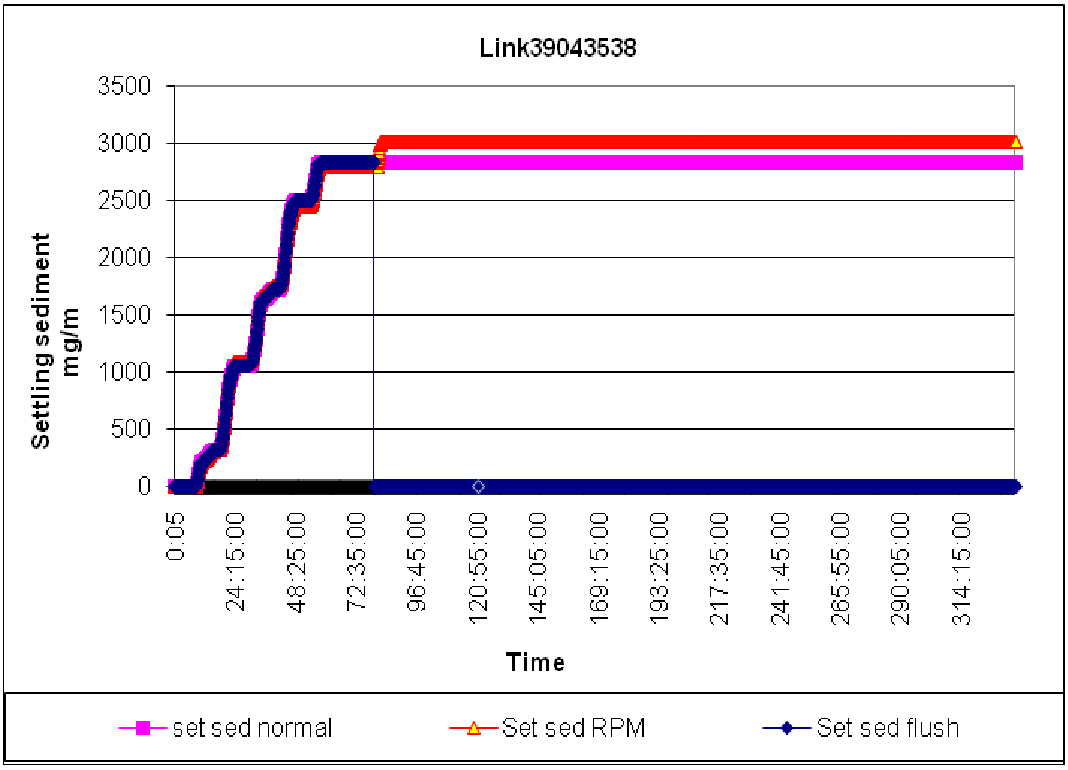


Figure 11.5: The PSM results of Link 39043538.

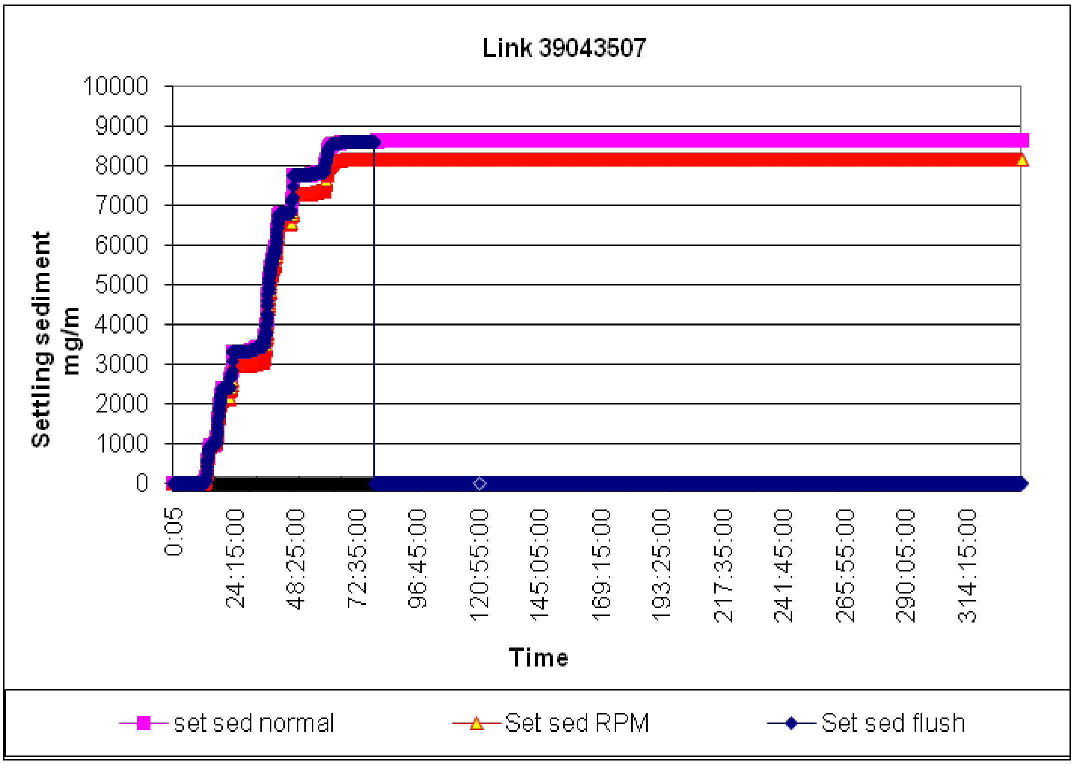


Figure 11.6: The PSM results of Link 39043507.

11.5.1 Results of Controlled RPM Cleaning Method

Unidirectional flushing is very effective in flushing the required pipe with the least amount of water. With the unidirectional flushing method, the "planned" pipe was completely cleaned; Link 39043534 achieved a 0 mg/m settled sediment by flushing it at 3L/s for a predetermined period, based on the unidirectional length of the pipe and the flow velocity. The results from the PSM, however, gave a clean pipe after the first interval of cleaning (i.e., after the first five minutes where the calculation time was set at five minutes. If another calculation time was set, the PSM predicted zero sediment concentration at the end of that period). In addition, because there were some valves that were closed, another two pipes (Link 39043542 and Link 39043544) were completely cleaned as illustrated in Figure 11.7. Table 11.1 illustrates the summary of the PSM results using a controlled RPM cleaning method.

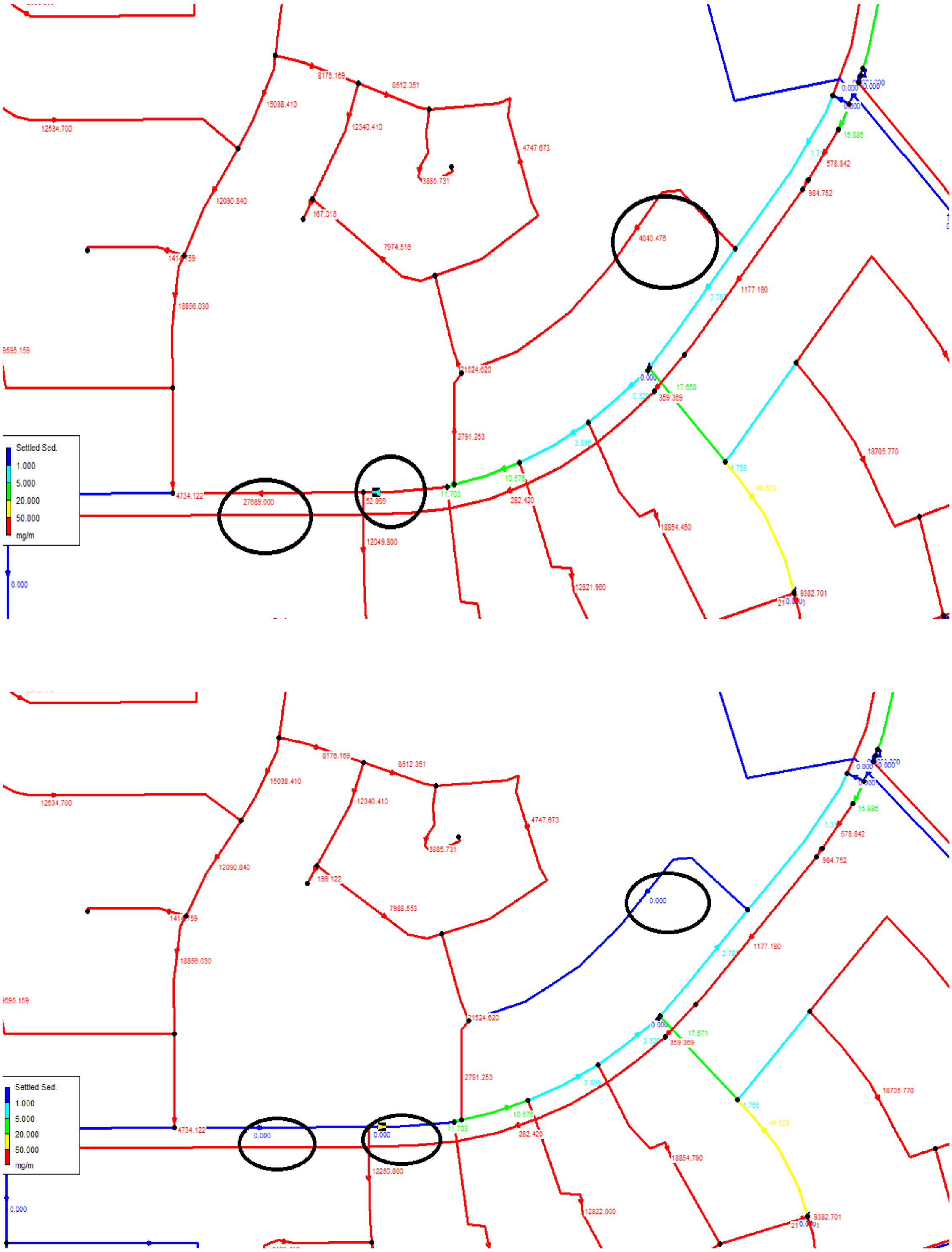


Figure 11.7: Settling sediment before and after cleaning with controlled RPM. The circle shows the affected pipes (settling sediment = 0).

Table 11.1: PSM result cleaning with controlled RPM cleaning.

Cleaning pipes by controlled RPM			
Pipe ID	Length m	Origin Settled sediment mg/m	Settled Sediment after cleaning. mg/m
Pipe 39043544	178.1	28200.18	0
Pipe 39043534	323.5	3914.817	0; built some set. sed. after open valves but it still too much less than the original value as illustrated in Figure 11.2
Pipe 39043542	78.1	52.072	0
sum length	579.7		0

11.5.2 Results of Conventional Flushing

The same pipe network was flushed using the conventional flushing method. The sediment concentrations and pipe history were as per the other cleaning methods. Analysis of the results showed no settled sediments were removed and the settled sediment concentration remained as was originally the case for Link 39043534; the “planned clean” pipe. From this, it was assumed that during conventional flushing (i.e., when the valves were not closed to guide the water through the desired pipe as with the unidirectional case), water simply flows through other joined pipes or comes to the node (fire hydrant) through other connected pipes. Thus the velocity in the target pipe was less than 0.4

m/s. Even if the time of flushing was longer, it is more likely that water would flow through other joined pipes and no settled sediment would be removed in the target pipe. It can also be seen that two other pipes were completely clean (Link 39043538 and Link 39043507), as illustrated in Figure 11.8.

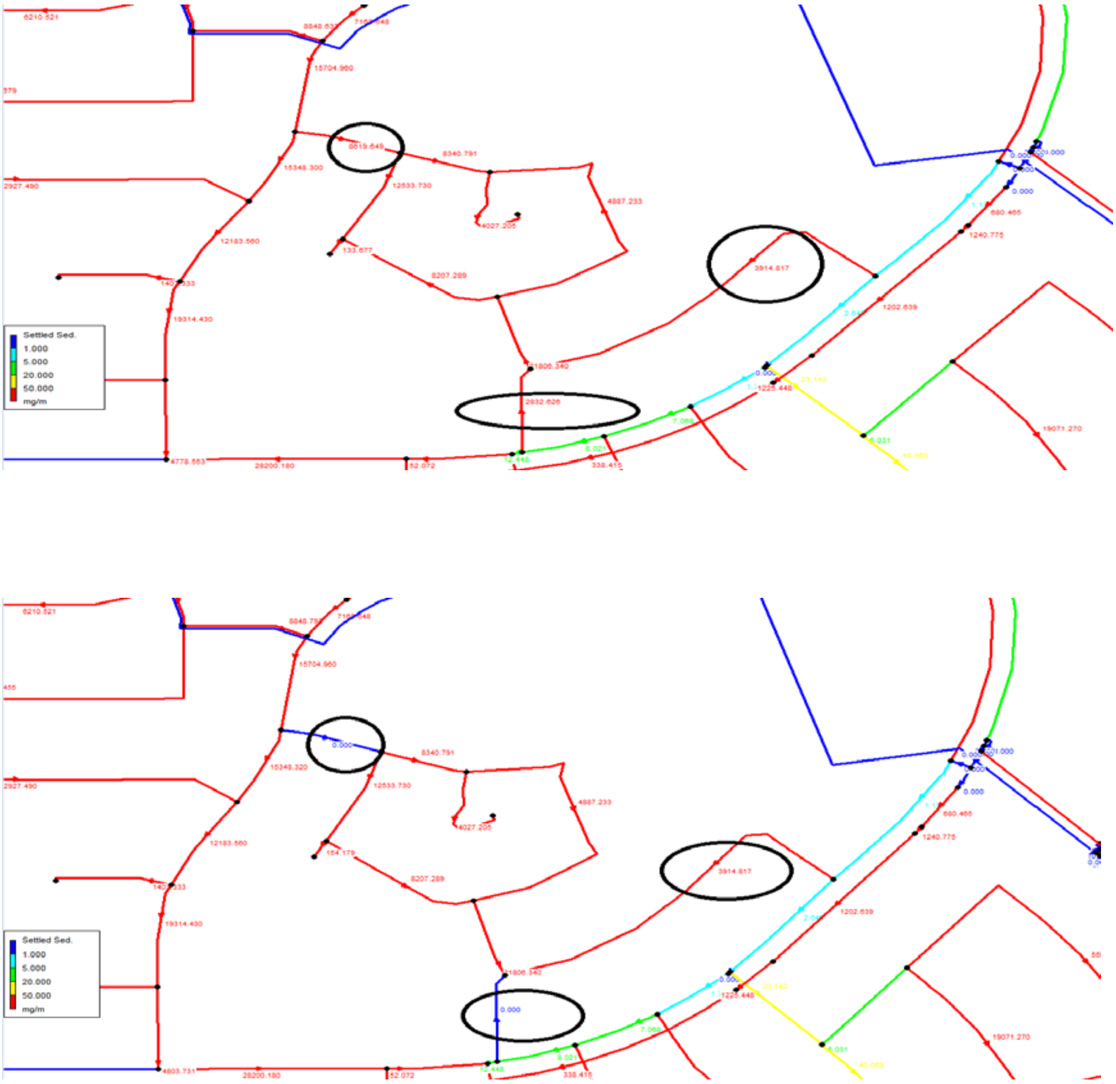


Figure 11.8: Settling sediment before and after cleaning with conventional flushing. The circle shows the affected pipes (settling sediment = 0) and the “planned” pipe to clean.

Although the aim of this flushing was to flush link 39043534, links 39043538 and 39043507 also eventuated in being flushed. When conventional flushing is carried out, it is inevitable that some pipes will be flushed with increased demand. However, it is more important that the required pipes get flushed, as is the case of unidirectional flushing with the least amount of water, instead of conventional flushing which uses almost twice as much water to flush any other joined pipes. Although the demand was increased to 10 L/S and the flushing continued for 15 minutes instead of 10 minutes, (as the required pipe still was not clean after 10 minutes), the settled sediment for link 39043534 remained at 3915 mg/m at 80:10 hours, as with the origin case shown in Figure 11.2, and as illustrated by a circle in Figure 11.8. The settled sediment in links 39043538 and 39043507 were completely removed by the conventional flushing method although these links were not planned to be flushed, as illustrated in Tables 11.2. Table 11.3 summaries the comparison for PSM result between controlled RPM cleaning and conventional flushing.

Table 11.2: PSM result cleaning with conventional flushing cleaning.

clean pipe by conventional flushing			
Pipes ID	Length m	origin Settled sediment mg/m	Settled Sediment after cleaning. mg/m
Pipe 39043538	87.8	2832.626	0
Pipe 39043507	80.5	8620.195	0
sum length	168.3		

Table 11.3: Comparison for PSM result between controlled RPM cleaning and conventional flushing.

Pipe ID	Length m	Origin Settled sediment mg/m	Settled Sediment after cleaning. mg/m	
			controlled RPM	conventional flushing
Pipe 39043544	178.1	28200.18	0	28200.18
Pipe 39043534	323.5	3914.817	0	3914.817
Pipe 39043542	78.1	52.072	0	52.072
Pipe 39043538	87.8	2832.626	2791.253	0
Pipe 39043507	80.5	8620.195	8176.169	0

In the loop network therefore, the unidirectional flushing is the most effective flushing method. The problem with conventional flushing is that the pipe that actually needs the most amount of water to flow through in order to be flushed is not getting enough flow, since the water flows through other connected pipes.

11.6 Conclusion

The results ultimately prove that unidirectional flushing is the most efficient flushing method over the conventional flushing method. It cleaned 579.7 m of pipe with a zero sediment concentration and it was very effective in flushing the required pipe with the least amount of water at 3L/s for a period depending on the unidirectional length of the pipe. Conventional flushing was not as effective as the valves were not closed to guide the water through the desired pipe as with the unidirectional case. Water simply came to the node through other connected pipes to satisfy the set demand in a particular node or to satisfy the flushing value through the fire hydrant point. Only 168.3 m of pipe was cleaned, with a zero sediment concentration. Therefore, even if the flushing time was increased during conventional flushing, it is more likely that the water would flow with a velocity of less than 0.4 m/s. Under these circumstances, no deposits would be removed from the target dirty pipe although the flushing may clean other pipes that were not the target. In addition, the full flush method could disturb the sediment as with burst pipe event and this would cause complaints.

The controlled RPM is a possible replacement for mains full flush cleaning. This means that water losses during mains cleaning could be reduced by about two thirds. The RPM could be adjusted to be undertaken depending on unidirectional pipe length rather than restricted to a uniform 15 minutes duration.

CHAPTER 12 CONCLUSIONS AND RECOMMENDATIONS

12.1 Introduction

The majority of customer complaints received by water utilities in Australia and many parts of the world are due to discoloured water. These usually constitute between 60% to 80% of water quality related customer complaints. The problem is amplified by the fact that these complaints are simply incorporated into key performance and compliance indicators in the water industry. In order to combat the problem, water utilities adopt mostly emergency cleaning procedures by opening a hydrant close to the address of the complaint(s). This is done until the water clears at the tap of the customer(s) who made the complaint(s). When a suburb receives a very high number of complaints, all pipes in the suburb are cleaned by an expensive and labour intensive air-scouring process.

This research started by analysing the pattern and causes of complaints. It then attempted to understand the effectiveness of the current available practices and tools used to manage the discolouration risk. Several significant findings were made which are expected to change the way water utilities manage customer complaints. Such improvements would lead to cost savings in a more targeted proactive cleaning of water mains. Additionally, customer satisfaction would increase and water utilities would be more in compliance with the turbidity standards in Perth Water Guidelines.

12.2 Conclusions

From this work, the following conclusions were reached:

12.2.1 Complaints and Burst pipe Data Analysis

Of all the complaints registered by a water utility, complaints about discoloured are in the majority. For discoloured events to occur, suspended particles should be present and they should be carried to the customer. To understand the causative factors, historical patterns of complaints caused by breaking mains (burst pipes) events were analysed with the hypothesis that hydraulic events could be the major cause of complaints. The conclusions reached are summarised below:

- In general, suburbs which had a higher population registered more complaints and neighbouring suburbs were mutually affected by each other when a burst pipe occurred in one suburb.
- Batch complaints – two or more complaints, received in a single suburb in a single day, accounted for 63.8 % of complaints over the seven-year period of study. Of the total complaints and batch complaints, events such as burst pipe (burst water main) accounted for almost 53% and 66% of complaints, respectively. The remainder of the complaints did not have an associated specific event recorded.
- When the analysis was performed for 2004, a high complaints year, it showed that 63.3% and 81.2% of total and batch complaints respectively were attributable to burst water main events.
- Analysis of isolated complaints assisted in the realisation of the fact that this type of complaint originated from places where the water

usage pattern was heavily affected by changes in land use patterns, i.e., increases in population/housing density.

- When suburb D was analysed, 40 households had a history of regular complaints and interestingly they accounted for 42.2% of all complaints over the period from 2003 to 2005.
- 55% of the above 40 householder complaints came from either units, duplexes, or triplexes. About 41% of these households recorded complaints within one year or less from the date that the property type changed from a single detached house to one of the above types of dwelling.
- Although air-scouring reduced the number of complaints during the following year in the suburbs studied, hydraulic events showed a much stronger relationship to complaints per 1000 person across the whole study period, including the year 2004, which was analysed in detail.

12.2.2 The Resuspension Potential Method

To draw conclusions regarding the impact of the dirtiness of pipes on customer complaints, the resuspension potential method was put into practice at a number of locations and analysed, in combination with customer complaints, burst pipes events and air-scouring. From the RPM testing and the comparison of results with complaints and burst pipes data, the following noteworthy conclusions were made:

- The RPM testing provided a good indication of the dirtiness of a pipe as a ranking score, although the evaluation procedure to produce a ranking score could be improved. Although it is a sound approach, it is labour intensive and large amount of water is wasted.

- Pipes in the same area showed approximately the same results in terms of cleanliness (close ranking scores), although the dead-end and loop pipes provided slightly higher ranking scores than the through pipes.

- The dirtiness of a pipe (or ranking score of a pipe) is greatly affected by hydraulic events. Pipes closer to burst pipe(s) event(s) were found to be cleaner than those that were further away. Similarly, pipes located closer to the locations of recent complaints were found to be cleaner. The higher the number of complaints, the cleaner the pipes were. This was due to emergency cleaning or the protocol adopted by the Water Corporation to flush adjacent pipes at high velocity until the water became cleaner.

- When a clean pipe was tested after 18 months, it was found to be dirty. It is not clear how long it takes a pipe to become dirty or dirty to a level that causes complaints. This requires further investigation.

- Interestingly, the results showed that the suburbs recording a higher number of complaints showed less RPM values, i.e., pipes were found to be clean. In contrast, the suburbs which registered a lower number of complaints and low burst pipes events did not have a chance to flush out the turbid material present in the pipe, thus resulting in higher RPM measurements. The number of complaints in a given area is not directly related to dirtiness; therefore careful consideration must be taken, prior to adopting any cleaning strategies to reduce complaints about discoloured water.

- Since burst pipes events are found to be one of the major causes of discolouration complaints, the current approach by the Water Corporation of Western Australia, of targeting and flushing suburbs with the highest number of complaints is ineffective.

12.2.3 Improvement of the RPM method

The evaluation method of of Vreeburg et al., 2004a considers the time to clear the pipe (time to reach base level turbidity after the disturbance has been stopped by intervention), as one of four important considerations. The lower the base level turbidity, the longer the time it will take to reach base level turbidity after the disturbance is stopped (time to clear). The longer time it takes, the higher the ranking score, indicating that the pipe is dirty. If the base level turbidity is below the turbidity in question then there can be a problem with this approach. For example, even if the turbidity continued to stay at a higher level than the base level turbidity, it might not cause complaints if it is below the Australian Drinking Water Guidelines (ADWG, 2004). Hence, the RPM evaluation method needs improvement.

- Two improvement methods to the RPM analysis have been proposed. An improvement to the procedure of Vreeburg et al., 2004a was made by giving scores for both base level turbidity and average turbidity in the first five minutes after the disturbance had been stopped (TADS).

- Method-2 of improvement results provided an effective indication regarding pipe conditions. This should assist in avoiding unnecessary expenditure on pipes if water utilities opt to clean the pipes.

12.2.4 PSM application

Simulation runs were undertaken to evaluate the prediction by EPAnet-PSM. As an example, burst pipes data from 28/12/2006 was selected, and related complaints were used for matching with the PSM results. In addition, fieldwork (FW) was conducted by manually creating a hydraulic event and monitoring the flow and turbidity as well as complaints for all surrounding areas. Results from the EPAnet-PSM were subsequently compared with the field results to understand the feasibility of using PSM as a tool to predict complaints. From these two applications, interesting conclusions were made:

- The resuspension velocity needs to be lower than a usually used value of 0.6 m/s, as PSM predictions with 0.2 and 0.4 m/s runs were found to be more reasonable than that obtained with 0.6 m/s. In addition, during the fieldwork, higher turbidity was recorded with a velocity equal to 0.18 m/s, not 0.6 m/s or over.
- The PSM could be used to understand the potential risks associated with a hydraulic event but not in predicting exactly where complaints will or will not occur.
- When implementing PSM, several issues were identified. These were:

❖ An option to introduce some sediment in the pipe at the very beginning of a simulation was a requirement (it causes difficulty in understanding the sediment movement during the simulation especially with burst pipes).

- The option to add sediment to a reservoir or a tank as an initial sediment quality also required activation.

- The PSM does not have an option to introduce a partially open valve.

- The relationship between sediment movement and pipe length should be considered in the PSM; the results from the PSM indicated clean pipes after the first simulation interval.

- The PSM takes a very long time to calculate the sediment movement if a small simulation interval is selected, and it takes up considerable computer hardware space to save every result.

12.2.5 Real Resuspension Velocity

The obvious conclusion from previous investigations with field trials and PSM predictions was that the resuspension velocity was less than 0.6 m/s. The value of the resuspension velocity in real systems has been investigated by another fieldwork study which was conducted at five sites in which the velocity (additional velocity to that arising from real time demand) was gradually increased from 0.1 to 0.7 m/s, followed by a full flushing to understand the behaviour of sediments in the pipeline. The conclusions were;

- The maximum turbidity was recorded with a lower velocity (<0.1 m/s). The resuspension velocity was found to be lower than a usually used value of 0.6 m/s.

- A new theory was confirmed about the required mobilisation velocity of accumulated particles within distribution networks, i.e., it is dependent upon the original velocity in the pipe and the history of sediment as well as the type of sediment and pipe. This means that the resuspension velocity can vary depending on the velocity a pipe regularly experiences, or the velocity it experienced prior to the burst pipe event. In other words a velocity higher than the historically exposed velocity is needed to induce sediment movement.

12.2.6 New Cleaning Strategy

The way that the Water Corporation deals with complaints is to fully flush the pipe by opening a hydrant without closing any valves. This is referred to as the "conventional flushing method" which disturbs the sediment in a similar way to burst pipe event and it can potentially cause more complaints. Therefore, a new approach is proposed for cleaning the pipes which can potentially save water, clean the target pipes, save money, and reduce complaints.

- Higher turbidity noted during a low velocity disturbance is larger than that during full flushing. Hence, a possible approach to cleaning is proposed as a replacement to full flushing. It modifies the RPM method by either extending/shortening the time or increasing the flow to achieve the required velocity. This would mean that water losses during mains cleaning could be reduced by about two thirds, saving water. The RPM method could be adjusted to be undertaken until the water is clear or depending on unidirectional length rather than restricted to the 15 minutes duration.

- The results ultimately prove that unidirectional flushing is the most efficient flushing method, rather than the conventional flushing method.

12.3 Recommendations

- Complaints data should be appropriately analysed before deciding on the area for cleaning and it should be understood that the more complaints that are made, the cleaner the pipe becomes and it is the hydraulic event that causes the complaints.

- The Resuspension Potential Method is an efficient tool when determining the requirement of a mains cleaning. Therefore, regular measurements covering all network systems should be undertaken to assess which area needs cleaning. However the problem of evaluation of the data arising from the field data to create a ranking in the RPM needs modification, and the Method-2 proposed in the thesis could help water utilities to correct that issue. Method-2 incorporates the initial turbidity and the average turbidity in the first five minutes after the disturbance has been stopped (TADS) when calculating the ranking point.

- By performing RPM measurements, it is easily observed if an easily resuspendable sediment layer is present in water mains. If so, the main needs to be cleaned. If not, no cleaning needs to be carried out and within several months a new RPM measurement should to be taken.

- Flushing with RPM velocity should be carried out in a sequential manner from the treatment plant, i.e., one should work from the water treatment plant or other source towards the periphery of the distribution system. While doing so, valve isolation is a part of the RPM which should be carried out to ensure unidirectional water flow. Without valve isolation, the water to the hydrant may flow from several mains in the vicinity of the open hydrant. As a result, the velocity in each individual main may remain lower than if valve isolation is used. Furthermore, if valves are not isolated and unidirectional flushing is not performed sequentially, the water used to flush a particular main may not originate from the target segment. When this occurs, the water flowing to the hydrant may actually bring dirty water into the area being flushed and devalue the whole process.

- Although air-scouring may have reduced the number of complaints slightly in the following year, it was not found to be effective in the long-term. Our study did not incorporate the period of effectiveness, although in two years of cleaning the complaints in the air-scoured suburbs did not greatly differ from those in the other suburbs. Due to its short-term impact, it is questionable whether air-scouring should be adopted as a method to reduce the number of complaints especially as the cost of air-scouring a pipe is around $1000 per km.

- As burst pipes events cause dirty water incidents it is important to understand which pipes are more critical to the causing of more dirty water incidents. This is only possible if reliable software is present and it can reasonably predict the water flow in many pipes. The availability of software would reduce the running costs of the system in emergency cleaning. It would also reduce: other cleaning such as air-scouring, deciding which pipes to clean, deciding which pipes to replace, deciding the pipe to pressure manage, etc. Therefore it is important that a reliable software program is in place.

- Many problems in the PSM program require rectifying in order to reliably use it to predict sediment movement and deposition hence to use it reliably. The following points must be considered:

- An option to introduce some sediment in the pipe at the very beginning of a simulation was not present and this causes difficulty in simulation and in understanding which pipes are critical in the cleaning process.
- In the PSM a fixed resuspension velocity is entered. However, the resuspension velocity of sediment is found to be linked to the previous hydraulic history of the pipe rather than a fixed value. The program needs to be modified to cater for this phenomenon.
- The option to add sediment to a reservoir or a tank as an initial sediment quality needed to be activated
- The relationship between sediment movement and pipe length should be considered in the PSM. The results from the PSM indicated a clean pipe after the first simulation interval (a simulation interval is a user defined time and it can vary from a few seconds to many hours) i.e., after the first five minutes the pipe became clean whatever the length of the pipe if 5 minutes is entered as the simulation interval. However, in practice it depends on the unidirectional length of the pipe and the velocity of water travelling in the pipe.

- The PSM takes a great deal of time to calculate sediment movement if a small simulation interval is selected and it takes considerable space to save every result, hence it becomes difficult to manage. However, recently, USEPA has introduced a multiple species model (MSX) to model many water quality parameters. One of them is sediment. The combination of MSX and EPANET is able to perform the calculation very efficiently hence provides much faster and more reliable results.

The incorporation of the sediment factor into the EPAnet-MSX software is simple and this should be considered by the water utility to avoid computer crashes and obtain reliable results.

- Previous studies have confirmed that there is a significant positive correlation between the turbidity and both the iron and manganese concentrations of the samples. The significance of these elements and how they might link with dirty water events is not fully understood at this stage.

- The investigation carried out earlier by Grainger et al., 2003 suggested that particulates in sample bottles exhibited a gel-like behaviour. How this is linked to actual dirty water complaints is not known and therefore this requires further investigation.

- The majority of the dead-end type pipes in the whole of the pipe network did not have a fire hydrant located at the far end (checked using the Litespatial program). It is recommended that a fire hydrant be installed at the far end of this type of pipe network, thus an effective flushing can be carried out.

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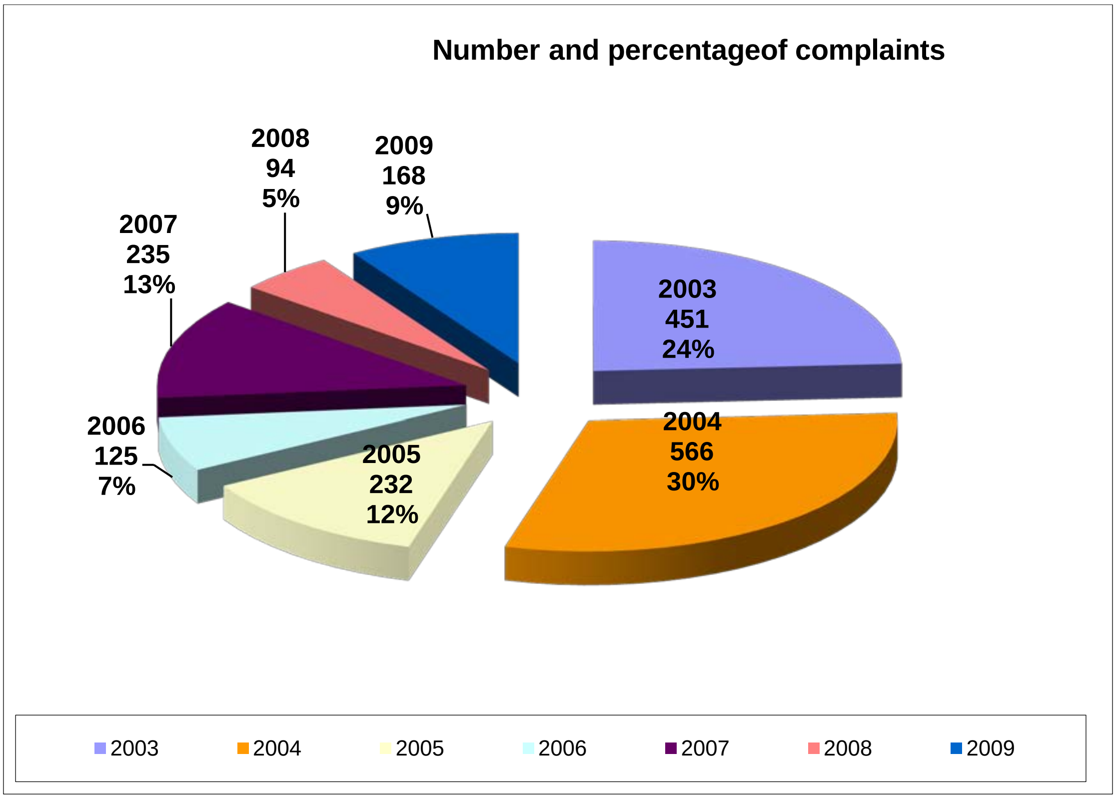

Figure A.1: Number and percentage of complaints over seven years.

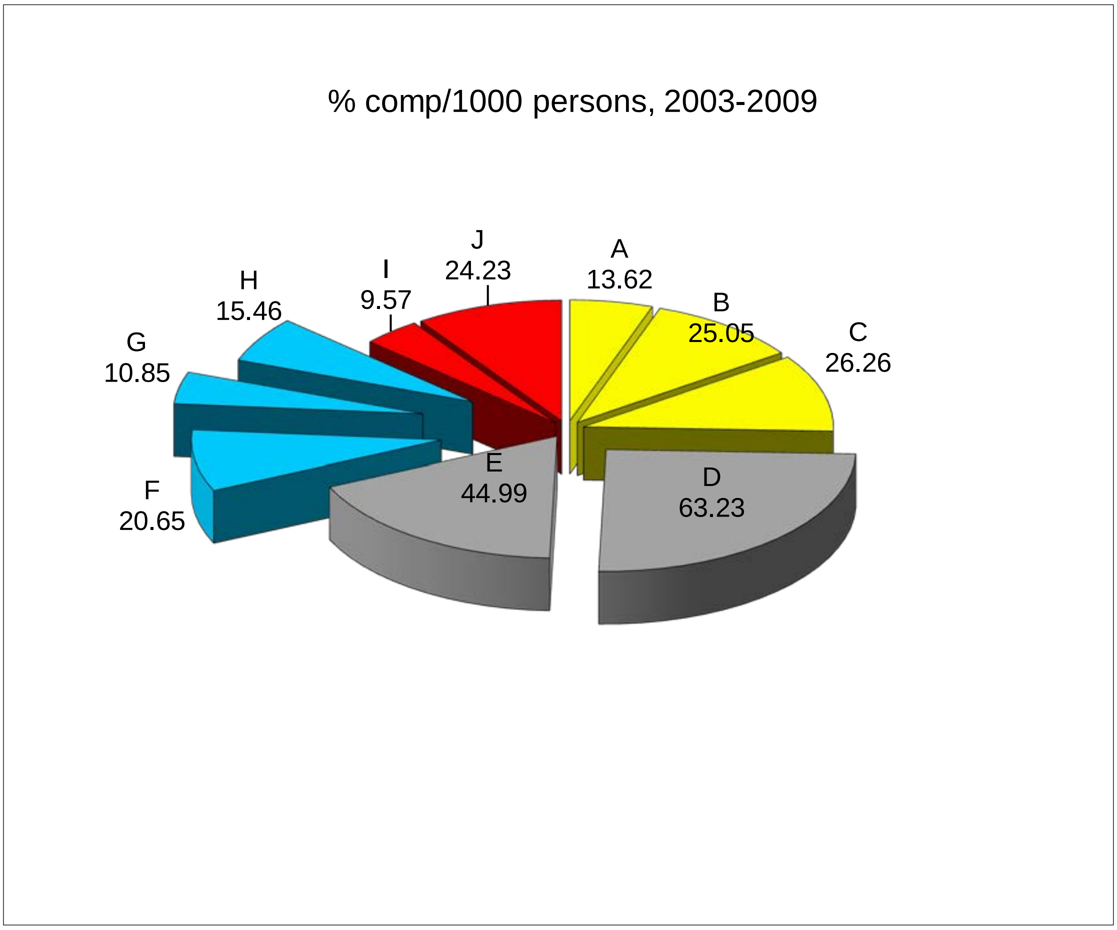

Figure A.2: Percentage of complaints/1000 persons over seven years for all suburbs.

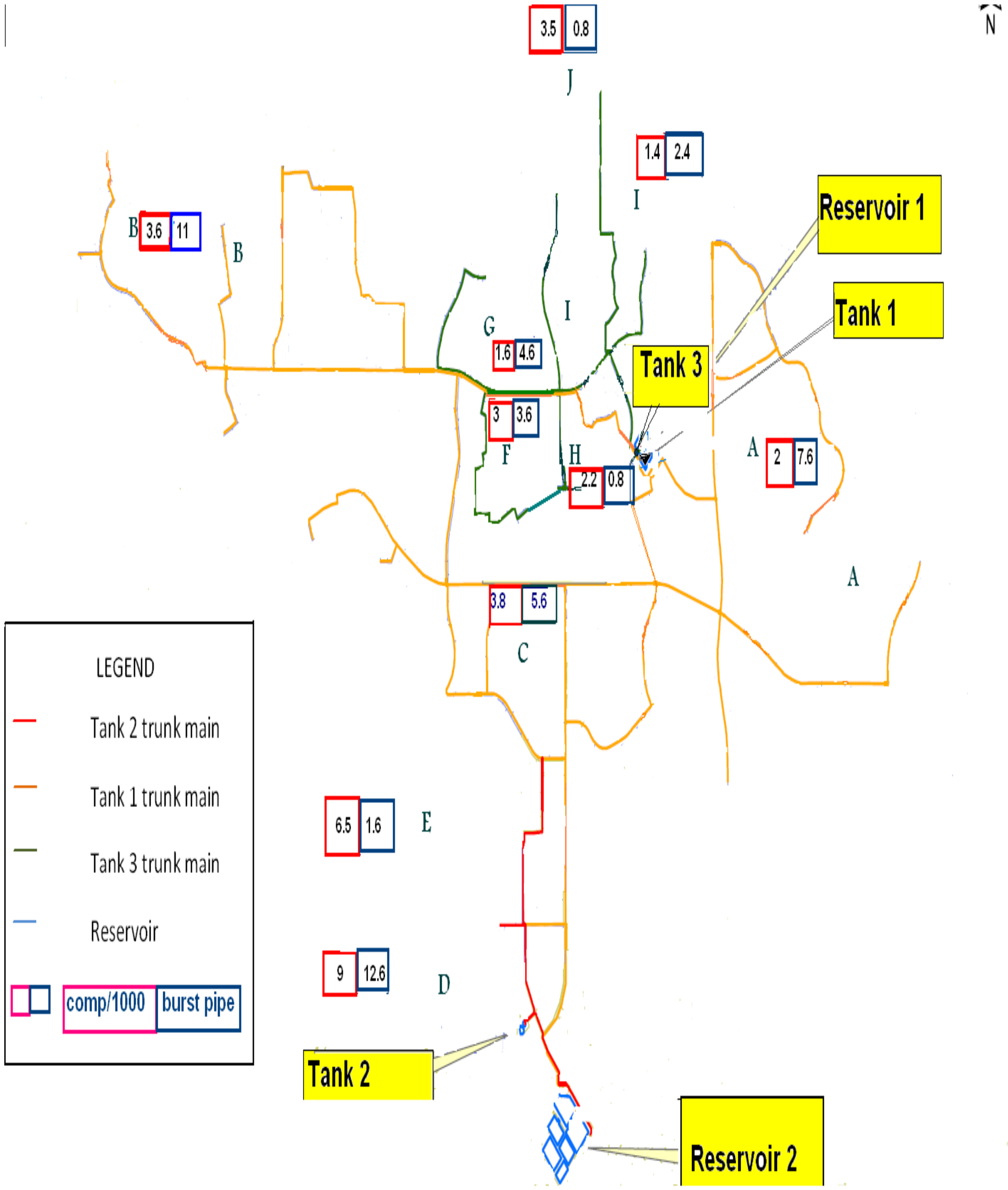

Figure A.3: Schematic diagram of tanks and main trunk of the studied water supply sub-system "M" with number of complaints/1000 persons and number of burst pipes for all 10 suburbs.

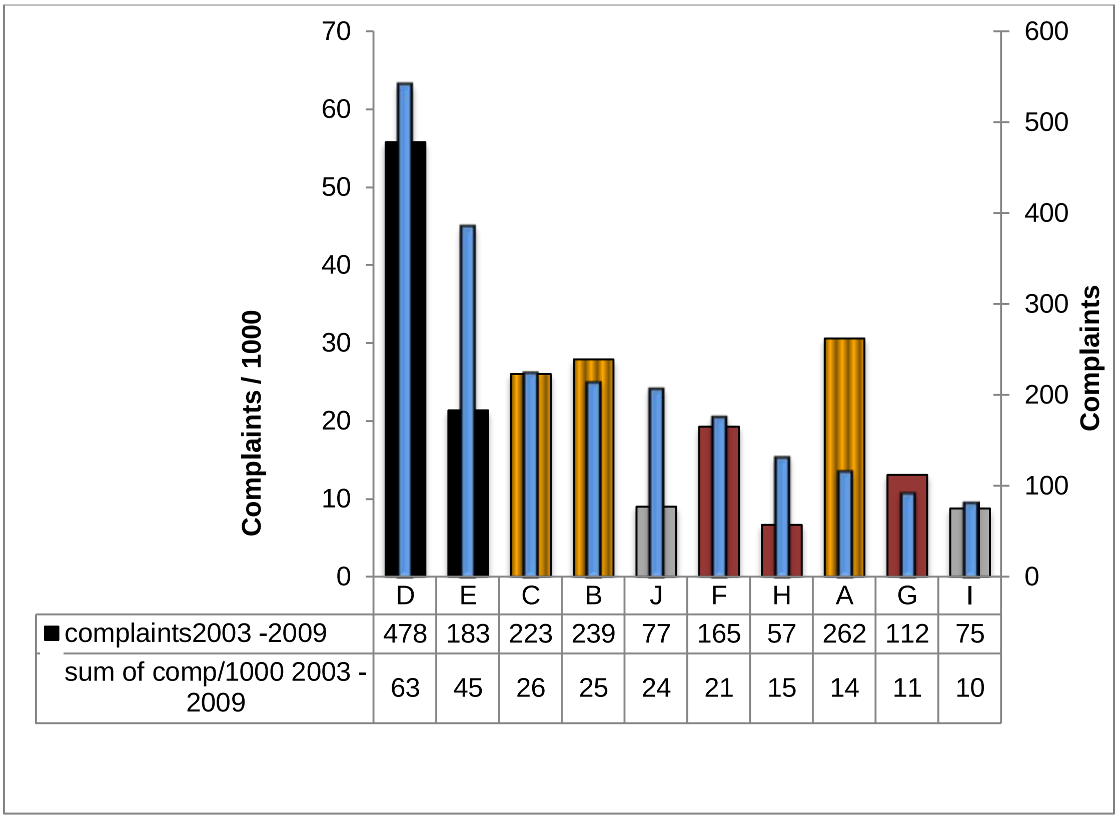

Figure A.4: Customer complaints and complaints/1000 persons for each suburb for seven years from 2003 to 2009.

Table A.1: Raw data of complaints over nine years (2001-2009); from 01 January 2001 to 31 December 2009.

Contact Received Date	Suburb
7/01/2001	A
24/01/2001	I
4/02/2001	A
4/02/2001	E
13/02/2001	A
13/02/2001	A
13/02/2001	A
13/02/2001	D
21/02/2001	E
26/02/2001	D
11/03/2001	F

11/03/2001	F
11/03/2001	F
11/03/2001	F
11/03/2001	F
11/03/2001	F
11/03/2001	F
11/03/2001	F
11/03/2001	D
31/03/2001	C
2/04/2001	C
8/04/2001	F
17/04/2001	E
18/04/2001	C
18/04/2001	C
18/04/2001	C
21/04/2001	F
27/04/2001	F
27/04/2001	F
28/04/2001	A
14/05/2001	G
17/05/2001	F
17/05/2001	F
17/05/2001	F
11/06/2001	D
15/06/2001	D
18/06/2001	B
24/06/2001	H
24/06/2001	H
24/06/2001	H
24/06/2001	H
24/06/2001	H
24/06/2001	H
24/06/2001	H
27/06/2001	A
6/07/2001	I
19/07/2001	B
21/07/2001	G
24/07/2001	C
24/07/2001	C
24/07/2001	C
24/07/2001	H
24/07/2001	H
3/08/2001	C

8/08/2001	C
9/08/2001	D
9/08/2001	D
9/08/2001	D
9/08/2001	D
9/08/2001	E
10/08/2001	I
10/08/2001	C
10/08/2001	C
10/08/2001	C
10/08/2001	C
10/08/2001	C
10/08/2001	C
10/08/2001	C
10/08/2001	C
10/08/2001	F
10/08/2001	F
10/08/2001	F
10/08/2001	F
10/08/2001	F
10/08/2001	F
10/08/2001	F
10/08/2001	F
10/08/2001	F
10/08/2001	F
10/08/2001	G
10/08/2001	G
12/08/2001	C
13/08/2001	C
14/08/2001	B
14/08/2001	B
14/08/2001	B
16/08/2001	E
18/08/2001	A
19/08/2001	C
19/08/2001	C
20/08/2001	I
21/08/2001	D
21/08/2001	D
22/08/2001	C
30/08/2001	D
1/09/2001	D
10/09/2001	D

10/09/2001	D
11/09/2001	C
11/09/2001	C
11/09/2001	C
11/09/2001	C
11/09/2001	C
11/09/2001	C
16/09/2001	D
17/09/2001	E
17/09/2001	E
17/09/2001	E
18/09/2001	A
19/09/2001	A
25/09/2001	B
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	C
26/09/2001	F
26/09/2001	F
26/09/2001	F

26/09/2001	F
26/09/2001	F
26/09/2001	F
26/09/2001	F
26/09/2001	F
26/09/2001	F
26/09/2001	B
26/09/2001	B
26/09/2001	B
26/09/2001	B
26/09/2001	B
26/09/2001	B
26/09/2001	B
26/09/2001	B
26/09/2001	B
26/09/2001	B
26/09/2001	B
26/09/2001	B
26/09/2001	B
26/09/2001	B
26/09/2001	B
26/09/2001	B
26/09/2001	B
26/09/2001	B
26/09/2001	B
26/09/2001	B
26/09/2001	B
26/09/2001	B
26/09/2001	B
26/09/2001	G
26/09/2001	G
26/09/2001	G
26/09/2001	G
26/09/2001	E
26/09/2001	E
27/09/2001	B
27/09/2001	B
27/09/2001	B
27/09/2001	B
27/09/2001	G
27/09/2001	G
28/09/2001	F
30/09/2001	A

30/09/2001	A
30/09/2001	A
30/09/2001	A
30/09/2001	A
30/09/2001	A
30/09/2001	A
30/09/2001	A
30/09/2001	A
30/09/2001	A
1/10/2001	C
1/10/2001	A
2/10/2001	I
2/10/2001	C
2/10/2001	C
7/10/2001	A
7/10/2001	A
7/10/2001	A
7/10/2001	A
7/10/2001	A
7/10/2001	B
10/10/2001	A
10/10/2001	G
11/10/2001	D
11/10/2001	D
11/10/2001	D
13/10/2001	F
16/10/2001	A
18/10/2001	D
18/10/2001	D
18/10/2001	E
18/10/2001	E
18/10/2001	E
19/10/2001	E
22/10/2001	D
24/10/2001	C
24/10/2001	C
24/10/2001	C
24/10/2001	C
24/10/2001	C
25/10/2001	C
25/10/2001	C
26/10/2001	C
28/10/2001	A

28/10/2001	B
30/10/2001	C
2/11/2001	G
3/11/2001	D
5/11/2001	C
7/11/2001	A
7/11/2001	A
8/11/2001	D
8/11/2001	D
8/11/2001	D
8/11/2001	E
8/11/2001	E
8/11/2001	E
9/11/2001	I
11/11/2001	C
11/11/2001	B
12/11/2001	C
12/11/2001	A
13/11/2001	C
7/12/2001	I
7/12/2001	I
7/12/2001	I
12/12/2001	E
14/12/2001	D
18/12/2001	B
18/12/2001	B
22/12/2001	C
28/12/2001	H
3/01/2002	B
11/01/2002	H
12/01/2002	E
14/01/2002	A
14/01/2002	A
14/01/2002	B
16/01/2002	B
16/01/2002	B
16/01/2002	B
24/01/2002	I
24/01/2002	I
25/01/2002	A
25/01/2002	D
30/01/2002	F
1/02/2002	B

3/02/2002	B
3/02/2002	B
5/02/2002	F
8/02/2002	C
15/02/2002	B
19/02/2002	C
19/02/2002	B
22/02/2002	E
22/02/2002	E
22/02/2002	E
22/02/2002	E
24/02/2002	B
25/02/2002	F
26/02/2002	C
28/02/2002	G
28/02/2002	D
7/03/2002	G
8/03/2002	E
10/03/2002	F
12/03/2002	A
13/03/2002	B
15/03/2002	D
18/03/2002	B
19/03/2002	B
19/03/2002	B
19/03/2002	B
20/03/2002	I
21/03/2002	F
21/03/2002	B
22/03/2002	H
22/03/2002	D
23/03/2002	G
27/03/2002	C
6/04/2002	B
14/04/2002	B
15/04/2002	C
26/04/2002	E
29/04/2002	B
1/05/2002	A
6/05/2002	B
7/05/2002	G
7/05/2002	G
7/05/2002	G

7/05/2002	G
7/05/2002	G
7/05/2002	G
10/05/2002	G
10/05/2002	E
14/05/2002	B
14/05/2002	B
14/05/2002	B
14/05/2002	B
14/05/2002	B
14/05/2002	G
15/05/2002	B
21/05/2002	H
27/05/2002	D
2/06/2002	I
2/06/2002	C
2/06/2002	D
3/06/2002	C
5/06/2002	E
7/06/2002	B
8/06/2002	D
8/06/2002	D
8/06/2002	D
8/06/2002	E
8/06/2002	E
8/06/2002	E
9/06/2002	D
10/06/2002	F
10/06/2002	E
12/06/2002	B
12/06/2002	B
12/06/2002	D
20/06/2002	C
20/06/2002	C
20/06/2002	C
27/06/2002	C
27/06/2002	C
27/06/2002	C
1/07/2002	J
2/07/2002	B
3/07/2002	G
4/07/2002	G
16/07/2002	B

16/07/2002	H
17/07/2002	D
18/07/2002	D
19/07/2002	B
19/07/2002	B
19/07/2002	B
19/07/2002	B
19/07/2002	B
19/07/2002	B
19/07/2002	B
19/07/2002	B
19/07/2002	B
19/07/2002	B
19/07/2002	B
19/07/2002	B
19/07/2002	G
19/07/2002	G
19/07/2002	G
19/07/2002	G
19/07/2002	G
19/07/2002	G
19/07/2002	G
19/07/2002	G
19/07/2002	D
19/07/2002	D
19/07/2002	D
19/07/2002	D
19/07/2002	D
19/07/2002	D
19/07/2002	D
19/07/2002	E
19/07/2002	E
19/07/2002	E
20/07/2002	I
20/07/2002	A
20/07/2002	A
20/07/2002	A
20/07/2002	A
20/07/2002	A
20/07/2002	A
20/07/2002	A
20/07/2002	A
20/07/2002	F

20/07/2002	D
20/07/2002	D
20/07/2002	D
20/07/2002	D
20/07/2002	E
22/07/2002	A
22/07/2002	A
22/07/2002	A
22/07/2002	A
23/07/2002	A
23/07/2002	G
25/07/2002	D
26/07/2002	C
27/07/2002	C
27/07/2002	A
29/07/2002	F
4/08/2002	A
6/08/2002	I
6/08/2002	I
6/08/2002	I
6/08/2002	I
6/08/2002	I
6/08/2002	I
6/08/2002	I
6/08/2002	I
6/08/2002	I
6/08/2002	I
7/08/2002	A
7/08/2002	A
7/08/2002	A
7/08/2002	A
7/08/2002	A
7/08/2002	A
7/08/2002	A
7/08/2002	A
7/08/2002	A
7/08/2002	A
7/08/2002	A
7/08/2002	A
7/08/2002	A
7/08/2002	A
7/08/2002	A
7/08/2002	G

7/08/2002	G
7/08/2002	G
20/08/2002	D
20/08/2002	E
20/08/2002	E
22/08/2002	D
24/08/2002	I
25/08/2002	D
26/08/2002	A
26/08/2002	D
27/08/2002	D
27/08/2002	D
27/08/2002	D
27/08/2002	D
27/08/2002	D
27/08/2002	D
27/08/2002	D
27/08/2002	D
27/08/2002	D
27/08/2002	D
27/08/2002	D
27/08/2002	D
27/08/2002	E
27/08/2002	E
28/08/2002	D
29/08/2002	I
30/08/2002	G
1/09/2002	B
1/09/2002	B
5/09/2002	C
6/09/2002	B
6/09/2002	B
7/09/2002	B
7/09/2002	B
7/09/2002	B
7/09/2002	B
7/09/2002	B
16/09/2002	F
16/09/2002	F
16/09/2002	F
16/09/2002	F
22/09/2002	A
22/09/2002	A

22/09/2002	A
25/09/2002	C
25/09/2002	C
25/09/2002	A
26/09/2002	B
26/09/2002	B
27/09/2002	B
1/10/2002	B
1/10/2002	B
1/10/2002	B
2/10/2002	C
2/10/2002	C
2/10/2002	C
2/10/2002	G
2/10/2002	G
3/10/2002	G
10/10/2002	D
11/10/2002	A
11/10/2002	A
12/10/2002	B
14/10/2002	B
16/10/2002	H
16/10/2002	D
16/10/2002	D
16/10/2002	D
16/10/2002	D
20/10/2002	A
22/10/2002	B
24/10/2002	B
24/10/2002	B
25/10/2002	C
25/10/2002	B
25/10/2002	D
25/10/2002	D
26/10/2002	B
26/10/2002	B
26/10/2002	B
26/10/2002	B
29/10/2002	I
29/10/2002	I
3/11/2002	E
3/11/2002	E
4/11/2002	C

4/11/2002	F
7/11/2002	C
7/11/2002	D
8/11/2002	F
8/11/2002	F
9/11/2002	B
9/11/2002	B
9/11/2002	D
10/11/2002	B
11/11/2002	D
14/11/2002	B
15/11/2002	C
15/11/2002	B
27/11/2002	C
28/11/2002	D
28/11/2002	D
28/11/2002	D
28/11/2002	D
28/11/2002	D
28/11/2002	D
28/11/2002	D
28/11/2002	D
28/11/2002	D
28/11/2002	D
28/11/2002	D
28/11/2002	D
28/11/2002	D
28/11/2002	D
28/11/2002	D
28/11/2002	D
28/11/2002	D
28/11/2002	E
28/11/2002	E
29/11/2002	D
29/11/2002	E
3/12/2002	E
6/12/2002	I
6/12/2002	I
6/12/2002	I
6/12/2002	I
6/12/2002	I
6/12/2002	I
6/12/2002	I

6/12/2002	A
8/12/2002	G
9/12/2002	F
10/12/2002	B
10/12/2002	B
10/12/2002	G
10/12/2002	G
11/12/2002	G
12/12/2002	D
12/12/2002	D
12/12/2002	D
12/12/2002	D
12/12/2002	D
14/12/2002	A
14/12/2002	A
17/12/2002	D
18/12/2002	C
18/12/2002	C
18/12/2002	C
18/12/2002	C
19/12/2002	G
23/12/2002	I
23/12/2002	C
24/12/2002	C
24/12/2002	C
27/12/2002	C
27/12/2002	C
27/12/2002	D
27/12/2002	D
27/12/2002	D
2/01/2003	C
2/01/2003	A
2/01/2003	A
2/01/2003	A
3/01/2003	F
13/01/2003	A
17/01/2003	A
17/01/2003	A
17/01/2003	A
18/01/2003	D
20/01/2003	C
23/01/2003	G
25/01/2003	C

25/01/2003	C
28/01/2003	E
3/02/2003	D
3/02/2003	D
10/02/2003	C
16/02/2003	A
16/02/2003	A
16/02/2003	A
18/02/2003	C
27/02/2003	E
27/02/2003	E
1/03/2003	D
1/03/2003	D
1/03/2003	D
1/03/2003	D
1/03/2003	D
1/03/2003	D
1/03/2003	D
1/03/2003	D
1/03/2003	D
1/03/2003	D
1/03/2003	D
1/03/2003	D
1/03/2003	D
1/03/2003	D
1/03/2003	D
1/03/2003	D
1/03/2003	D
1/03/2003	D
1/03/2003	D
1/03/2003	D
1/03/2003	D
1/03/2003	D
1/03/2003	E
1/03/2003	E
1/03/2003	E
1/03/2003	E
1/03/2003	E
1/03/2003	E
1/03/2003	E
1/03/2003	E
1/03/2003	E

2/03/2003	E
4/03/2003	D
10/03/2003	E
10/03/2003	E
11/03/2003	F
12/03/2003	B
14/03/2003	C
14/03/2003	F
15/03/2003	H
19/03/2003	B
19/03/2003	G
1/04/2003	D
1/04/2003	D
18/04/2003	D
18/04/2003	D
18/04/2003	D
18/04/2003	D
6/05/2003	C
6/05/2003	D
6/05/2003	D
6/05/2003	D
6/05/2003	D
6/05/2003	D
6/05/2003	D
6/05/2003	D
6/05/2003	D
7/05/2003	C
7/05/2003	D
10/05/2003	D
11/05/2003	D
11/05/2003	D
13/05/2003	C
13/05/2003	C
13/05/2003	C
13/05/2003	C
13/05/2003	C
13/05/2003	C
13/05/2003	C
13/05/2003	C
13/05/2003	D
14/05/2003	C
14/05/2003	A
23/05/2003	D

26/05/2003	D
29/05/2003	C
30/05/2003	D
5/06/2003	F
5/06/2003	F
5/06/2003	F
9/06/2003	A
9/06/2003	A
9/06/2003	B
9/06/2003	B
9/06/2003	B
9/06/2003	B
9/06/2003	B
9/06/2003	B
9/06/2003	B
10/06/2003	B
10/06/2003	B
10/06/2003	B
10/06/2003	B
18/06/2003	F
18/06/2003	F
18/06/2003	F
18/06/2003	F
18/06/2003	F
18/06/2003	B
18/06/2003	B
18/06/2003	B
18/06/2003	B
18/06/2003	B
18/06/2003	G
18/06/2003	G
18/06/2003	G
18/06/2003	G
18/06/2003	G
18/06/2003	G
18/06/2003	G
18/06/2003	G
18/06/2003	G
19/06/2003	F
19/06/2003	F
19/06/2003	F
19/06/2003	F
19/06/2003	G

19/06/2003	G
20/06/2003	C
20/06/2003	B
23/06/2003	A
23/06/2003	D
23/06/2003	D
23/06/2003	D
24/06/2003	D
25/06/2003	G
25/06/2003	E
26/06/2003	B
3/07/2003	C
9/07/2003	B
9/07/2003	B
9/07/2003	B
9/07/2003	B
9/07/2003	B
9/07/2003	B
9/07/2003	B
9/07/2003	B
10/07/2003	G
12/07/2003	D
15/07/2003	F
20/07/2003	D
27/07/2003	D
1/08/2003	D
1/08/2003	D
3/08/2003	E
13/08/2003	E
13/08/2003	E
17/08/2003	D
18/08/2003	B
18/08/2003	D
19/08/2003	I
19/08/2003	I
19/08/2003	I
19/08/2003	I
19/08/2003	C
19/08/2003	C
19/08/2003	C
19/08/2003	C
19/08/2003	A
19/08/2003	A

19/08/2003	F
19/08/2003	F
19/08/2003	F
19/08/2003	F
19/08/2003	F
19/08/2003	B
19/08/2003	B
19/08/2003	B
19/08/2003	B
19/08/2003	B
19/08/2003	B
19/08/2003	B
19/08/2003	B
19/08/2003	B
19/08/2003	B
19/08/2003	B
19/08/2003	B
19/08/2003	B
19/08/2003	H
19/08/2003	G
19/08/2003	G
20/08/2003	I
20/08/2003	I
20/08/2003	A
20/08/2003	A
20/08/2003	A
20/08/2003	A
20/08/2003	A
20/08/2003	A
20/08/2003	A
20/08/2003	A
20/08/2003	A
20/08/2003	B
20/08/2003	G
20/08/2003	G
20/08/2003	D
21/08/2003	A
21/08/2003	A
23/08/2003	D
25/08/2003	C
25/08/2003	C
25/08/2003	C
26/08/2003	C

27/08/2003	C
27/08/2003	D
27/08/2003	D
1/09/2003	D
2/09/2003	D
2/09/2003	D
2/09/2003	D
2/09/2003	D
2/09/2003	D
2/09/2003	D
2/09/2003	D
2/09/2003	D
2/09/2003	D
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30/07/2005	G
30/07/2005	G
31/07/2005	A
31/07/2005	A
31/07/2005	A
31/07/2005	A
31/07/2005	A
31/07/2005	A
31/07/2005	A
31/07/2005	G
1/08/2005	I
1/08/2005	A
1/08/2005	A
2/08/2005	A
5/08/2005	D
13/08/2005	B
13/08/2005	B
13/08/2005	B
13/08/2005	B
13/08/2005	B
18/08/2005	F
18/08/2005	F
18/08/2005	F
20/08/2005	E
21/08/2005	B
22/08/2005	F
30/08/2005	C

31/08/2005	J
31/08/2005	J
1/09/2005	C
1/09/2005	H
4/09/2005	J
6/09/2005	A
7/09/2005	H
8/09/2005	D
8/09/2005	D
9/09/2005	E
9/09/2005	E
10/09/2005	E
18/09/2005	E
19/09/2005	A
19/09/2005	F
19/09/2005	F
21/09/2005	F
22/09/2005	D
22/09/2005	D
22/09/2005	D
22/09/2005	D
22/09/2005	D
22/09/2005	D
22/09/2005	D
22/09/2005	D
23/09/2005	I
24/09/2005	D
24/09/2005	D
26/09/2005	D
28/09/2005	C
4/10/2005	C
8/10/2005	C
8/10/2005	H
8/10/2005	H
10/10/2005	C
10/10/2005	D
10/10/2005	D
14/10/2005	B
15/10/2005	A
15/10/2005	A
16/10/2005	E
19/10/2005	E
20/10/2005	D

23/10/2005	D
23/10/2005	E
4/11/2005	D
7/11/2005	F
7/11/2005	F
14/11/2005	A
14/11/2005	A
15/11/2005	A
15/11/2005	A
16/11/2005	D
20/11/2005	D
21/11/2005	C
21/11/2005	F
23/11/2005	C
23/11/2005	C
24/11/2005	E
30/11/2005	E
6/12/2005	A
6/12/2005	A
6/12/2005	A
7/12/2005	D
7/12/2005	D
7/12/2005	D
7/12/2005	D
7/12/2005	D
7/12/2005	D
8/12/2005	D
15/12/2005	C
17/12/2005	E
19/12/2005	D
20/12/2005	B
21/12/2005	B
10/01/2006	H
20/01/2006	D
20/01/2006	D
21/01/2006	D
23/01/2006	D
26/01/2006	D
1/02/2006	F
8/02/2006	B
20/02/2006	B
1/03/2006	B
10/03/2006	C

14/03/2006	D
21/03/2006	C
21/03/2006	D
28/03/2006	C
18/04/2006	F
19/04/2006	D
19/04/2006	E
21/04/2006	D
21/04/2006	E
24/04/2006	F
28/04/2006	B
28/04/2006	B
28/04/2006	B
4/05/2006	B
5/05/2006	E
23/05/2006	D
23/05/2006	D
25/05/2006	D
25/05/2006	D
29/05/2006	I
30/05/2006	B
5/06/2006	B
6/06/2006	A
21/06/2006	C
28/06/2006	C
29/06/2006	C
1/07/2006	C
4/07/2006	C
6/07/2006	B
10/07/2006	D
10/07/2006	D
21/07/2006	A
21/07/2006	A
21/07/2006	A
21/07/2006	A
21/07/2006	A
21/07/2006	A
21/07/2006	A
21/07/2006	A
21/07/2006	A
22/07/2006	A
22/07/2006	D
26/07/2006	C

26/07/2006	A
26/07/2006	A
26/07/2006	A
30/07/2006	D
30/07/2006	E
1/08/2006	C
9/08/2006	A
18/08/2006	C
28/08/2006	C
29/08/2006	C
29/08/2006	B
4/09/2006	C
4/09/2006	E
8/09/2006	B
8/09/2006	B
8/09/2006	B
9/09/2006	I
9/09/2006	I
9/09/2006	I
9/09/2006	I
9/09/2006	I
9/09/2006	C
9/09/2006	A
9/09/2006	B
10/09/2006	F
16/09/2006	F
16/09/2006	F
17/09/2006	C
17/09/2006	F
17/09/2006	F
26/09/2006	A
27/09/2006	B
2/10/2006	A
3/10/2006	D
11/10/2006	C
12/10/2006	C
12/10/2006	C
24/10/2006	G
24/10/2006	G
7/11/2006	J
9/11/2006	F
11/11/2006	E
13/11/2006	C

13/11/2006	C
13/11/2006	C
13/11/2006	C
13/11/2006	C
14/11/2006	C
14/11/2006	B
22/11/2006	I
22/11/2006	I
24/11/2006	D
4/12/2006	C
15/12/2006	D
16/12/2006	C
16/12/2006	C
23/12/2006	D
28/12/2006	A
28/12/2006	A
28/12/2006	A
28/12/2006	A
28/12/2006	A
28/12/2006	A
28/12/2006	A
28/12/2006	F
28/12/2006	F
28/12/2006	F
28/12/2006	F
28/12/2006	F
28/12/2006	F
28/12/2006	F
3/01/2007	F
6/01/2007	E
6/01/2007	E
11/01/2007	C
11/01/2007	G
17/01/2007	E
22/01/2007	C
24/01/2007	C
24/01/2007	C
26/01/2007	C
27/01/2007	C
27/01/2007	C
1/02/2007	D
10/02/2007	D
15/02/2007	D

15/02/2007	D
27/02/2007	C
9/03/2007	H
12/03/2007	E
21/03/2007	E
22/03/2007	E
23/03/2007	B
24/03/2007	B
6/04/2007	I
12/04/2007	C
16/04/2007	C
16/04/2007	C
16/04/2007	D
18/04/2007	C
19/04/2007	C
21/04/2007	A
22/04/2007	C
23/04/2007	A
23/04/2007	A
1/05/2007	A
8/05/2007	C
8/05/2007	C
8/05/2007	C
6/06/2007	F
6/06/2007	F
7/06/2007	F
7/06/2007	F
2/07/2007	D
2/07/2007	D
2/07/2007	D
14/07/2007	E
31/07/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D

1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	D

1/08/2007	D
1/08/2007	D
1/08/2007	D
1/08/2007	E
1/08/2007	E
1/08/2007	E
1/08/2007	E
1/08/2007	E
1/08/2007	E
1/08/2007	E
1/08/2007	E
1/08/2007	E
1/08/2007	E
1/08/2007	E
1/08/2007	E
2/08/2007	B
2/08/2007	D
2/08/2007	D
2/08/2007	D
2/08/2007	D
2/08/2007	D
2/08/2007	D
2/08/2007	D
2/08/2007	D
2/08/2007	D
2/08/2007	D
2/08/2007	D
2/08/2007	D
2/08/2007	D
2/08/2007	D
2/08/2007	E
2/08/2007	E
2/08/2007	E
2/08/2007	E
2/08/2007	E
2/08/2007	E
2/08/2007	E
3/08/2007	A
3/08/2007	D
3/08/2007	D
3/08/2007	E
3/08/2007	E
3/08/2007	E

3/08/2007	E
4/08/2007	D
4/08/2007	D
4/08/2007	E
4/08/2007	E
4/08/2007	E
12/08/2007	E
16/08/2007	D
19/08/2007	E
20/08/2007	C
20/08/2007	C
29/08/2007	D
31/08/2007	E
1/09/2007	J
2/09/2007	A
3/09/2007	D
3/09/2007	D
3/09/2007	D
3/09/2007	D
3/09/2007	D
3/09/2007	D
3/09/2007	D
3/09/2007	D
3/09/2007	D
3/09/2007	D
3/09/2007	D
3/09/2007	D
3/09/2007	D
3/09/2007	D
3/09/2007	D
3/09/2007	D
3/09/2007	E
3/09/2007	E
3/09/2007	E
4/09/2007	D
4/09/2007	D
4/09/2007	D
4/09/2007	E
6/09/2007	D
6/09/2007	D
12/09/2007	B
13/09/2007	C
13/09/2007	B

16/09/2007	A
17/09/2007	D
17/09/2007	D
21/09/2007	C
23/09/2007	F
23/09/2007	F
23/09/2007	F
5/10/2007	D
10/10/2007	G
23/10/2007	C
25/10/2007	D
27/10/2007	D
29/10/2007	F
29/10/2007	F
29/10/2007	D
9/11/2007	E
9/11/2007	E
10/11/2007	D
15/11/2007	A
15/11/2007	E
16/11/2007	C
16/11/2007	C
16/11/2007	C
22/11/2007	C
22/11/2007	C
23/11/2007	J
23/11/2007	J
23/11/2007	J
23/11/2007	J
23/11/2007	J
23/11/2007	J
23/11/2007	J
23/11/2007	J
23/11/2007	J
25/11/2007	C
30/11/2007	E
1/12/2007	H
1/12/2007	H
1/12/2007	H
7/12/2007	C
11/12/2007	C
12/12/2007	C
13/12/2007	F

15/12/2007	C
15/12/2007	C
15/12/2007	C
16/12/2007	C
19/12/2007	B
2/01/2008	B
6/01/2008	C
7/01/2008	C
7/01/2008	C
7/01/2008	A
15/01/2008	B
8/02/2008	D
16/02/2008	D
22/02/2008	A
6/03/2008	C
13/03/2008	D
17/03/2008	B
27/03/2008	C
28/03/2008	F
3/04/2008	B
8/04/2008	C
15/05/2008	I
15/05/2008	I
19/05/2008	D
22/05/2008	E
29/05/2008	D
30/05/2008	E
5/06/2008	A
25/06/2008	H
29/06/2008	A
29/06/2008	A
29/06/2008	A
3/07/2008	H
8/07/2008	E
19/07/2008	C
19/07/2008	C
21/07/2008	F
22/07/2008	I
23/07/2008	F
23/07/2008	B
4/08/2008	B
4/08/2008	B
7/08/2008	G

8/08/2008	D
13/08/2008	E
28/08/2008	D
28/08/2008	E
5/09/2008	B
9/09/2008	C
9/09/2008	C
9/09/2008	C
9/09/2008	C
9/09/2008	E
9/09/2008	E
11/09/2008	D
11/09/2008	D
11/09/2008	D
1/10/2008	E
6/10/2008	A
7/10/2008	A
8/10/2008	D
8/10/2008	D
8/10/2008	D
12/10/2008	J
12/10/2008	J
12/10/2008	J
18/10/2008	B
25/10/2008	D
31/10/2008	F
5/11/2008	C
5/11/2008	C
5/11/2008	C
6/11/2008	C
10/11/2008	H
10/11/2008	H
10/11/2008	H
10/11/2008	D
11/11/2008	H
12/11/2008	B
12/11/2008	H
18/11/2008	I
25/11/2008	A
3/12/2008	C
6/12/2008	D
10/12/2008	D
12/12/2008	G

12/12/2008	G
12/12/2008	G
12/12/2008	G
12/12/2008	G
12/12/2008	G
12/12/2008	G
13/12/2008	G
14/12/2008	F
15/12/2008	G
22/12/2008	J
22/12/2008	J
29/12/2008	E
30/12/2008	D
8/01/2009	G
6/02/2009	I
9/02/2009	C
9/02/2009	C
9/02/2009	C
9/02/2009	C
9/02/2009	D
12/02/2009	I
13/02/2009	C
13/02/2009	E
25/02/2009	D
27/02/2009	B
10/03/2009	C
18/03/2009	E
1/04/2009	I
16/04/2009	B
8/05/2009	A
11/05/2009	C
14/05/2009	D
31/05/2009	A
2/06/2009	G
5/06/2009	B
5/06/2009	B
5/06/2009	B
22/06/2009	J
22/06/2009	E
23/06/2009	E
11/07/2009	D
15/07/2009	D
15/07/2009	D

15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	D
15/07/2009	E
15/07/2009	E
15/07/2009	E
15/07/2009	E
15/07/2009	E
15/07/2009	E
15/07/2009	E
15/07/2009	E
17/07/2009	D
20/07/2009	D
22/07/2009	D
28/07/2009	F
28/07/2009	D

4/08/2009	F
4/08/2009	F
5/08/2009	F
5/08/2009	F
5/08/2009	F
5/08/2009	F
5/08/2009	F
5/08/2009	F
5/08/2009	F
5/08/2009	F
5/08/2009	F
5/08/2009	F
5/08/2009	F
5/08/2009	F
5/08/2009	F
7/08/2009	E
12/08/2009	I
12/08/2009	I
12/08/2009	I
12/08/2009	I
12/08/2009	I
12/08/2009	I
12/08/2009	I
12/08/2009	I
12/08/2009	I
12/08/2009	I
12/08/2009	I
12/08/2009	I
12/08/2009	I
12/08/2009	I
12/08/2009	I
12/08/2009	I
12/08/2009	C
13/08/2009	C
13/08/2009	C
13/08/2009	A
14/08/2009	C
15/08/2009	D
16/08/2009	D
19/08/2009	E
21/08/2009	A
21/08/2009	E
21/08/2009	E

21/08/2009	E
21/08/2009	E
21/08/2009	E
22/08/2009	C
22/08/2009	C
22/08/2009	A
23/08/2009	C
2/09/2009	H
8/09/2009	F
9/09/2009	F
12/09/2009	C
15/09/2009	D
21/09/2009	A
21/09/2009	A
21/09/2009	A
21/09/2009	A
21/09/2009	A
22/09/2009	A
29/09/2009	A
4/10/2009	A
5/10/2009	D
5/10/2009	D
6/10/2009	J
7/10/2009	D
9/10/2009	D
15/10/2009	C
15/10/2009	D
16/10/2009	C
17/10/2009	A
17/10/2009	G
17/10/2009	G
17/10/2009	E
17/10/2009	E
18/10/2009	E
26/10/2009	A
28/10/2009	I
2/11/2009	B
5/11/2009	D
11/11/2009	E
11/11/2009	E
12/11/2009	H
12/11/2009	H
15/11/2009	F

21/11/2009	D
21/11/2009	D
21/11/2009	D
30/11/2009	F
1/12/2009	I
1/12/2009	I
3/12/2009	D
10/12/2009	F
10/12/2009	F

Table A.2: Raw data of burst pipe events over six years; from 01 July 2003 to 31 December 2008.

location	Desired Start date	Actual Start Date	Actual Finish Date	Pipe Material	Pipe Size	Primary Fault Desc	Fault Cause Desc	Properties affected
F	18/12/2000	3/01/2003	3/01/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
H	18/12/2000	3/01/2003	3/01/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
B	26/02/2002	28/02/2002	28/03/2002			Please enter appropriate position code	Please enter appropriate primary fault	0
B	5/03/2002	2/01/2003	2/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	436563
F	24/05/2002	7/01/2003	7/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
G	19/06/2002	2/01/2003	2/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	283664
A	21/06/2002	2/01/2003	2/01/2003	P	100 MM	Hydrant	Leak	280583
A	21/06/2002	31/12/2002	2/01/2003	P	100 MM	Hydrant	Leak	280611
D	19/07/2002	17/02/2003	20/02/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
D	19/07/2002	17/02/2003	20/02/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
G	23/07/2002	8/01/2003	10/01/2003	RC	100 MM	Hydrant	Leak	246441
D	7/08/2002	1/11/2002	8/01/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
D	9/08/2002	21/01/2003	21/01/2003	RC	100	Please enter appropriate	Please enter appropriate	0

					MM	position code	primary fault	
D	9/08/2002	14/01/2003	21/01/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
B	27/08/2002	2/01/2003	10/01/2003			Meter	Quality	195932
E	27/08/2002	28/08/2002	13/01/2003			Meter	Missing	0
C	28/08/2002	19/02/2003	19/02/2003			Meter	Quality	252333
C	2/09/2002	29/01/2003	31/01/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
C	2/09/2002	31/01/2003	31/01/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
F	2/09/2002	13/09/2002	2/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
C	3/09/2002	2/01/2003	2/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	173968
D	3/09/2002	9/09/2002	2/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
C	4/09/2002	2/01/2003	2/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
C	11/09/2002	18/09/2002	9/01/2003			Meter	Quality	172355
H	16/09/2002	25/09/2002	2/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	155059
H	20/09/2002	30/01/2003	30/01/2003			Meter	Leak	190234
D	20/09/2002	22/01/2003	22/01/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
E	20/09/2002	16/01/2003	16/01/2003			Meter	Broken	169942
D	26/09/2002	24/01/2003	24/01/2003			Meter	Seized	173150
D	26/09/2002	24/01/2003	24/01/2003			Stopcock	Quality	173119
G	1/10/2002					Meter	Please enter appropriate primary fault	174193
A	2/10/2002	9/01/2003	9/01/2003			Meter	Quality	142322
D	11/10/2002	2/01/2003	17/01/2003	RC	100	Hydrant	Leak	141153

					MM			
D	11/10/2002	2/01/2003	24/01/2003	RC	100 MM	Hydrant	Leak	150926
D	11/10/2002	2/01/2003	3/02/2003	RC	100 MM	Hydrant	Leak	165403
D	11/10/2002	6/01/2003	3/02/2003	RC	100 MM	Hydrant	Leak	165522
D	11/10/2002	2/01/2003	11/02/2003	RC	100 MM	Hydrant	Seized	119194
E	15/10/2002	17/10/2002	18/10/2002			Meter	Missing	0
D	22/10/2002	2/01/2003	11/02/2003	RC	100 MM	Hydrant	Seized	103742
E	22/10/2002	13/01/2003	15/01/2003	RC	100 MM	Hydrant	Leak	122370
D	24/10/2002	3/01/2003	3/01/2003			Meter	Seized	101803
F	29/10/2002	17/02/2003	19/02/2003	RC	100 MM	Hydrant	Quality	162947
G	30/10/2002	31/12/2002	31/12/2002	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
G	30/10/2002	31/12/2002	31/12/2002	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
D	31/10/2002	4/11/2002	4/11/2002	S	1,065 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
F	14/11/2002	7/01/2003	7/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
G	14/11/2002	17/02/2003	19/02/2003	RC	100 MM	Hydrant	Leak	139819
D	25/11/2002	23/01/2003	23/01/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
D	25/11/2002	23/01/2003	23/01/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
A	29/11/2002	7/01/2003	7/01/2003			Please enter appropriate	Please enter appropriate	0

						position code	primary fault	
B	29/11/2002	6/01/2003	6/01/2003	RC	100 MM	Box	Quality	0
F	4/12/2002	16/01/2003	16/01/2003			Meter	Broken	61805
B	4/12/2002	13/01/2003	13/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
F	10/12/2002	11/12/2002	3/01/2003			Piping	Leak	0
B	19/12/2002	30/12/2002	2/01/2003	RC	220 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
D	20/12/2002	2/01/2003	8/01/2003	RC	100 MM	Meter	Seized	27011
D	20/12/2002	2/01/2003	2/01/2003			Meter	Seized	18326
D	20/12/2002	2/01/2003	2/01/2003			Meter	Seized	18265
D	20/12/2002	2/01/2003	2/01/2003			Meter	Seized	18294
D	20/12/2002	10/02/2003	10/02/2003			Meter	Quality	74844
D	23/12/2002	23/12/2002	23/12/2002			Valve	Leak	0
D	23/12/2002	2/01/2003	2/01/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
D	23/12/2002	2/01/2003	27/02/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
D	23/12/2002	2/01/2003	27/02/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
D	23/12/2002	2/01/2003	27/02/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
D	23/12/2002	2/01/2003	27/02/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
D	23/12/2002	2/01/2003	27/02/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
D	23/12/2002	2/01/2003	27/02/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
H	27/12/2002	3/01/2003	3/01/2003			Meter	Leak	9942

I	30/12/2002	31/12/2002	31/12/2002			Meter	No water	1541
C	30/12/2002	31/12/2002	31/12/2002			Stopcock	Seized	1794
F	30/12/2002	2/01/2003	2/01/2003			Meter	Seized	4327
G	30/12/2002	31/12/2002	31/12/2002			Stopcock	Seized	1783
D	30/12/2002	31/12/2002	31/12/2002			Stopcock	Leak	1427
D	30/12/2002	31/12/2002	31/12/2002	RC	100 MM	Hydrant	Leak	0
D	30/12/2002	31/12/2002	31/12/2002			Piping	Leak	1283
E	30/12/2002	3/01/2003	7/02/2003			Hydrant	Quality	0
A	31/12/2002	31/12/2002	31/12/2002			Fitting	Leak	70
F	31/12/2002	31/12/2002	31/12/2002			Meter	Broken	44
C	1/01/2003	1/01/2003	1/01/2003			Piping	Broken	35
C	1/01/2003	1/01/2003	1/01/2003			Fitting	Leak	0
D	1/01/2003	1/01/2003	1/01/2003	RC	100 MM	Main	Leak	326
D	1/01/2003	1/01/2003	1/01/2003			Fitting	Broken	43
I	2/01/2003	4/01/2003	4/01/2003			Fitting	Leak	3082
I	2/01/2003	4/01/2003	4/01/2003			Stopcock	Seized	2944
C	2/01/2003	2/01/2003	2/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
C	2/01/2003	3/01/2003	3/01/2003			Stopcock	Leak	1417
A	2/01/2003	14/01/2003	14/01/2003			Meter	Seized	17493
A	2/01/2003	2/01/2003	2/01/2003			Fitting	Broken	97
A	2/01/2003	2/01/2003	3/01/2003	P	100 MM	Main	Quality	0
J	2/01/2003	5/02/2003	5/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
F	2/01/2003	15/01/2003	15/01/2003			Meter	Seized	18810
D	2/01/2003	2/01/2003	2/01/2003			Main	Plastic taste	442
D	2/01/2003	3/01/2003	3/01/2003			Stopcock	Seized	792

I	3/01/2003	7/01/2003	10/01/2003	DI	200 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
A	3/01/2003	6/01/2003	6/01/2003			Stopcock	Seized	4825
J	3/01/2003	13/01/2003	13/01/2003	P	200 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
F	3/01/2003	3/01/2003	3/01/2003	RC	100 MM	Main	Burst	455
F	3/01/2003	3/01/2003	3/01/2003	RC	100 MM	Main	Leak	0
F	3/01/2003	6/01/2003	6/01/2003			Stopcock	Seized	3746
B	3/01/2003	4/01/2003	4/01/2003			Stopcock	Seized	1695
B	3/01/2003	6/01/2003	6/01/2003			Piping	Broken	4028
G	3/01/2003	6/01/2003	6/01/2003			Stopcock	Seized	4546
D	3/01/2003	4/01/2003	4/01/2003			Fitting	Leak	1373
I	4/01/2003	4/01/2003	4/01/2003			Fitting	Broken	0
C	5/01/2003	5/01/2003	5/01/2003			Piping	Leak	201
C	5/01/2003	4/01/2003	4/01/2003			Piping	Leak	0
C	5/01/2003	5/01/2003	5/01/2003			Fitting	Leak	80
A	5/01/2003	4/01/2003	4/01/2003			Fitting	Leak	9999999
F	5/01/2003	5/01/2003	5/01/2003			Fitting	Broken	122
E	5/01/2003	4/01/2003	4/01/2003			Fitting	Leak	9999999
C	6/01/2003	7/01/2003	7/01/2003			Stopcock	Seized	1849
C	6/01/2003	7/01/2003	7/01/2003			Meter	No water	1728
C	6/01/2003	6/01/2003	6/01/2003			Meter	Seized	173
C	6/01/2003	7/01/2003	7/01/2003			Stopcock	Seized	1724
C	6/01/2003	7/01/2003	7/01/2003			Meter	Leak	888
A	6/01/2003	6/01/2003	6/01/2003			Meter	Leak	162
A	6/01/2003	8/01/2003	8/01/2003			Stopcock	Seized	2652
A	6/01/2003	8/01/2003	8/01/2003			Stopcock	Seized	2536
J	6/01/2003	13/01/2003	13/01/2003	P	100	Please enter appropriate	Please enter appropriate	0

					MM	position code	primary fault	
B	6/01/2003	8/01/2003	8/01/2003			Stopcock	Seized	3339
B	6/01/2003	7/01/2003	7/01/2003			Stopcock	Seized	2044
B	6/01/2003	8/01/2003	8/01/2003			Meter	Noise	3294
B	6/01/2003	7/01/2003	7/01/2003			Stopcock	Seized	1758
B	6/01/2003	7/01/2003	7/01/2003			Stopcock	Seized	1128
G	6/01/2003	7/01/2003	7/01/2003			Stopcock	Seized	1897
G	6/01/2003	6/01/2003	6/01/2003			Stopcock	Seized	50
G	6/01/2003	17/02/2003	19/02/2003	RC	100 MM	Hydrant	Leak	63138
D	6/01/2003	6/01/2003	6/01/2003	RC	100 MM	Main	Leak	220
D	6/01/2003	7/01/2003	7/01/2003			Stopcock	Quality	0
E	6/01/2003	6/01/2003	6/01/2003			Fitting	Leak	23
E	6/01/2003	7/01/2003	7/01/2003			Stopcock	Seized	1699
E	6/01/2003	6/01/2003	6/01/2003			Stopcock	Seized	207
E	6/01/2003	7/01/2003	7/01/2003			Stopcock	Seized	1514
C	7/01/2003	7/01/2003	7/01/2003			Stopcock	Seized	37
A	7/01/2003	8/01/2003	8/01/2003			Stopcock	Seized	1377
J	7/01/2003	13/01/2003	13/01/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
J	7/01/2003	13/01/2003	13/01/2003	P	200 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
J	7/01/2003	13/01/2003	13/01/2003	P	200 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
F	7/01/2003	8/01/2003	8/01/2003			Stopcock	Seized	1531
F	7/01/2003	8/01/2003	8/01/2003			Stopcock	Seized	1349
G	7/01/2003	8/01/2003	8/01/2003			Stopcock	Seized	1857
G	7/01/2003	8/01/2003	8/01/2003			Piping	Leak	1877
E	7/01/2003	8/01/2003	8/01/2003			Stopcock	Seized	1269

A	8/01/2003	9/01/2003	9/01/2003			Stopcock	Seized	1578
A	8/01/2003	8/01/2003	8/01/2003	CU	50 MM	Fitting	Leak	274
J	8/01/2003	13/01/2003	13/01/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
J	8/01/2003	13/01/2003	13/01/2003	P	200 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
J	8/01/2003	8/01/2003	8/01/2003			Fitting	Leak	0
F	8/01/2003	8/01/2003	8/01/2003			Meter	Leak	178
G	8/01/2003	9/01/2003	9/01/2003			Stopcock	Seized	1804
D	8/01/2003	8/01/2003	8/01/2003	RC	100 MM	Piping	Leak	0
D	8/01/2003	10/01/2003	10/01/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
I	9/01/2003	10/01/2003	10/01/2003			Stopcock	Seized	1449
C	9/01/2003	9/01/2003	9/01/2003	S	100 MM	Piping	Leak	0
A	9/01/2003	9/01/2003	9/01/2003			Piping	Leak	0
B	9/01/2003	9/01/2003	9/01/2003			Stopcock	Seized	575
B	9/01/2003	9/01/2003	9/01/2003			Stopcock	Seized	75
I	10/01/2003	13/01/2003	13/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
I	10/01/2003	10/01/2003	10/01/2003			Fitting	Leak	632
C	10/01/2003	13/01/2003	13/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
C	10/01/2003	10/01/2003	10/01/2003			Fitting	Broken	149
A	10/01/2003	14/01/2003	14/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	10/01/2003	13/01/2003	13/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	10/01/2003	10/01/2003	10/01/2003			Stopcock	Seized	184
J	10/01/2003	13/01/2003	13/01/2003	P	100	Please enter appropriate	Please enter appropriate	0

					MM	position code	primary fault	
F	10/01/2003	11/01/2003	11/01/2003			Stopcock	Leak	1754
F	10/01/2003	14/01/2003	14/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
F	10/01/2003	13/01/2003	13/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
F	10/01/2003	13/01/2003	13/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
F	10/01/2003	13/01/2003	13/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
G	10/01/2003	13/01/2003	13/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
D	10/01/2003	13/01/2003	13/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
D	10/01/2003	10/01/2003	10/01/2003			Stopcock	Seized	67
D	10/01/2003	11/01/2003	11/01/2003			Stopcock	Leak	1689
D	10/01/2003	16/01/2003	16/01/2003			Meter	Broken	8509
E	10/01/2003	13/01/2003	13/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
E	10/01/2003	10/01/2003	10/01/2003			Stopcock	Seized	60
C	11/01/2003	12/01/2003	12/01/2003			Stopcock	Leak	917
A	11/01/2003	11/01/2003	11/01/2003			Fitting	Leak	60
F	11/01/2003	11/01/2003	11/01/2003			Fitting	Broken	137
I	12/01/2003	13/01/2003	13/01/2003			Stopcock	Seized	1002
I	13/01/2003	13/01/2003	13/01/2003	P	100 MM	Piping	Leak	0
I	13/01/2003	14/01/2003	14/01/2003			Fitting	Leak	1433
I	13/01/2003	13/01/2003	13/01/2003			Stopcock	Broken	70
A	13/01/2003	13/01/2003	13/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	13/01/2003	14/01/2003	14/01/2003			Stopcock	Seized	1591

A	13/01/2003	14/01/2003	14/01/2003			Stopcock	Seized	1501
D	13/01/2003	14/01/2003	14/01/2003			Stopcock	Seized	1462
D	13/01/2003	14/01/2003	14/01/2003			Piping	Leak	0
D	13/01/2003	16/01/2003	22/01/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
D	13/01/2003	28/01/2003	28/01/2003	RC	100 MM	Meter	Missing	0
I	14/01/2003	15/01/2003	15/01/2003			Stopcock	Seized	1382
C	14/01/2003	14/01/2003	14/01/2003	RC	100 MM	Hydrant	Leak	0
C	14/01/2003	14/01/2003	14/01/2003			Piping	Leak	96
A	14/01/2003	14/01/2003	14/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
J	14/01/2003	22/01/2003	22/01/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
J	14/01/2003	22/01/2003	22/01/2003	P	200 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
F	14/01/2003	14/01/2003	14/01/2003			Piping	Leak	0
F	14/01/2003	14/01/2003	14/01/2003			Piping	Leak	97
D	14/01/2003	15/01/2003	15/01/2003			Stopcock	Seized	1381
I	15/01/2003	16/01/2003	16/01/2003			Stopcock	Seized	0
I	15/01/2003	15/01/2003	15/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
C	15/01/2003	21/01/2003	21/01/2003	RC	100 MM	Meter	Quality	8706
A	15/01/2003	15/01/2003	15/01/2003			Stopcock	Seized	207
J	15/01/2003	20/01/2003	20/01/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
J	15/01/2003	20/01/2003	20/01/2003	P	150 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
J	15/01/2003	20/01/2003	20/01/2003	P	100	Please enter appropriate	Please enter appropriate	0

					MM	position code	primary fault	
J	15/01/2003	20/01/2003	20/01/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
F	15/01/2003	16/01/2003	16/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
B	15/01/2003	18/01/2003	18/01/2003			Stopcock	Seized	4400
B	15/01/2003	18/01/2003	18/01/2003			Stopcock	Seized	4651
B	15/01/2003	18/01/2003	18/01/2003			Stopcock	Seized	4587
B	15/01/2003	15/01/2003	15/01/2003			Meter	Leak	84
H	15/01/2003	15/01/2003	15/01/2003			Stopcock	Seized	441
G	15/01/2003	15/01/2003	15/01/2003	RC	100 MM	Main	Burst	291
G	15/01/2003	16/01/2003	16/01/2003			Stopcock	Seized	1630
C	16/01/2003	16/01/2003	16/01/2003	RC	100 MM	Ferrule cock	Leak	310
A	16/01/2003	16/01/2003	16/01/2003			Meter	Leak	52
J	16/01/2003	22/01/2003	22/01/2003	P	150 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
F	16/01/2003	17/01/2003	17/01/2003			Meter	No water	944
B	16/01/2003	16/01/2003	16/01/2003			Stopcock	Seized	56
B	16/01/2003	20/01/2003	20/01/2003			Stopcock	Seized	5671
H	16/01/2003	16/01/2003	16/01/2003			Fitting	Leak	428
D	16/01/2003	16/01/2003	16/01/2003			Hydrant	Leak	0
E	16/01/2003	17/01/2003	17/01/2003			Stopcock	Seized	1360
E	16/01/2003	24/01/2003	24/01/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
C	17/01/2003	17/01/2003	17/01/2003	RC	100 MM	Main	Leak	0
C	17/01/2003	22/01/2003	22/01/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
A	17/01/2003	17/01/2003	17/01/2003	P	200	Ferrule cock	Leak	349

					MM			
J	17/01/2003	22/01/2003	22/01/2003	P	150 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
J	17/01/2003	29/01/2003	29/01/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
F	17/01/2003	20/01/2003	20/01/2003			Stopcock	Seized	4630
B	17/01/2003	17/01/2003	17/01/2003	CU	50 MM	Stopcock	Leak	385
B	17/01/2003	20/01/2003	20/01/2003			Fitting	Leak	3858
G	17/01/2003	18/01/2003	18/01/2003			Stopcock	Seized	1535
D	17/01/2003	22/01/2003	22/01/2003	RC	305 MM	Please enter appropriate position code	Please enter appropriate primary fault	7542
D	17/01/2003	17/01/2003	17/01/2003			Piping	Leak	0
D	17/01/2003	17/01/2003	19/01/2003			Fitting	Leak	2684
D	17/01/2003	17/01/2003	17/01/2003			Ferrule cock	No water	214
E	17/01/2003	17/01/2003	17/01/2003			Stopcock	Seized	36
E	17/01/2003	23/01/2003	23/01/2003	RC	100 MM	Meter	Quality	8417
A	18/01/2003	18/01/2003	18/01/2003			Meter	Leak	156
G	18/01/2003	18/01/2003	18/01/2003	RC	100 MM	Main	Burst	341
C	19/01/2003	19/01/2003	19/01/2003			Stopcock	Seized	5
F	19/01/2003	19/01/2003	19/01/2003			Fitting	Leak	113
C	20/01/2003	20/01/2003	20/01/2003	RC	100 MM	Hydrant	Leak	0
A	20/01/2003	21/01/2003	21/01/2003			Stopcock	Seized	1467
A	20/01/2003	21/01/2003	21/01/2003			Stopcock	Seized	1633
A	20/01/2003	21/01/2003	21/01/2003			Stopcock	Seized	1593
J	20/01/2003	20/01/2003	20/01/2003	CI	100 MM	Piping	Leak	0
F	20/01/2003	21/01/2003	21/01/2003			Stopcock	Seized	1861

F	20/01/2003	21/01/2003	21/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
F	20/01/2003	23/01/2003	23/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
F	20/01/2003	21/01/2003	21/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
F	20/01/2003	21/01/2003	21/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
F	20/01/2003	21/01/2003	21/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
B	20/01/2003	21/01/2003	21/01/2003			Stopcock	Seized	1642
G	20/01/2003	22/01/2003	22/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
G	20/01/2003	22/01/2003	22/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
G	20/01/2003	22/01/2003	22/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
G	20/01/2003	22/01/2003	22/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
G	20/01/2003	22/01/2003	22/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
G	20/01/2003	22/01/2003	24/01/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
D	20/01/2003	20/01/2003	20/01/2003			Stopcock	Seized	26
D	20/01/2003	20/01/2003	20/01/2003			Fitting	Leak	0
E	20/01/2003	21/01/2003	21/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
C	21/01/2003	21/01/2003	21/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
F	21/01/2003	21/01/2003	21/01/2003			Piping	Leak	105
G	21/01/2003	22/01/2003	22/01/2003			Piping	No water	1572
D	21/01/2003	22/01/2003	22/01/2003			Stopcock	Seized	1625

D	21/01/2003	22/01/2003	22/01/2003			Piping	Pressure	1221
D	21/01/2003	22/01/2003	5/02/2003			Stopcock	Seized	21331
C	22/01/2003	23/01/2003	23/01/2003			Stopcock	Seized	994
A	22/01/2003	29/01/2003	29/01/2003	AC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
J	22/01/2003	28/01/2003	28/01/2003	P	150 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
F	22/01/2003	22/01/2003	22/01/2003			Stopcock	Seized	236
B	22/01/2003	23/01/2003	23/01/2003			Stopcock	Seized	1350
G	22/01/2003	23/01/2003	23/01/2003			Stopcock	Seized	1893
G	22/01/2003	22/01/2003	22/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
G	22/01/2003	23/01/2003	23/01/2003			Stopcock	Seized	1192
D	22/01/2003	22/01/2003	22/01/2003			Meter	Leak	87
D	22/01/2003	24/01/2003	31/01/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
J	23/01/2003	30/01/2003	30/01/2003	P	150 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
F	23/01/2003	23/01/2003	23/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
D	23/01/2003	24/01/2003	24/01/2003			Stopcock	Leak	960
E	23/01/2003	23/01/2003	23/01/2003			Stopcock	Seized	77
I	24/01/2003	28/01/2003	28/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
I	24/01/2003	28/01/2003	28/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
I	24/01/2003	30/01/2003	30/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
C	24/01/2003	25/01/2003	25/01/2003			Stopcock	Seized	1421
A	24/01/2003	28/01/2003	28/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0

A	24/01/2003	30/01/2003	30/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	24/01/2003	28/01/2003	28/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	24/01/2003	28/01/2003	28/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
J	24/01/2003	29/01/2003	29/01/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
J	24/01/2003	31/01/2003	31/01/2003	P	250 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
B	24/01/2003	26/01/2003	26/01/2003			Stopcock	Seized	3415
B	24/01/2003	24/01/2003	24/01/2003			Fitting	Leak	90
H	24/01/2003	30/01/2003	30/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
H	24/01/2003	28/01/2003	28/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
H	24/01/2003	28/01/2003	28/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
H	24/01/2003	28/01/2003	28/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
G	24/01/2003	24/01/2003	24/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
D	24/01/2003	29/01/2003	29/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
D	24/01/2003	25/01/2003	25/01/2003			Fitting	Leak	0
B	25/01/2003	25/01/2003	31/01/2003			Meter	Leak	8441
D	25/01/2003	25/01/2003	19/02/2003			Piping	Broken	58
D	25/01/2003	25/01/2003	25/01/2003			Stopcock	Seized	0
H	26/01/2003	27/01/2003	27/01/2003			Stopcock	Seized	832
G	26/01/2003	26/01/2003	26/01/2003			Stopcock	Seized	34
G	26/01/2003	26/01/2003	26/01/2003			Stopcock	Seized	62

A	28/01/2003	29/01/2003	29/01/2003			Stopcock	Seized	1959
J	28/01/2003	30/01/2003	30/01/2003	P	200 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
F	28/01/2003	28/01/2003	28/01/2003			Piping	Broken	0
B	28/01/2003	28/01/2003	28/01/2003			Fitting	Leak	54
B	28/01/2003	28/01/2003	28/01/2003			Fitting	Leak	111
H	28/01/2003	28/01/2003	29/01/2003			Piping	Leak	48
D	28/01/2003	29/01/2003	29/01/2003			Stopcock	Seized	1445
D	28/01/2003	28/01/2003	28/01/2003			Stopcock	Seized	0
D	28/01/2003	29/01/2003	11/02/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	20056
E	28/01/2003	29/01/2003	29/01/2003			Stopcock	Seized	1487
C	29/01/2003	3/02/2003	10/02/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
A	29/01/2003	30/01/2003	30/01/2003			Stopcock	Seized	1462
A	29/01/2003	29/01/2003	29/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	29/01/2003	29/01/2003	29/01/2003			Fitting	Leak	106
F	29/01/2003	29/01/2003	29/01/2003			Fitting	Leak	248
F	29/01/2003	30/01/2003	30/01/2003			Piping	Leak	896
B	29/01/2003	29/01/2003	29/01/2003			Stopcock	Seized	488
B	29/01/2003	29/01/2003	29/01/2003			Stopcock	Seized	85
C	30/01/2003	3/02/2003	3/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
C	30/01/2003	3/02/2003	3/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
J	30/01/2003	3/02/2003	3/02/2003	P	200 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
F	30/01/2003	4/02/2003	12/02/2003	RC	150 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
F	30/01/2003	31/01/2003	31/01/2003			Stopcock	Seized	1727

F	30/01/2003	31/01/2003	31/01/2003	RC	100 MM	Hydrant	Leak	0
H	30/01/2003	31/01/2003	31/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
G	30/01/2003	3/02/2003	3/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
G	30/01/2003	31/01/2003	31/01/2003			Stopcock	Seized	932
D	30/01/2003	31/01/2003	3/02/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	5644
D	30/01/2003	30/01/2003	30/01/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
D	30/01/2003	31/01/2003	31/01/2003			Stopcock	Seized	1852
I	31/01/2003	3/02/2003	3/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
I	31/01/2003	31/01/2003	31/01/2003			Stopcock	Seized	135
C	31/01/2003	7/02/2003	7/02/2003			Meter	Quality	10512
C	31/01/2003	3/02/2003	3/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
C	31/01/2003	3/02/2003	3/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
C	31/01/2003	3/02/2003	3/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
C	31/01/2003	1/02/2003	1/02/2003			Stopcock	Seized	1295
C	31/01/2003	31/01/2003	31/01/2003	CU	50 MM	Main	Leak	350
C	31/01/2003	3/02/2003	3/02/2003			Stopcock	Seized	3813
A	31/01/2003	5/02/2003	16/02/2003	AC	200 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
A	31/01/2003	3/02/2003	3/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	31/01/2003	4/02/2003	4/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0

A	31/01/2003	4/02/2003	4/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	31/01/2003	3/02/2003	3/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	31/01/2003	3/02/2003	3/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	31/01/2003	4/02/2003	4/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	31/01/2003	3/02/2003	3/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	31/01/2003	3/02/2003	3/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	31/01/2003	31/01/2003	31/01/2003			Fitting	Leak	69
A	31/01/2003	1/02/2003	1/02/2003			Meter	Broken	984
J	31/01/2003	3/02/2003	3/02/2003	P	200 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
J	31/01/2003	4/02/2003	4/02/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
J	31/01/2003	4/02/2003	4/02/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
J	31/01/2003	4/02/2003	4/02/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
J	31/01/2003	4/02/2003	4/02/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
J	31/01/2003	4/02/2003	4/02/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
J	31/01/2003	4/02/2003	4/02/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
J	31/01/2003	4/02/2003	4/02/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
B	31/01/2003	4/02/2003	4/02/2003	RC	150 MM	Please enter appropriate position code	Please enter appropriate primary fault	6221

D	31/01/2003	31/01/2003	3/02/2003	RC	100 MM	Piping	Leak	197
D	31/01/2003	31/01/2003	31/01/2003			Stopcock	Seized	145
E	31/01/2003	31/01/2003	31/01/2003			Fitting	Leak	161
C	1/02/2003	1/02/2003	1/02/2003			Piping	Blockage	0
F	1/02/2003	3/02/2003	3/02/2003			Fitting	Leak	2453
B	1/02/2003	1/02/2003	1/02/2003			Stopcock	Seized	125
D	1/02/2003	1/02/2003	1/02/2003	RC	100 MM	Piping	Leak	235
C	2/02/2003	2/02/2003	2/02/2003			Valve	Broken	0
C	2/02/2003	2/02/2003	2/02/2003			Fitting	Leak	209
A	2/02/2003	3/02/2003	4/02/2003			Meter	Leak	2751
I	3/02/2003	3/02/2003	3/02/2003			Stopcock	Seized	77
A	3/02/2003	3/02/2003	3/02/2003			Stopcock	Seized	69
A	3/02/2003	3/02/2003	3/02/2003			Meter	Leak	273
F	3/02/2003	3/02/2003	3/02/2003			Stopcock	Seized	62
F	3/02/2003	4/02/2003	4/02/2003			Stopcock	Seized	1369
D	3/02/2003	3/02/2003	3/02/2003			Stopcock	Seized	73
D	3/02/2003	4/02/2003	4/02/2003			Stopcock	Seized	1444
D	3/02/2003	3/02/2003	3/02/2003			Stopcock	Seized	57
D	3/02/2003	4/02/2003	4/02/2003			Stopcock	Seized	1434
D	3/02/2003	3/02/2003	3/02/2003	RC	100 MM	Main	Quality	0
D	3/02/2003	4/02/2003	4/02/2003			Stopcock	Seized	1286
E	3/02/2003	5/02/2003	6/02/2003			Ferrule cock	Pressure	4160
C	4/02/2003	5/02/2003	5/02/2003			Stopcock	Seized	1813
C	4/02/2003	5/02/2003	5/02/2003			Stopcock	Seized	1118
A	4/02/2003	5/02/2003	5/02/2003			Stopcock	Seized	1772
F	4/02/2003	4/02/2003	4/02/2003			Piping	Leak	242

B	4/02/2003	5/02/2003	5/02/2003			Stopcock	Seized	1849
B	4/02/2003	4/02/2003	4/02/2003			Meter	Leak	142
D	4/02/2003	4/02/2003	4/02/2003			Stopcock	Seized	136
E	4/02/2003	5/02/2003	5/02/2003			Stopcock	Seized	1333
C	5/02/2003	6/02/2003	6/02/2003	RC	100 MM	Stopcock	Leak	1291
C	5/02/2003	5/02/2003	5/02/2003			Fitting	Leak	200
F	5/02/2003	5/02/2003	5/02/2003			Piping	Broken	73
B	5/02/2003	6/02/2003	6/02/2003			Stopcock	Seized	1139
G	5/02/2003	5/02/2003	5/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
G	5/02/2003	6/02/2003	6/02/2003	P	200 MM	Valve	Leak	0
G	5/02/2003	5/02/2003	5/02/2003			Hydrant	Leak	0
G	5/02/2003	5/02/2003	5/02/2003			Hydrant	Leak	0
D	5/02/2003	5/02/2003	5/02/2003			Stopcock	Seized	0
D	5/02/2003	6/02/2003	6/02/2003			Stopcock	Seized	1342
C	6/02/2003	6/02/2003	7/02/2003			Stopcock	Seized	1393
J	6/02/2003	7/02/2003	7/02/2003	P	200 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
F	6/02/2003	6/02/2003	6/02/2003	RC	100 MM	Main	Leak	0
F	6/02/2003	6/02/2003	6/02/2003	RC	100 MM	Meter	Leak	0
F	6/02/2003	7/02/2003	7/02/2003			Stopcock	Seized	1170
F	6/02/2003	6/02/2003	6/02/2003			Piping	Leak	0
D	6/02/2003	6/02/2003	7/02/2003	RC	100 MM	Ferrule cock	Leak	1911
I	7/02/2003	10/02/2003	10/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
C	7/02/2003	7/02/2003	7/02/2003			Stopcock	Seized	100

A	7/02/2003	11/02/2003	11/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
J	7/02/2003	19/02/2003	19/02/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
J	7/02/2003	17/02/2003	17/02/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
J	7/02/2003	17/02/2003	17/02/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
F	7/02/2003	12/02/2003	12/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
F	7/02/2003	10/02/2003	10/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
F	7/02/2003	10/02/2003	10/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
F	7/02/2003	10/02/2003	10/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
F	7/02/2003	10/02/2003	10/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
F	7/02/2003	8/02/2003	8/02/2003			Meter	Leak	1058
B	7/02/2003	13/02/2003	13/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
B	7/02/2003	11/02/2003	11/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
B	7/02/2003	13/02/2003	13/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
B	7/02/2003	11/02/2003	11/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
H	7/02/2003	11/02/2003	11/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
H	7/02/2003	11/02/2003	11/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
G	7/02/2003	10/02/2003	10/02/2003			Please enter appropriate	Please enter appropriate	0

						position code	primary fault	
G	7/02/2003	10/02/2003	10/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
G	7/02/2003	10/02/2003	10/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
G	7/02/2003	7/02/2003	7/02/2003			Stopcock	Seized	38
D	7/02/2003	7/02/2003	7/02/2003			Fitting	Leak	187
D	7/02/2003	13/02/2003	13/02/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
D	7/02/2003	11/02/2003	11/02/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
D	7/02/2003	11/02/2003	11/02/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
D	7/02/2003	7/02/2003	7/02/2003			Fitting	Leak	127
E	7/02/2003	7/02/2003	7/02/2003			Meter	No water	0
E	7/02/2003					Please enter appropriate position code	Please enter appropriate primary fault	0
A	8/02/2003	8/02/2003	8/02/2003			Fitting	Leak	130
D	8/02/2003	8/02/2003	8/02/2003			Stopcock	Leak	198
D	8/02/2003	8/02/2003	8/02/2003			Ferrule cock	No water	101
E	8/02/2003	8/02/2003	8/02/2003			Fitting	Leak	44
C	9/02/2003	9/02/2003	9/02/2003			Stopcock	Seized	105
A	9/02/2003	9/02/2003	9/02/2003			Piping	Broken	122
C	10/02/2003	10/02/2003	10/02/2003			Fitting	Leak	0
C	10/02/2003	11/02/2003	11/02/2003			Stopcock	Seized	1348
C	10/02/2003	10/02/2003	10/02/2003	RC	100 MM	Fitting	Leak	189
A	10/02/2003	10/02/2003	11/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	10/02/2003	11/02/2003	11/02/2003			Stopcock	Seized	1134
J	10/02/2003	13/02/2003	24/02/2003	P	100	Please enter appropriate	Please enter appropriate	0

					MM	position code	primary fault	
G	10/02/2003	11/02/2003	11/02/2003			Stopcock	Seized	1444
E	10/02/2003	10/02/2003	10/02/2003			Stopcock	Seized	209
C	11/02/2003	12/02/2003	12/02/2003			Meter	No water	1083
C	11/02/2003	12/02/2003	12/02/2003			Ferrule cock	No water	296
A	11/02/2003	12/02/2003	12/02/2003			Stopcock	Seized	2107
A	11/02/2003	11/02/2003	11/02/2003			Stopcock	Seized	74
A	11/02/2003	11/02/2003	11/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
J	11/02/2003	17/02/2003	17/02/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
F	11/02/2003	11/02/2003	11/02/2003			Meter	Seized	377
F	11/02/2003	11/02/2003	11/02/2003	RC	100 MM	Main	Leak	0
G	11/02/2003	13/02/2003	13/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
G	11/02/2003	11/02/2003	12/02/2003	RC	220 MM	Hydrant	Leak	310
D	11/02/2003	11/02/2003	11/02/2003	RC	100 MM	Main	Burst	270
D	11/02/2003	11/02/2003	11/02/2003	RC	100 MM	Hydrant	Leak	0
D	11/02/2003	18/02/2003	18/02/2003			Meter	Seized	9560
D	11/02/2003	18/02/2003	18/02/2003			Meter	Seized	9470
D	11/02/2003	18/02/2003	18/02/2003			Meter	Seized	9500
D	11/02/2003	20/02/2003	20/02/2003			Stopcock	Broken	12364
D	11/02/2003	13/02/2003	13/02/2003			Meter	Seized	2669
D	11/02/2003	14/02/2003	14/02/2003			Meter	Seized	3858
D	11/02/2003	13/02/2003	13/02/2003			Meter	Seized	2608
D	11/02/2003	20/02/2003	20/02/2003			Stopcock	Broken	12348

D	11/02/2003	13/02/2003	13/02/2003			Meter	Seized	2703
D	11/02/2003	18/02/2003	18/02/2003			Stopcock	Seized	10056
D	11/02/2003	13/02/2003	13/02/2003			Meter	Seized	2686
E	11/02/2003	14/02/2003	14/02/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	4087
E	11/02/2003	14/02/2003	14/02/2003			Meter	Seized	3901
E	11/02/2003	14/02/2003	14/02/2003			Meter	Seized	3925
E	11/02/2003	12/02/2003	12/02/2003			Stopcock	Leak	1089
C	12/02/2003	13/02/2003	13/02/2003			Stopcock	Seized	1888
C	12/02/2003	15/02/2003	15/02/2003			Stopcock	Seized	4517
A	12/02/2003	13/02/2003	13/02/2003			Stopcock	Seized	1485
A	12/02/2003	12/02/2003	12/02/2003			Fitting	Leak	0
A	12/02/2003	13/02/2003	13/02/2003			Fitting	Leak	0
J	12/02/2003	17/02/2003	17/02/2003	P	250 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
G	12/02/2003	18/02/2003	18/02/2003			Piping	Leak	8463
D	12/02/2003	13/02/2003	13/02/2003			Stopcock	Seized	1656
D	12/02/2003	18/02/2003	18/02/2003			Meter	Seized	8377
I	13/02/2003	13/02/2003	13/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
I	13/02/2003	17/02/2003	20/02/2003	DI	200 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
A	13/02/2003	14/02/2003	14/02/2003			Stopcock	Seized	1616
J	13/02/2003	13/02/2003	13/02/2003			Fitting	Broken	0
F	13/02/2003	13/02/2003	13/02/2003			Piping	Leak	267
G	13/02/2003	13/02/2003	13/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
D	13/02/2003	13/02/2003	13/02/2003			Meter	Seized	0
D	13/02/2003	18/02/2003	18/02/2003			Meter	Seized	6786
D	13/02/2003	18/02/2003	18/02/2003			Meter	Seized	6754

D	13/02/2003	20/02/2003	20/02/2003			Stopcock	Seized	0
E	13/02/2003	14/02/2003	14/02/2003			Fitting	Leak	89
I	14/02/2003	18/02/2003	18/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
C	14/02/2003	14/02/2003	14/02/2003			Fitting	Leak	633
C	14/02/2003	15/02/2003	15/02/2003			Stopcock	Seized	1899
C	14/02/2003	20/02/2003	20/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	14/02/2003	18/02/2003	18/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	14/02/2003	20/02/2003	20/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	14/02/2003	18/02/2003	18/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	14/02/2003	18/02/2003	18/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	14/02/2003	17/02/2003	17/02/2003			Piping	Leak	0
J	14/02/2003	19/02/2003	19/02/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
F	14/02/2003	20/02/2003	20/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
F	14/02/2003	15/02/2003	15/02/2003			Stopcock	Seized	1457
F	14/02/2003	14/02/2003	14/02/2003			Piping	Leak	81
B	14/02/2003	17/02/2003	17/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
B	14/02/2003	17/02/2003	17/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
D	14/02/2003	19/02/2003	19/02/2003			Meter	Seized	7027
D	14/02/2003	19/02/2003	19/02/2003			Meter	Broken	7274
E	14/02/2003	18/02/2003	18/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0

E	14/02/2003	20/02/2003	20/02/2003			Meter	Seized	8336
C	15/02/2003	15/02/2003	15/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	15/02/2003	15/02/2003	15/02/2003			Piping	Leak	370
F	15/02/2003	15/02/2003	15/02/2003			Fitting	Leak	73
H	15/02/2003	15/02/2003	15/02/2003	RC	220 MM	Meter	Leak	0
C	16/02/2003	17/02/2003	17/02/2003			Stopcock	Seized	1459
A	16/02/2003	16/02/2003	16/02/2003	P	100 MM	Main	Quality	0
A	16/02/2003	17/02/2003	17/02/2003	RC	200 MM	Valve	Leak	0
F	16/02/2003	17/02/2003	17/02/2003			Stopcock	Seized	1461
B	16/02/2003	16/02/2003	16/02/2003			Stopcock	Seized	259
B	16/02/2003	17/02/2003	17/02/2003			Meter	Pressure	1163
C	17/02/2003	18/02/2003	18/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	17/02/2003	17/02/2003	17/02/2003	MDPE	63 MM	Ferrule cock	Broken	282
A	17/02/2003	17/02/2003	17/02/2003			Fitting	Leak	311
A	17/02/2003	18/02/2003	18/02/2003			Meter	Seized	1214
B	17/02/2003	18/02/2003	18/02/2003			Stopcock	Seized	1483
B	17/02/2003	17/02/2003	17/02/2003			Meter	Seized	143
D	17/02/2003	17/02/2003	17/02/2003			Meter	Leak	137
D	17/02/2003	17/02/2003	17/02/2003			Fitting	Seized	64
C	18/02/2003	18/02/2003	18/02/2003	RC	100 MM	Main	Quality	0
C	18/02/2003	19/02/2003	19/02/2003			Stopcock	Seized	1278
J	18/02/2003	21/02/2003	21/02/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
F	18/02/2003	19/02/2003	19/02/2003			Stopcock	Seized	1656

F	18/02/2003	19/02/2003	19/02/2003			Stopcock	Seized	1671
F	18/02/2003	19/02/2003	19/02/2003			Stopcock	Seized	1685
F	18/02/2003	18/02/2003	18/02/2003			Meter	Leak	0
B	18/02/2003	19/02/2003	19/02/2003			Stopcock	Seized	1327
H	18/02/2003	19/02/2003	19/02/2003			Stopcock	Seized	1464
H	18/02/2003	18/02/2003	18/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
D	18/02/2003	19/02/2003	19/02/2003			Meter	Missing	0
D	18/02/2003	25/02/2003	25/02/2003			Meter	Seized	9773
D	18/02/2003	20/02/2003	20/02/2003			Meter	Seized	3031
D	18/02/2003	20/02/2003	20/02/2003			Stopcock	Seized	0
E	18/02/2003	19/02/2003	20/02/2003	RC	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
I	19/02/2003	20/02/2003	20/02/2003			Meter	No water	1275
C	19/02/2003	19/02/2003	19/02/2003			Stopcock	Seized	115
C	19/02/2003	21/02/2003	26/02/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
C	19/02/2003	19/02/2003	19/02/2003			Piping	Leak	97
J	19/02/2003	20/02/2003	20/02/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
J	19/02/2003	20/02/2003	20/02/2003	P	150 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
G	19/02/2003	20/02/2003	20/02/2003			Stopcock	Seized	1539
D	19/02/2003	20/02/2003	20/02/2003			Stopcock	Seized	1416
D	19/02/2003	24/02/2003	24/02/2003			Meter	Seized	7137
E	19/02/2003	20/02/2003	20/02/2003			Stopcock	Seized	1695
C	20/02/2003	21/02/2003	21/02/2003			Piping	Leak	5909
A	20/02/2003	25/02/2003	25/02/2003			Meter	Seized	7128
A	20/02/2003	20/02/2003	20/02/2003			Stopcock	Seized	36
J	20/02/2003	24/02/2003	24/02/2003	P	100	Please enter appropriate	Please enter appropriate	0

					MM	position code	primary fault	
B	20/02/2003	20/02/2003	20/02/2003			Stopcock	Seized	108
G	20/02/2003	21/02/2003	21/02/2003			Piping	Leak	0
D	20/02/2003	20/02/2003	20/02/2003			Fitting	Leak	64
D	20/02/2003	21/02/2003	21/02/2003			Stopcock	Seized	1614
I	21/02/2003	27/02/2003	27/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
I	21/02/2003	24/02/2003	24/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
I	21/02/2003	24/02/2003	24/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
I	21/02/2003	24/02/2003	24/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
I	21/02/2003	24/02/2003	24/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
I	21/02/2003	24/02/2003	24/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
I	21/02/2003	25/02/2003	25/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
I	21/02/2003	25/02/2002	25/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
C	21/02/2003	22/02/2003	22/02/2003			Stopcock	Seized	824
A	21/02/2003	24/02/2003	24/02/2003			Stopcock	Seized	4591
A	21/02/2003	24/02/2003	24/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	21/02/2003	25/02/2003	25/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	21/02/2003	24/02/2003	24/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	21/02/2003	24/02/2003	24/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0

A	21/02/2003	24/02/2003	24/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	21/02/2003	24/02/2003	24/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	21/02/2003	24/02/2003	24/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	21/02/2003	27/02/2003	27/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	21/02/2003	25/02/2003	25/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	21/02/2003	27/02/2003	27/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	21/02/2003	27/02/2003	27/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	21/02/2003	27/02/2003	27/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	21/02/2003	27/02/2003	27/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	21/02/2003	27/02/2003	27/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	21/02/2003	27/02/2003	27/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
A	21/02/2003	24/02/2003	24/02/2003			Stopcock	Leak	4181
A	21/02/2003	21/02/2003	21/02/2003			Meter	Leak	155
F	21/02/2003	25/02/2003	25/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
F	21/02/2003	24/02/2003	24/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
F	21/02/2003	24/02/2003	24/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
B	21/02/2003	22/02/2003	22/02/2003			Stopcock	Seized	1684
B	21/02/2003	24/02/2003	24/02/2003			Fitting	Leak	4043

G	21/02/2003	24/02/2003	24/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
G	21/02/2003	24/02/2003	24/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
C	23/02/2003	23/02/2003	23/02/2003			Fitting	Broken	63
A	23/02/2003	23/02/2003	23/02/2003			Stopcock	Seized	229
F	23/02/2003	23/02/2003	23/02/2003	RC	100 MM	Piping	Leak	76
E	23/02/2003	24/02/2003	24/02/2003			Stopcock	Seized	1147
A	24/02/2003	25/02/2003	25/02/2003			Stopcock	Seized	1432
A	24/02/2003	24/02/2003	24/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
J	24/02/2003	26/02/2003	26/02/2003	P	100 MM	Please enter appropriate position code	Please enter appropriate primary fault	0
G	24/02/2003	25/02/2003	25/02/2003			Meter	Seized	1239
D	24/02/2003	25/02/2003	25/02/2003			Stopcock	Seized	1180
D	24/02/2003	24/02/2003	24/02/2003			Piping	Leak	224
D	24/02/2003	25/02/2003	25/02/2003			Stopcock	Seized	1016
D	24/02/2003	25/02/2003	25/02/2003			Stopcock	Seized	917
E	24/02/2003	24/02/2003	24/02/2003			Piping	Leak	439
E	24/02/2003	24/02/2003	24/02/2003	RC	100 MM	Piping	Leak	120
C	25/02/2003	25/02/2003	25/02/2003			Stopcock	Seized	78
F	25/02/2003	25/02/2003	25/02/2003			Fitting	Leak	149
B	25/02/2003	26/02/2003	26/02/2003			Stopcock	Seized	1716
B	25/02/2003	25/02/2003	25/02/2003			Stopcock	Seized	46
B	25/02/2003	26/02/2003	26/02/2003			Fitting	Leak	1137
B	25/02/2003	26/02/2003	26/02/2003			Stopcock	Seized	9999999
D	25/02/2003	26/02/2003	26/02/2003			Stopcock	Leak	0
C	26/02/2003	27/02/2003	27/02/2003			Stopcock	Seized	1408

C	26/02/2003	27/02/2003	27/02/2003			Stopcock	Seized	1461
C	26/02/2003	27/02/2003	27/02/2003			Stopcock	Seized	1530
F	26/02/2003	27/02/2003	27/02/2003			Stopcock	Seized	1133
F	26/02/2003	27/02/2003	27/02/2003			Stopcock	Seized	948
B	26/02/2003	27/02/2003	27/02/2003			Stopcock	Seized	1407
D	26/02/2003	26/02/2003	26/02/2003			Stopcock	Seized	98
D	26/02/2003	26/02/2003	26/02/2003			Please enter appropriate position code	Plastic taste	0
E	26/02/2003	26/02/2003	26/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
F	27/02/2003	27/02/2003	27/02/2003			Stopcock	Seized	80
D	27/02/2003	27/02/2003	27/02/2003			Piping	Broken	0
E	27/02/2003	27/02/2003	27/02/2003	RC	100 MM	Main	Quality	0
E	27/02/2003	27/02/2003	27/02/2003			Fitting	Leak	218
E	28/02/2003	28/02/2003	28/02/2003			Please enter appropriate position code	Please enter appropriate primary fault	0
2004								
	Desired Start Date	Actual Start Date	Actual Finish Date	Pipe Material	Pipe Size	Fault Location	Fault Cause Desc	Properties affected
G	10/01/2004	10/01/2004	10/01/2004	RC	100 MM	Main	Wear	1
D	13/01/2004	13/01/2004	13/01/2004	RC	100 MM	Piping	Wear	0
E	2/02/2004	3/02/2004	5/02/2004	RC	100 MM	Main	Roots	0
A	15/02/2004	15/02/2004	15/02/2004	CU	50 MM	Piping	Leak	5
D	16/02/2004	17/02/2004	17/02/2004			Piping	Blockage	40

B	18/02/2004	18/02/2004	20/02/2004	RC	100 MM	Piping	Unknown	0
B	23/03/2004	23/03/2004	23/03/2004	RC	220 MM	Piping	Broken	60
A	10/04/2004	10/04/2004	13/04/2004	CU	40 MM	Piping	Broken	1
D	17/04/2004	17/04/2004	17/04/2004	RC	100 MM	Piping	Leak	30
D	6/05/2004	7/05/2004	7/05/2004	RC	100 MM	Piping	Broken	49
H	7/05/2004	7/05/2004	7/05/2004	RC	150 MM	Fitting	Broken	60
F	18/05/2004	18/05/2004	18/05/2004	CU	50 MM	Piping	Leak	1
G	16/07/2004	16/07/2004	16/07/2004	RC	220 MM	Piping	Wear	15
I	19/07/2004	19/07/2004	28/07/2004	S	500 MM	Fitting	Leak	0
I	24/07/2004	24/07/2004	24/07/2004	P	200 MM	Piping	Leak	80
A	27/07/2004	27/07/2004	27/07/2004	AC	150 MM	Piping	Leak	50
B	29/07/2004	29/07/2004	29/07/2004	RC	150 MM	Piping	Broken	50
B	2/08/2004	2/08/2004	2/08/2004	RC	100 MM	Piping	Leak	25
D	16/08/2004	16/08/2004	16/08/2004	RC	100 MM	Piping	Broken	1
C	18/08/2004	18/08/2004	18/08/2004	RC	100 MM	Piping	Broken	60
D	31/08/2004	31/08/2004	31/08/2004			Fitting	Leak	1
F	3/09/2004	3/09/2004	4/09/2004	RC	100 MM	Piping	Unknown	60
B	12/10/2004	12/10/2004	12/10/2004			Piping	Unknown	40

F	16/10/2004	16/10/2004	16/10/2004	RC	100 MM	Piping	Broken	1
B	18/10/2004	18/10/2004	18/10/2004	RC	100 MM	Piping	Broken	1
F	20/10/2004	20/10/2004	20/10/2004	RC	100 MM	Piping	Leak	53
D	24/10/2004	23/10/2004	24/10/2004	RC	100 MM	Piping	Leak	1
C	24/10/2004	24/10/2004	28/10/2004	RC	215 MM	Piping	Leak	0
D	18/11/2004	18/11/2004	18/11/2004	RC	100 MM	Piping	Broken	60
B	26/11/2004	26/11/2004	27/11/2004	RC	100 MM	Piping	Broken	0
D	4/12/2004	4/12/2004	4/12/2004	RC	100 MM	Piping	Unknown	30
A	5/12/2004	5/12/2004	5/12/2004	P	200 MM	Piping	Unknown	150
D	5/12/2004	5/12/2004	5/12/2004	RC	100 MM	Piping	Broken	50
G	6/12/2004	6/12/2004	6/12/2004	RC	100 MM	Piping	Leak	1
2005								
location	Desired Start Date	Actual Start Date	Actual Finish Date	Pipe Material	Pipe Size	Fault Location Desc	Fault Cause Desc	Properties affected
C	10/01/2005	10/01/2005	10/01/2005	RC	100 MM	Piping	Broken	20
C	29/01/2005	29/01/2005	30/01/2005	RC	100 MM	Piping	Broken	100
D	1/02/2005	1/02/2005	1/02/2005	RC	100	Piping	Unknown	1

					MM			
G	14/02/2005	14/02/2005	15/02/2005	RC	305 MM	Piping	Leak	0
D	19/02/2005	19/02/2005	20/02/2005	RC	100 MM	Piping	Broken	1
E	22/02/2005	22/02/2005	22/02/2005	RC	100 MM	Piping	Blockage	0
D	23/02/2005	23/02/2005	24/02/2005	RC	215 MM	Piping	Leak	1
D	10/04/2005	10/04/2005	10/04/2005	RC	150 MM	Piping	Broken	60
G	28/04/2005	28/04/2005	29/04/2005	RC	100 MM	Piping	Unknown	60
F	4/05/2005	4/05/2005	4/05/2005			Piping	Unknown	59
A	5/05/2005	5/05/2005	5/05/2005			Fitting	Wear	50
G	8/05/2005	8/05/2005	9/05/2005			Piping	Unknown	0
B	17/05/2005	17/05/2005	18/05/2005			Piping	Leak	30
D	22/05/2005	22/05/2005	22/05/2005			Piping	Broken	0
B	30/05/2005	30/05/2005	30/05/2005	RC	100 MM	Fitting	Wear	40
A	21/06/2005	21/06/2005	21/06/2005	P	150 MM	Piping	Burst	0
D	22/06/2005	22/06/2005	22/06/2005			Piping	Leak	0
B	24/06/2005	24/06/2005	24/06/2005			Piping	Burst	0
B	1/07/2005	1/07/2005	28/07/2005			Piping	Burst	0
C	2/07/2005	2/07/2005	3/07/2005	RC	100 MM	Piping	Leak	0
B	11/07/2005	11/07/2005	11/07/2005	RC	220 MM	Piping	Burst	80
C	27/07/2005	27/07/2005	27/07/2005	RC	100 MM	Piping	Leak	40

C	27/07/2005	28/07/2005	28/07/2005			Piping	Leak	0
I	31/07/2005	31/07/2005	31/07/2005			Piping	Broken	0
B	31/07/2005	31/07/2005	31/07/2005	RC	100 MM	Piping	Wear	15
B	4/08/2005	4/08/2005	4/08/2005	RC	100 MM	Piping	Wear	50
D	5/08/2005	5/08/2005	5/08/2005			Piping	Unknown	0
C	9/08/2005	9/08/2005	9/08/2005	RC	220 MM	Fitting	Leak	100
F	12/08/2005	12/08/2005	12/08/2005	RC	150 MM	Piping	Wear	150
B	12/08/2005	13/08/2005	14/08/2005	RC	150 MM	Piping	Burst	30
F	14/08/2005	14/08/2005	14/08/2005	RC	150 MM	Piping	Leak	0
B	15/08/2005	15/08/2005	15/08/2005	RC	220 MM	Pipe barrel	Ruptured	0
B	18/08/2005	18/08/2005	18/08/2005			Fitting	Burst	0
B	15/08/2005	15/08/2005	15/08/2005	RC	220 MM	Pipe barrel	Ruptured	0
B	5/09/2005	5/09/2005	5/09/2005			Piping	Burst	0
D	10/09/2005	10/09/2005	10/09/2005	RC	100 MM	Piping	Leak	0
B	20/09/2005	20/09/2005	20/09/2005			Piping	Burst	0
I	22/09/2005	23/09/2005	23/09/2005			Fitting	Burst	0
D	23/09/2005	23/09/2005	23/09/2005	RC	100 MM	Piping	Burst	60
D	23/09/2005	23/09/2005	23/09/2005	RC	100 MM	Piping	Burst	0
C	1/10/2005	1/10/2005	1/10/2005			Piping	Leak	0
H	8/10/2005	8/10/2005	15/10/2005	RC	100	Piping	Broken	1

					MM			
E	9/10/2005	9/10/2005	9/10/2005	RC	150 MM	Piping	Wear	40
A	15/10/2005	15/10/2005	15/10/2005	AC	100 MM	Piping	Leak	50
C	17/10/2005	17/10/2005	17/10/2005	RC	220 MM	Piping	Broken	0
G	17/10/2005	17/10/2005	18/10/2005	RC	100 MM	Piping	Leak	1
G	18/10/2005	18/10/2005	18/10/2005	CU	40 MM	Piping	Burst	0
G	24/10/2005	24/10/2005	24/10/2005	RC	220 MM	Piping	Broken	50
D	25/10/2005	24/10/2005	25/10/2005	RC	100 MM	Piping	Burst	100
B	29/10/2005			RC	100 MM	Piping	Leak	0
D	3/11/2005	3/11/2005	3/11/2005	RC	100 MM	Piping	Unknown	0
D	4/11/2005	4/11/2005	7/11/2005			Piping	Unknown	0
I	5/11/2005	5/11/2005	5/11/2005			Piping	Leak	30
A	14/11/2005	14/11/2005	22/11/2005	AC	100 MM	Piping	Leak	0
A	21/11/2005	21/11/2005	21/11/2005	MDPE	100 MM	Piping	Leak	10
A	22/11/2005	22/11/2005	22/11/2005	AC	100 MM	Piping	Leak	100
A	2/12/2005	3/12/2005	3/12/2005			Piping	Burst	0
B	15/12/2005	15/12/2005	16/12/2005	CU	50 MM	Piping	Unknown	12
B	18/12/2005	18/12/2005	18/12/2005			Piping	Unknown	0
D	19/12/2005	19/12/2005	20/12/2005	RC	100 MM	Piping	Leak	50

B	20/12/2005	20/12/2005	20/12/2005	RC	220 MM	Piping	Leak	1
2006								
location	Desired Start Date	Actual Start Date	Actual Finish Date	Pipe Material	Pipe Size	Fault Location Desc	Fault Cause Desc	Properties affected
G	5/01/2006	5/01/2006	16/01/2006	P	150 MM	Piping	Corrosion	20
I	6/01/2006	6/01/2006	6/01/2006	P	100 MM	Piping	Leak	0
G	16/01/2006	16/01/2006	17/01/2006	DI	200 MM	Piping	Burst	1
B	24/01/2006	24/01/2006	24/01/2006			Piping	Leak	50
G	25/01/2006	25/01/2006	25/01/2006	RC	100 MM	Piping	Leak	100
A	18/02/2006	18/02/2006	18/02/2006	P	100 MM	Piping	Leak	80
B	20/02/2006	20/02/2006	20/02/2006	RC	150 MM	Piping	Burst	20
A	1/03/2006	1/03/2006	1/03/2006	P	100 MM	Piping	Broken	100
A	1/03/2006	1/03/2006	1/03/2006	P	100 MM	Piping	Burst	0
B	4/03/2006	4/03/2006	4/03/2006	RC	100 MM	Fitting	Unknown	55
A	29/03/2006	29/03/2006	30/03/2006	AC	100 MM	Piping	Corrosion	45
G	2/04/2006	2/04/2006	2/04/2006	RC	100 MM	Piping	Leak	1
B	28/04/2006			RC	220	Fitting	Burst	25

					MM			
I	11/05/2006	10/05/2006	11/05/2006	MDPE	63 MM	Piping	Leak	40
D	25/05/2006	25/05/2006	29/05/2006			Piping	Burst	60
B	5/06/2006	5/06/2006	16/06/2006	RC	220 MM	Piping	Burst	70
C	8/06/2006	8/06/2006	8/06/2006	RC	100 MM	Piping	Burst	55
B	20/06/2006	20/06/2006	20/06/2006			Joint	Burst	50
D	4/07/2006	4/07/2006	4/07/2006	RC	100 MM	Pipe barrel	Perforation / pitting	40
G	8/07/2006	8/07/2006	8/07/2006	CU	50 MM	Pipe barrel	Perforation / pitting	0
A	21/07/2006	21/07/2006	21/07/2006			Pipe barrel	Ruptured	150
I	23/07/2006	23/07/2006	23/07/2006	P	100 MM	Pipe barrel	Wear	30
D	26/07/2006	26/07/2006	27/07/2006	RC	100 MM	Pipe barrel	Perforation / pitting	1
D	7/08/2006	7/08/2006	8/08/2006	RC	100 MM	Pipe barrel	Perforation / pitting	0
J	8/08/2006	8/08/2006	8/08/2006	P	100 MM	Pipe barrel	Perforation / pitting	1
B	10/09/2006	10/09/2006	20/09/2006	RC	150 MM	Pipe barrel	Perforation / pitting	80
B	26/09/2006	26/09/2006	3/10/2006	RC	150 MM	Pipe barrel	Perforation / pitting	1
D	2/10/2006	2/10/2006	2/10/2006	RC	100 MM	Pipe barrel	Perforation / pitting	1
C	3/10/2006	3/10/2006	3/10/2006	S	100 MM	Pipe barrel	Ring/gasket failure	1
D	17/10/2006	17/10/2006	17/10/2006	RC	100 MM	Joint	Perforation / pitting	60
D	29/10/2006	29/10/2006	29/10/2006	RC	100 MM	Pipe barrel	Perforation / pitting	1

I	29/10/2006			P	100 MM	Tapping	Ruptured	0
I	29/10/2006			P	100 MM	Joint	Roots	0
B	4/11/2006	4/11/2006	5/11/2006	RC	150 MM	Pipe barrel	Perforation / pitting	0
B	9/11/2006	9/11/2006	9/11/2006	RC	100 MM	Pipe barrel	Ring/gasket failure	10
B	18/11/2006	18/11/2006	19/11/2006	RC	220 MM	Pipe barrel	Perforation / pitting	1
C	28/11/2006	28/11/2006	28/11/2006	RC	220 MM	Other	Other	0
C	3/12/2006	3/12/2006	5/12/2006			Pipe barrel	Perforation / pitting	0
C	4/12/2006	4/12/2006	5/12/2006			Pipe barrel	Perforation / pitting	0
E	4/12/2006	4/12/2006	4/12/2006	RC	100 MM	Pipe barrel	Perforation / pitting	0
E	13/12/2006	13/12/2006	13/12/2006	MSCL	100 MM	Pipe barrel	Perforation / pitting	0
D	22/12/2006	23/12/2006	23/12/2006	RC	100 MM	Bend / Tee / Reducer	Perforation / pitting	1
D	23/12/2006	23/12/2006	24/12/2006	RC	100 MM	Joint	Ruptured	1
F	25/12/2006	25/12/2006	25/12/2006			Joint	Ring/gasket failure	100
F	27/12/2006	28/12/2006	28/12/2006			Joint	Roots	0
A	28/12/2006	28/12/2006	28/12/2006	P	100 MM	Pipe barrel	Perforation / pitting	150
2007								
locati on	Desired Start Date	Actual Finish Date	Actual Finish Date	Pipe Material	Pipe Size	Fault Location Desc	Fault Cause Desc	Properties affected

E	5/01/2007	5/01/2007	5/01/2007	RC	150 MM	Pipe barrel	Perforation / pitting	0
A	16/01/2007	19/01/2007	19/01/2007	HDPE	63 MM	Pipe barrel	Perforation / pitting	0
E	17/01/2007	17/01/2007	17/01/2007	RC	150 MM	Pipe barrel	Perforation / pitting	1
D	24/01/2007	18/02/2007	18/02/2007	RC	100 MM	Joint	Roots	35
C	27/01/2007	27/01/2007	27/01/2007	RC	100 MM	Pipe repair fitting	Cracked around	0
A	31/01/2007	5/02/2007	5/02/2007	CU	50 MM	Pipe barrel	Ruptured	85
F	10/02/2007	20/02/2007	20/02/2007	RC	220 MM	Pipe barrel	Perforation / pitting	50
D	13/02/2007	13/02/2007	13/02/2007	RC	100 MM	Pipe barrel	Perforation / pitting	20
B	15/02/2007	16/02/2007	16/02/2007	RC	220 MM	Pipe barrel	Cracked around	0
F	17/02/2007	17/02/2007	17/02/2007	RC	100 MM	Pipe barrel	Perforation / pitting	60
A	2/03/2007	2/03/2007	2/03/2007	AC	100 MM	Other	Other	0
D	18/03/2007	18/03/2007	18/03/2007	RC	100 MM	Pipe barrel	Ruptured	1
B	22/03/2007	24/05/2007	24/05/2007	RC	100 MM	Pipe barrel	Perforation / pitting	1
D	26/03/2007	26/03/2007	26/03/2007	RC	100 MM	Bend / Tee / Reducer	Perforation / pitting	0
F	30/03/2007	30/03/2007	30/03/2007	RC	100 MM	Pipe barrel	Roots	30
B	13/04/2007	13/04/2007	13/04/2007	RC	220 MM	Pipe barrel	Impact	33
B	21/04/2007	21/04/2007	21/04/2007	RC	100	Pipe barrel	Perforation / pitting	0

					MM			
A	23/04/2007	23/04/2007	23/04/2007	P	100 MM	Pipe barrel	Perforation / pitting	50
B	2/06/2007	3/06/2007	3/06/2007	CU	50 MM	Pipe barrel	Perforation / pitting	100
D	11/07/2007	12/07/2007	12/07/2007	RC	100 MM	Bend / Tee / Reducer	Roots	20
G	6/08/2007	6/08/2007	6/08/2007	RC	100 MM	Joint	Perforation / pitting	25
G	8/08/2007	8/08/2007	8/08/2007	RC	150 MM	Pipe barrel	Ruptured	50
D	16/08/2007	16/08/2007	16/08/2007	RC	100 MM	Pipe barrel	Other	25
D	22/08/2007	22/08/2007	22/08/2007	RC	100 MM	Pipe barrel	Ruptured	50
F	26/08/2007	26/08/2007	26/08/2007	RC	100 MM	Pipe barrel	Roots	40
D	1/09/2007	5/09/2007	5/09/2007	RC	220 MM	Pipe barrel	Other	100
B	11/09/2007	12/09/2007	12/09/2007	RC	100 MM	Pipe barrel	Perforation / pitting	60
B	15/09/2007	15/09/2007	15/09/2007	RC	220 MM	Joint	Ring/gasket failure	70
A	16/09/2007	16/09/2007	16/09/2007	CU	50 MM	Pipe barrel	Perforation / pitting	50
D	22/09/2007	22/09/2007	22/09/2007	RC	100 MM	Pipe barrel	Perforation / pitting	40
B	22/09/2007	23/09/2007	23/09/2007	RC	220 MM	Pipe barrel	Other	50
F	23/09/2007	23/09/2007	23/09/2007	RC	220 MM	Pipe barrel	Other	60
C	24/09/2007	24/09/2007	24/09/2007	RC	100 MM	Pipe barrel	Other	30
A	4/10/2007	15/11/2007	15/11/2007	P	150	Pipe barrel	Perforation / pitting	40

					MM			
B	5/10/2007	6/10/2007	6/10/2007	RC	100 MM	Pipe barrel	Perforation / pitting	30
D	6/10/2007	6/10/2007	6/10/2007	RC	100 MM	Pipe barrel	Ruptured	30
A	8/10/2007	9/10/2007	9/10/2007	CU	50 MM	Pipe barrel	Ruptured	15
D	10/10/2007	11/10/2007	11/10/2007	RC	100 MM	Pipe barrel	Ruptured	40
A	19/10/2007	22/10/2007	22/10/2007	P	100 MM	Pipe barrel	Perforation / pitting	50
F	22/10/2007	22/10/2007	22/10/2007	RC	220 MM	Pipe barrel	Perforation / pitting	85
J	22/10/2007	22/10/2007	22/10/2007	MDPE	63 MM	Pipe barrel	Perforation / pitting	1
A	24/10/2007	31/10/2007	31/10/2007	AC	100 MM	Pipe barrel	Ruptured	0
A	12/11/2007	13/11/2007	13/11/2007	P	150 MM	Pipe barrel	Ruptured	60
I	14/11/2007	15/11/2007	15/11/2007	RC	100 MM	Pipe barrel	Perforation / pitting	30
J	19/11/2007	19/11/2007	19/11/2007	P	150 MM	Pipe barrel	Perforation / pitting	0
H	24/11/2007	25/11/2007	25/11/2007	RC	100 MM	Pipe barrel	Ruptured	1
C	25/11/2007	6/12/2007	6/12/2007	RC	100 MM	Pipe barrel	Roots	50
B	2/12/2007	2/12/2007	2/12/2007	RC	150 MM	Pipe barrel	Perforation / pitting	20
G	4/12/2007	4/12/2007	4/12/2007	CU	50 MM	Bend / Tee / Reducer	Other	0
A	4/12/2007	5/12/2007	5/12/2007	P	150 MM	Pipe barrel	Perforation / pitting	40
D	11/12/2007	11/12/2007	11/12/2007	RC	100 MM	Pipe barrel	Perforation / pitting	30

D	12/12/2007	13/12/2007	13/12/2007	RC	100 MM	Pipe barrel	Other	30
B	18/12/2007	18/12/2007	18/12/2007	RC	220 MM	Pipe barrel	Perforation / pitting	30
2008								
location	Desired Start Date		Actual Finish Date	Pipe Material	Pipe Size	Fault Location Desc	Fault Cause Desc	Properties affected
B	4/01/2008		4/01/2008	RC	220 MM	Bend / Tee / Reducer	PERFORATION / PITTING	50
C	5/01/2008		5/01/2008	RC	220 MM	Pipe barrel	PERFORATION / PITTING	50
C	6/01/2008		8/01/2008	RC	220 MM	Pipe barrel	PERFORATION / PITTING	35
D	10/01/2008		10/01/2008	RC	100 MM	Pipe barrel	PERFORATION / PITTING	40
F	11/01/2008		11/01/2008	RC	100 MM	Pipe barrel	PERFORATION / PITTING	30
B	14/01/2008		15/01/2008	RC	150 MM	Pipe barrel	RING/GASKET FAILURE	15
D	19/01/2008		20/01/2008	RC	100 MM	Pipe barrel	ROOTS	0
G	25/01/2008		25/01/2008	MDPE	63 MM	Pipe barrel	PERFORATION / PITTING	0
G	25/01/2008		25/01/2008	RC	100 MM	Joint	PERFORATION / PITTING	30
B	27/01/2008		28/01/2008	RC	220 MM	Pipe barrel	PERFORATION / PITTING	40
B	29/01/2008		29/01/2008	RC	220 MM	Pipe barrel	PERFORATION / PITTING	30
B	29/01/2008		29/01/2008	RC	220 MM	Pipe barrel	PERFORATION / PITTING	0

G	29/01/2008		5/02/2008	RC	100 MM	Pipe barrel	PERFORATION / PITTING	40
B	20/02/2008		21/02/2008	MDPE	63 MM	Pipe barrel	PERFORATION / PITTING	10
C	26/02/2008		27/02/2008	RC	150 MM	Pipe barrel	RUPTURED	0
G	26/02/2008		28/02/2008	RC	100 MM	Pipe barrel	OTHER	40
A	7/03/2008		8/03/2008	CU	50 MM	Pipe barrel	RUPTURED	10
D	7/03/2008		8/03/2008	RC	100 MM	Pipe barrel	RUPTURED	40
D	14/03/2008		14/03/2008	RC	100 MM	Pipe barrel	RING/GASKET FAILURE	75
D	17/03/2008		17/03/2008	RC	100 MM	Joint	PERFORATION / PITTING	35
F	28/03/2008		28/03/2008	RC	220 MM	Pipe barrel	RUPTURED	80
C	6/04/2008		6/04/2008	RC	150 MM	Pipe barrel	OTHER	1
D	7/04/2008		7/04/2008	RC	100 MM	Pipe barrel	PERFORATION / PITTING	1
J	7/05/2008		7/05/2008	P	100 MM	Pipe barrel	PERFORATION / PITTING	50
C	14/06/2008		15/06/2008	RC	100 MM	Pipe barrel	RING/GASKET FAILURE	45
A	16/06/2008		16/06/2008	AC	100 MM	Pipe barrel	ROOTS	50
A	29/06/2008		29/06/2008	AC	100 MM	Pipe barrel	RUPTURED	0
C	07/07/2008		07/07/2008	CU	50 MM	Weld	ROOTS	7
C	19/07/2008		19/07/2008	RC	100 MM	Pipe barrel	CRACKED AROUND	50
A	31/07/2008		31/07/2008	AC	100	Pipe barrel	RUPTURED	40

					MM			
C	04/08/2008		05/08/2008	RC	100 MM	Pipe barrel	RING/GASKET FAILURE	45
D	13/08/2008		13/08/2008	RC	100 MM	Pipe barrel	PERFORATION / PITTING	40
I	18/08/2008		18/08/2008	CU	40 MM	Pipe barrel	RUPTURED	0
B	18/08/2008		19/08/2008	RC	150 MM	Joint	RING/GASKET FAILURE	40
D	26/08/2008		27/08/2008			Pipe barrel	RUPTURED	0
D	28/08/2008		13/05/2009	RC		Pipe barrel	CRACKED AROUND	40
E	28/08/2008		28/08/2008	RC	100 MM	Pipe barrel	CRAKED ALONG	0
C	03/09/2008		03/09/2008	MDPE	63 MM	Weld	OTHER	20
B	04/09/2008		08/09/2008	RC	220 MM	Pipe barrel	PERFORATION / PITTING	50
C	12/09/2008		12/09/2008	RC	150 MM	Pipe barrel	CRACKED AROUND	0
A	21/09/2008		22/09/2008			Other	OTHER	0
B	16/10/2008		18/10/2008	RC	100 MM	Pipe barrel	CRACKED AROUND	40
D	23/10/2008		25/10/2008	CU	50 MM	Bend / Tee / Reducer	OTHER	0
D	28/10/2008		07/11/2008	RC	150 MM	Pipe barrel	CRAKED ALONG	50
F	31/10/2008		31/10/2008	RC	220 MM	Pipe barrel	RUPTURED	1
H	10/11/2008		10/11/2008	RC	220 MM	Joint	RUPTURED	40
G	16/11/2008		17/11/2008	RC	100 MM	Joint	RING/GASKET FAILURE	30
A	18/11/2008		19/11/2008	P	100 MM	Tapping	RING/GASKET FAILURE	0

A	23/11/2008		23/11/2008	AC	100 MM	Pipe barrel	RUPTURED	50
D	03/12/2008		03/12/2008	RC	100 MM	Weld	RUPTURED	0
D	10/12/2008		10/12/2008	RC	100 MM	Pipe barrel	CRACKED AROUND	40
B	11/12/2008		16/12/2008	RC	100 MM	Pipe barrel	CRACKED AROUND	0
A	17/12/2008		17/12/2008	P	100 MM	Other	OTHER	0
A	17/12/2008		17/12/2008	P	100 MM	Other	OTHER	0
G	20/12/2008		06/01/2009	RC	220 MM	Pipe barrel	PERFORATION / PITTING	0
D	24/12/2008		24/12/2008	RC	100 MM	Pipe barrel	CRAKED ALONG	0
D	24/12/2008		24/12/2008	RC	100 MM	Pipe barrel	RUPTURED	40
D	28/12/2008		29/12/2008	P	100 MM	Tapping	OTHER	60
D	29/12/2008		29/12/2008			Pipe barrel	IMPACT	0

APPENDIX B VALIDATION OF HYDRAULIC MODEL FOR ZONE M

Figures B.1 to B.5 show the validation of five pipes (pipes 4 to 8). The locations of these pipes are illustrated in Figure 7.2, all around Zone M system.

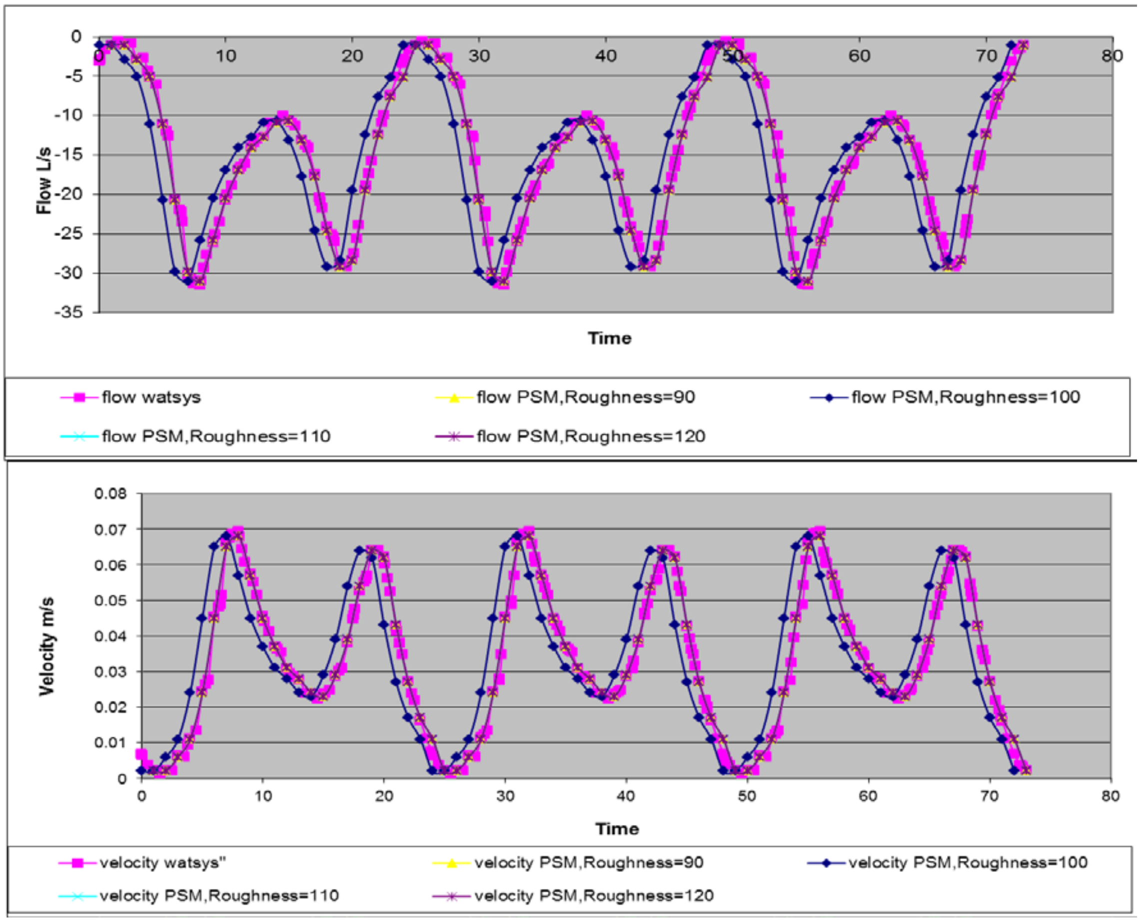


Figure B.1: Flow and velocity calibrations of randomly selected Link 4.

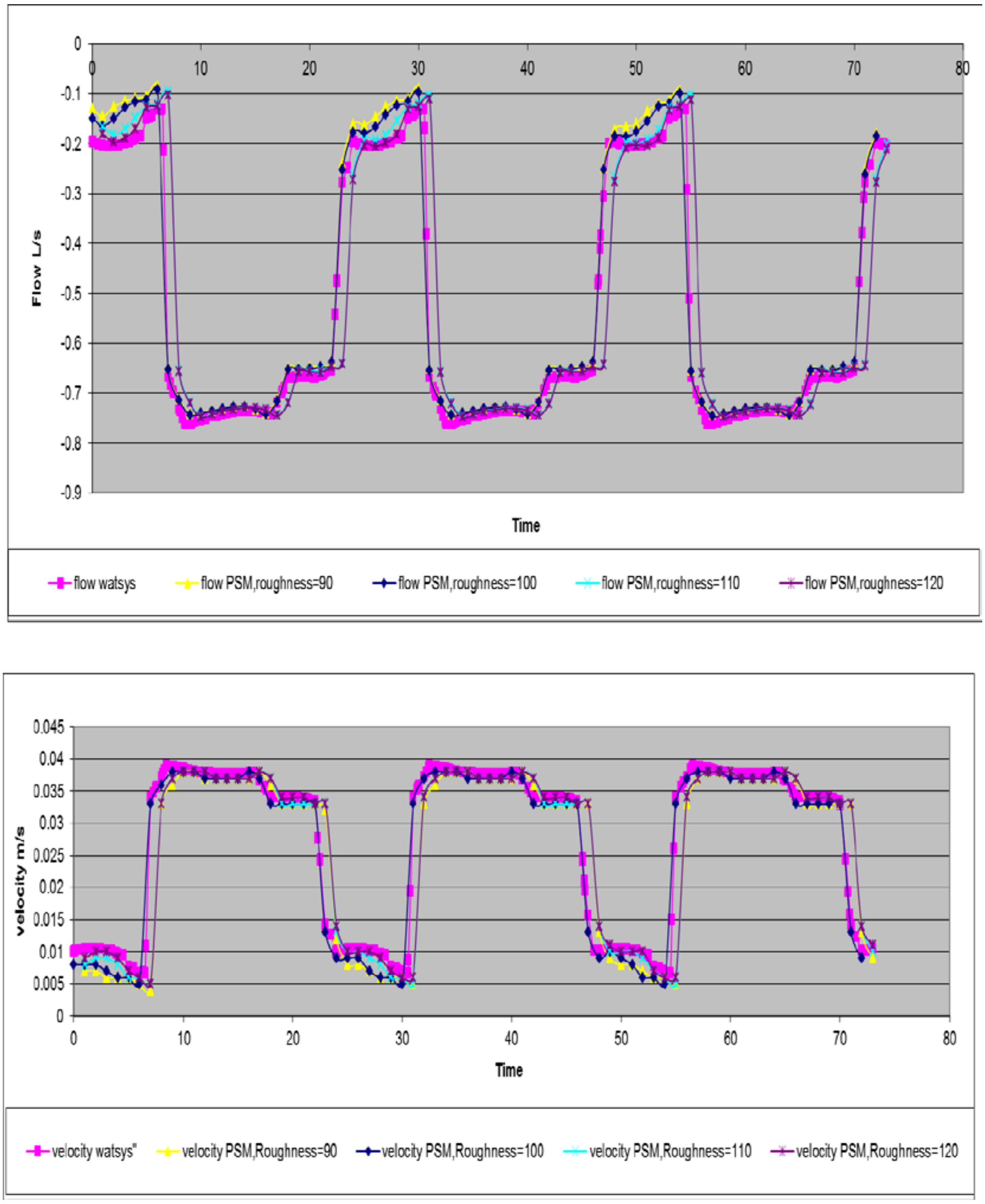
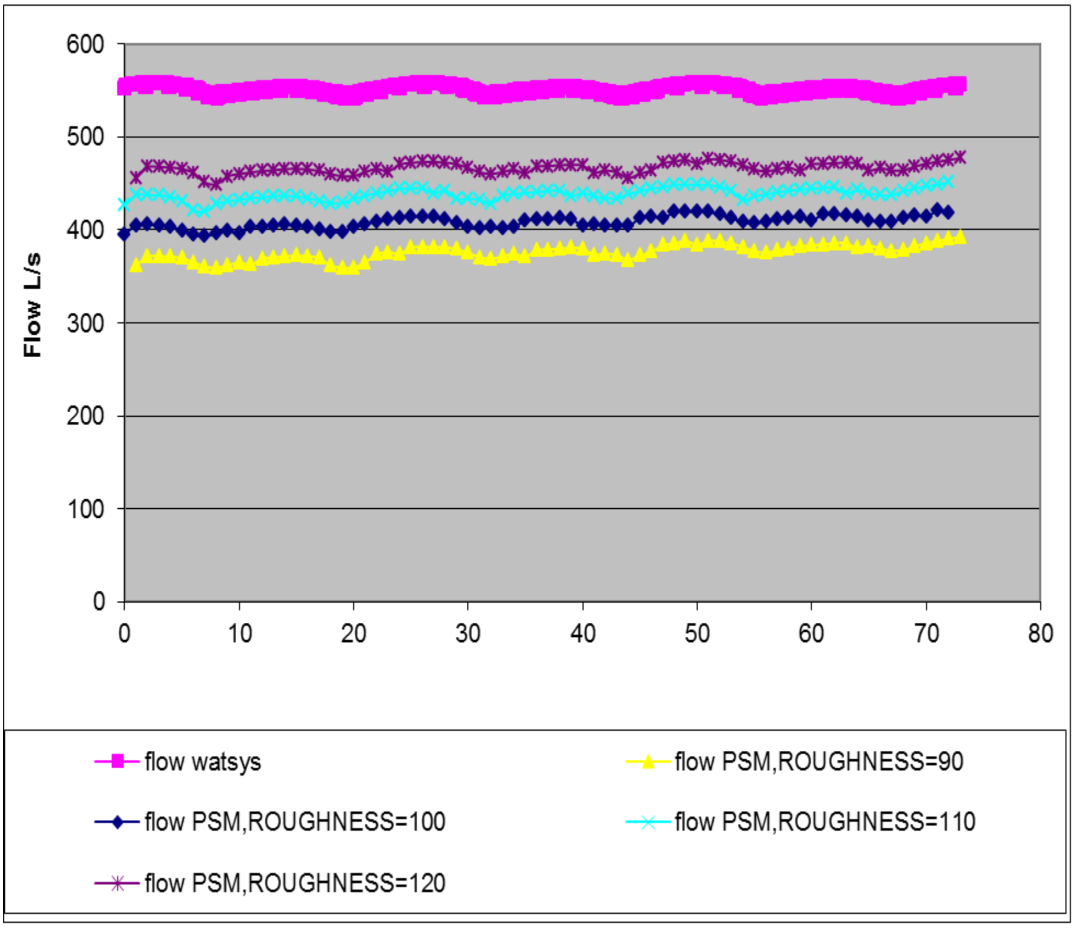


Figure B.2: Flow and velocity calibrations of randomly selected Link 5.



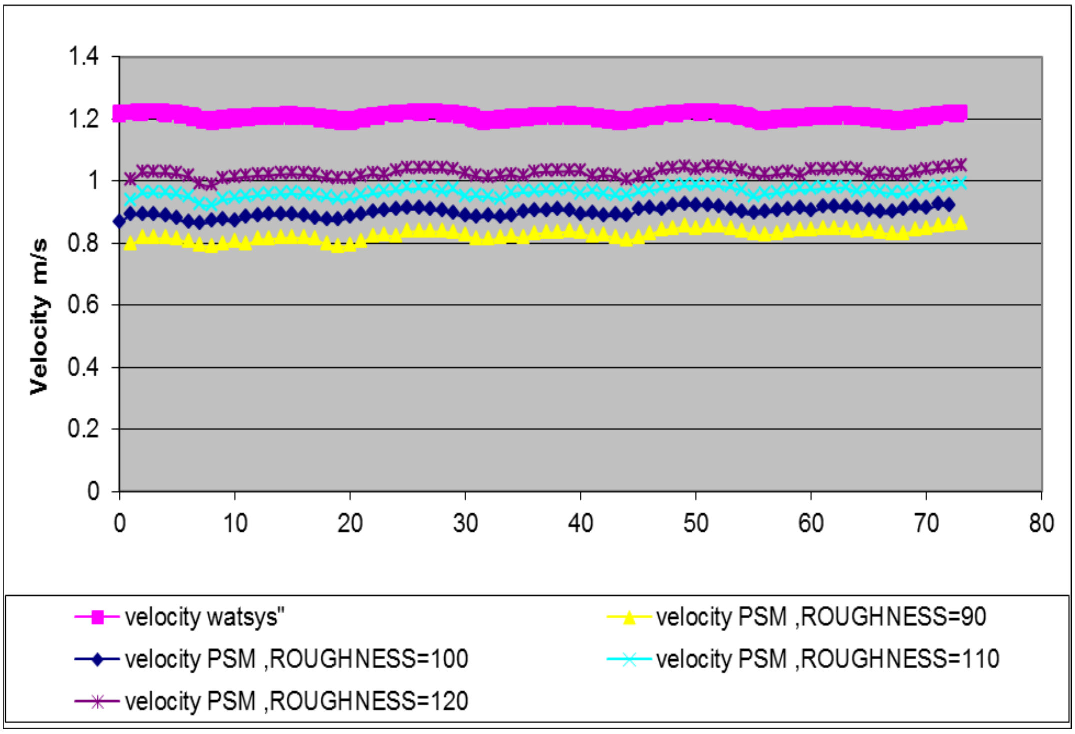
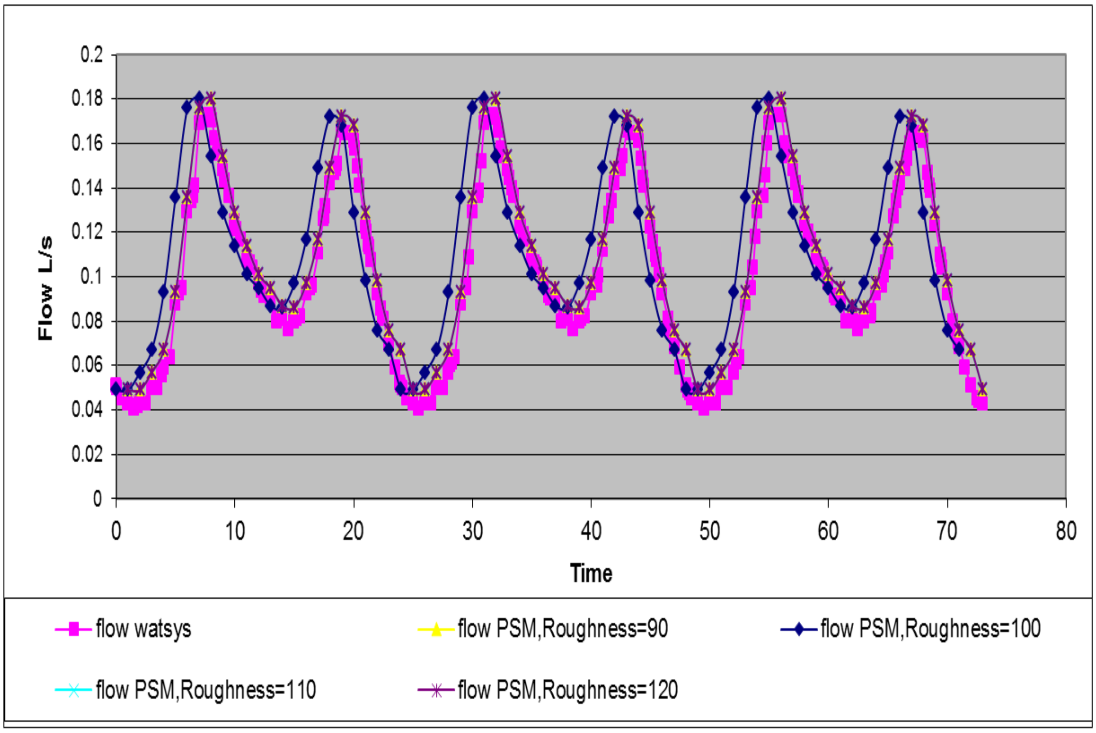


Figure B.3: Flow and velocity calibrations of randomly selected Link 6.



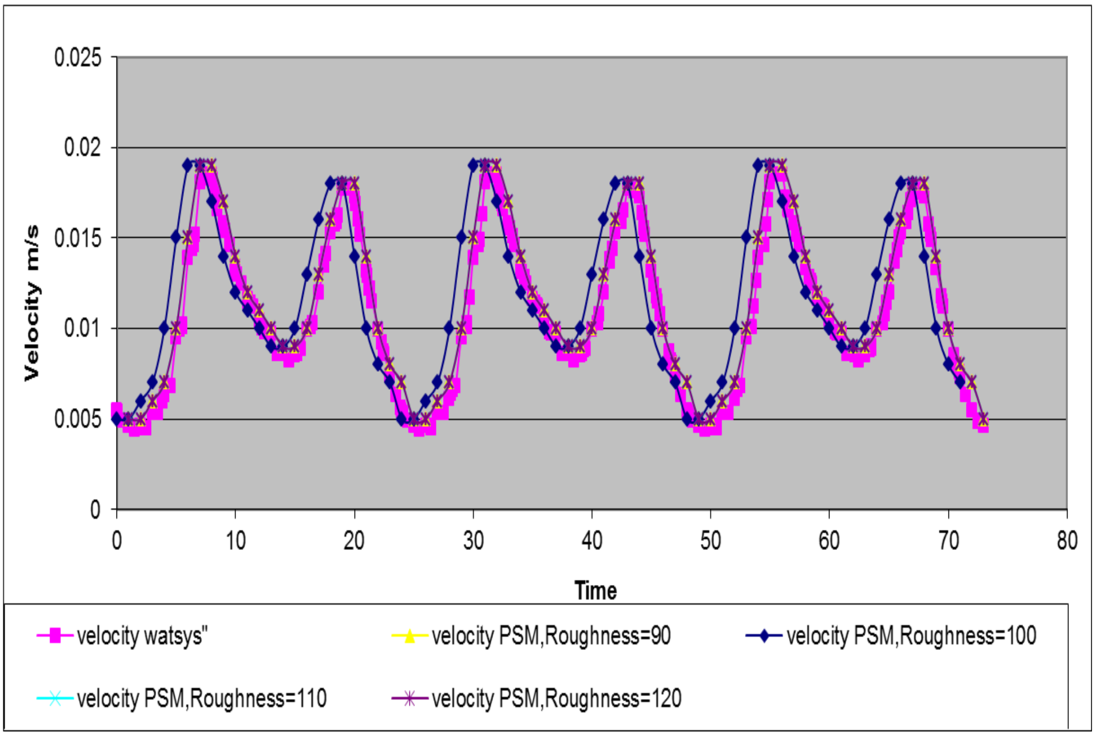


Figure B.4: Flow and velocity calibrations of randomly selected Link 7.

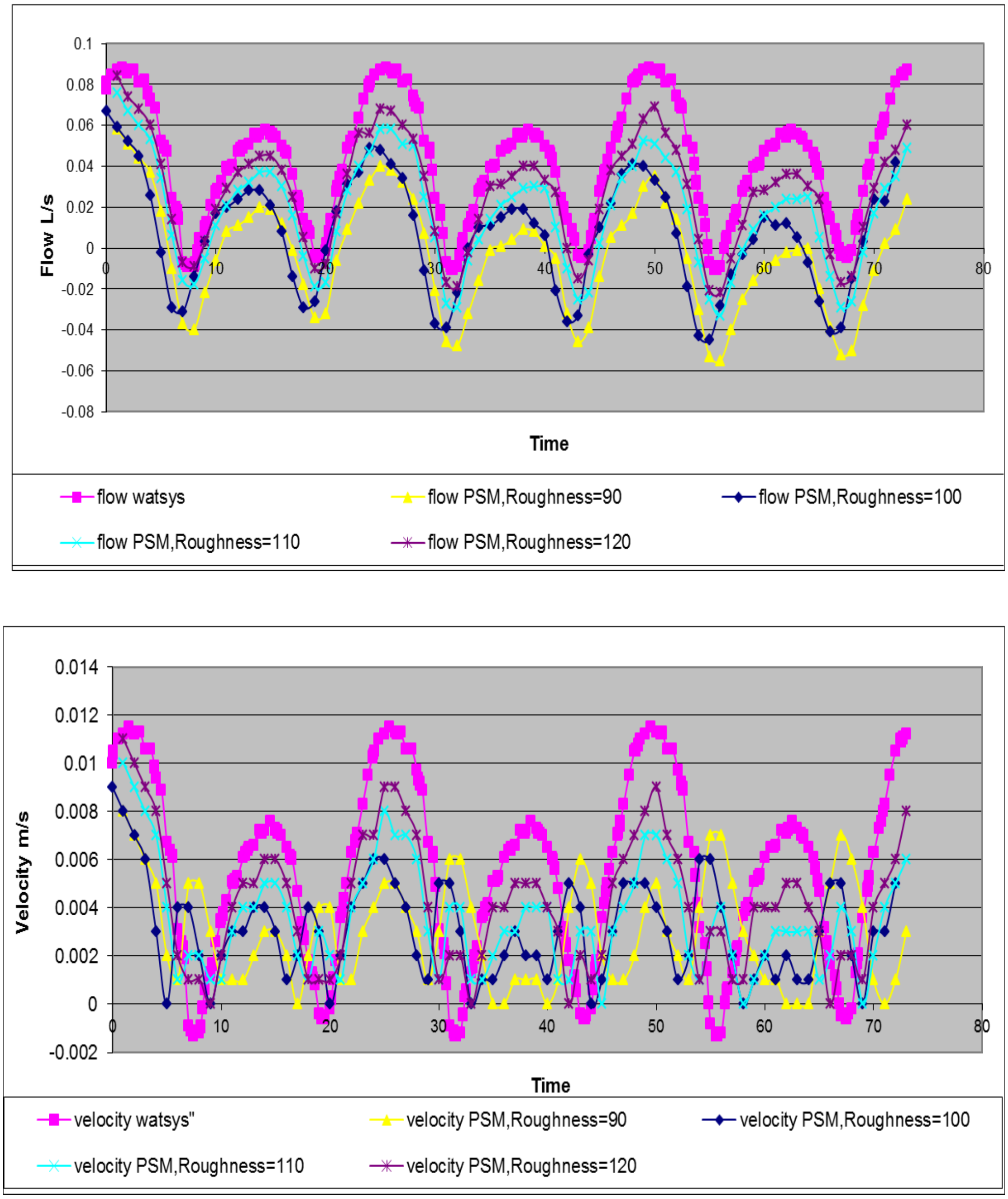


Figure B.5: Flow and velocity calibrations of randomly selected Link 8.

APPENDIX C EPANET-PSM RESULTS

EPAnet-PSM was run for a time period of over one week (168 hrs). Using one reservoir (Reservoir 2), the "source sediment quality" was nominally entered as 1000 mg/l for two days. This was achieved by simulating a 1000 mg/l sediment pattern for 2 days and zero for the rest of the time of the simulation. However, the velocities pattern did not match at all sites, especially sites Mi1 and Mi2 even before fieldwork started, as illustrated in Figures 9.24, 9.25 and 9.26. All comparisons were undertaken using 0.2 m/s and 0.4 m/s resuspension velocity with fieldwork results. The analysis of all results with 0.4 m/s resuspension velocity is illustrated in Figures C.1 to C.17.

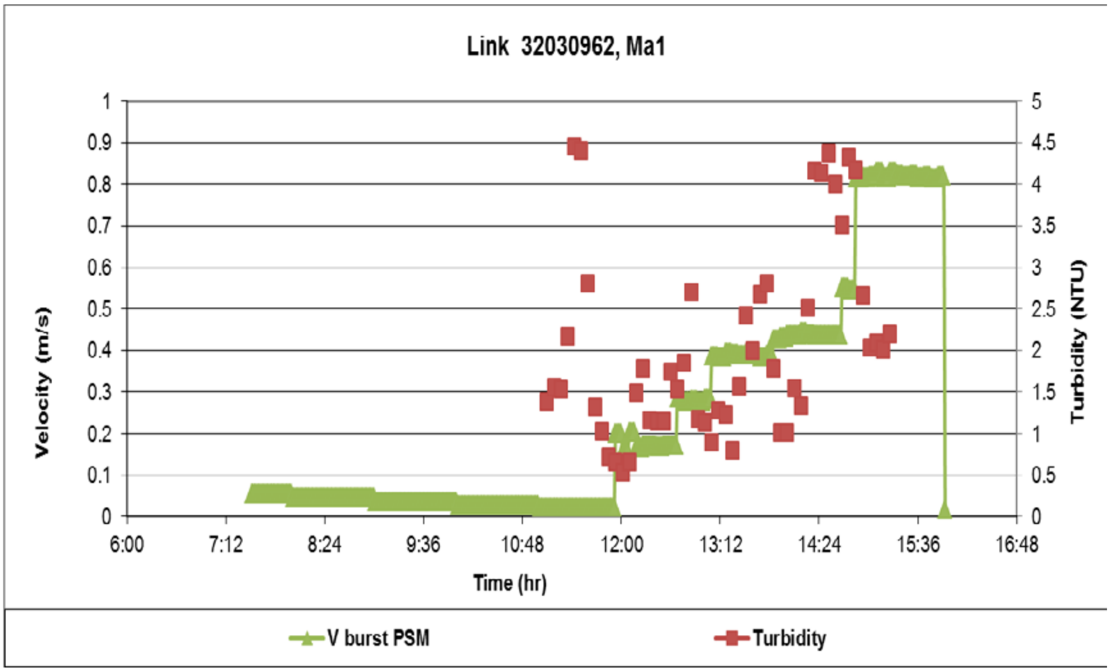


Figure C.1: EPAnet-PSM prediction for the velocity in a burst pipe situation in the Ma1 pipe compared with fieldwork turbidity results.

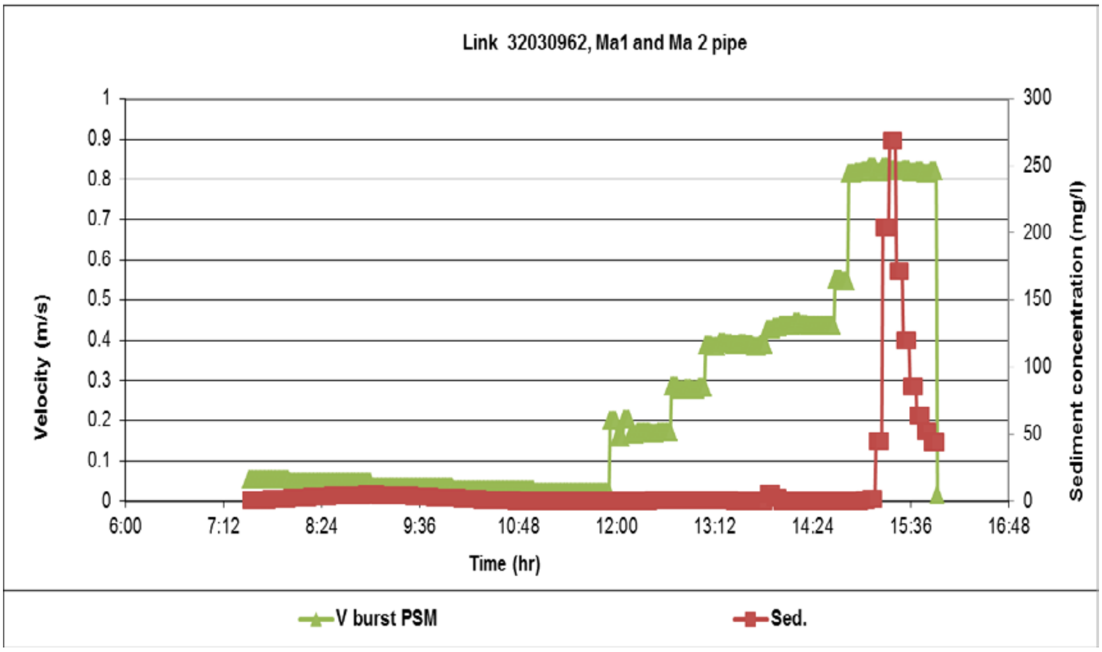


Figure C.2: EPAnet-PSM prediction for the velocity and sediment concentration in the major sites (Ma1 and Ma2) pipe using resuspension velocity equal to 0.4 m/s.

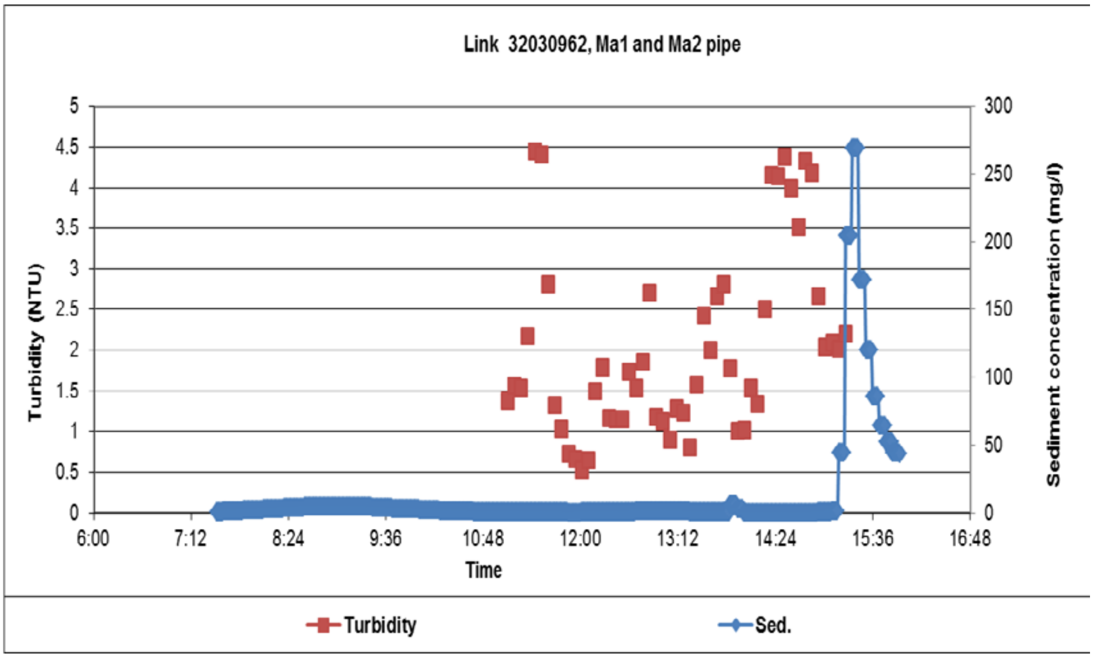


Figure C.3: EPAnet-PSM prediction for the sediment concentration in the major sites (Ma1 and Ma2) pipe using resuspension velocity equal to 0.4 m/s, compared with fieldwork turbidity results.

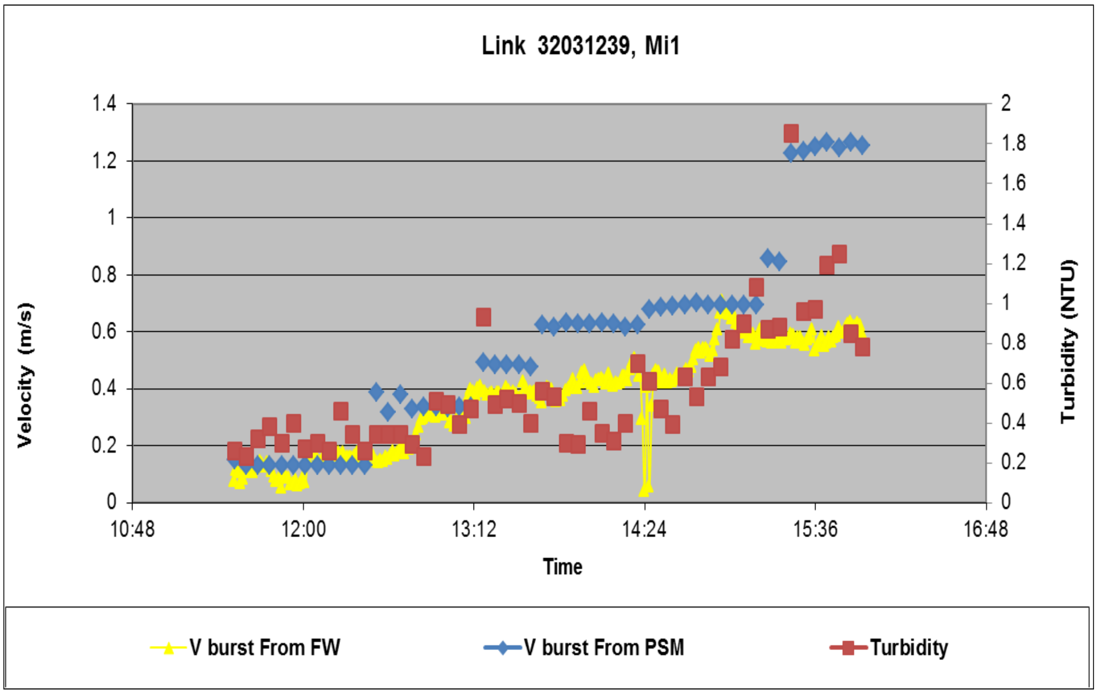


Figure C.4: EPAnet-PSM prediction for the velocity in a burst pipe situation in the Mi1 pipe compared with fieldwork turbidity and velocity results.

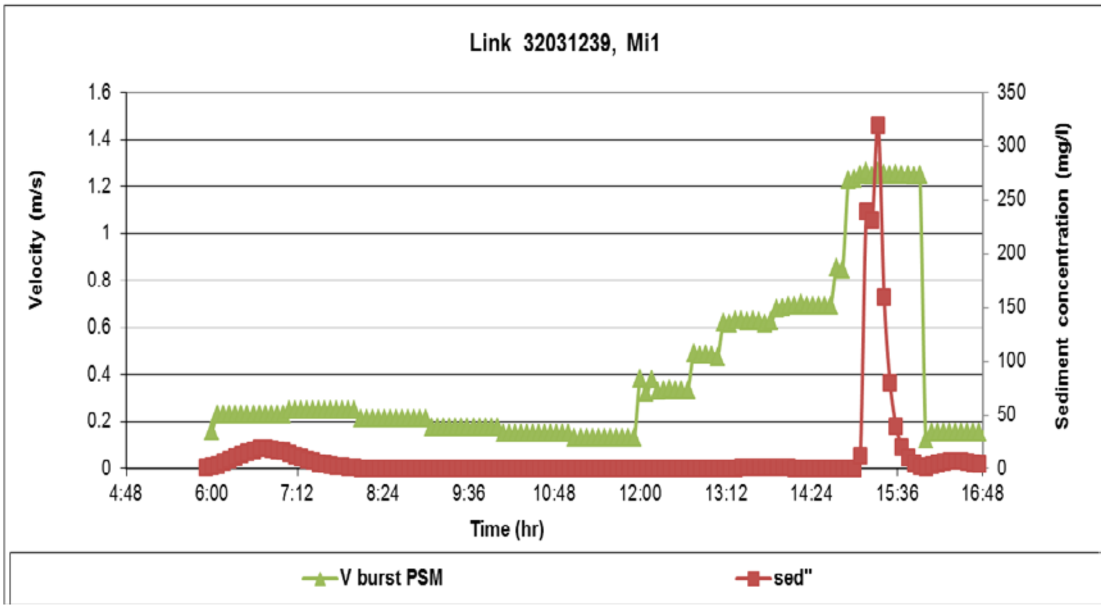


Figure C.5: EPAnet-PSM prediction for the velocity and sediment concentration in the Mi1 pipe using resuspension velocity equal to 0.4 m/s.

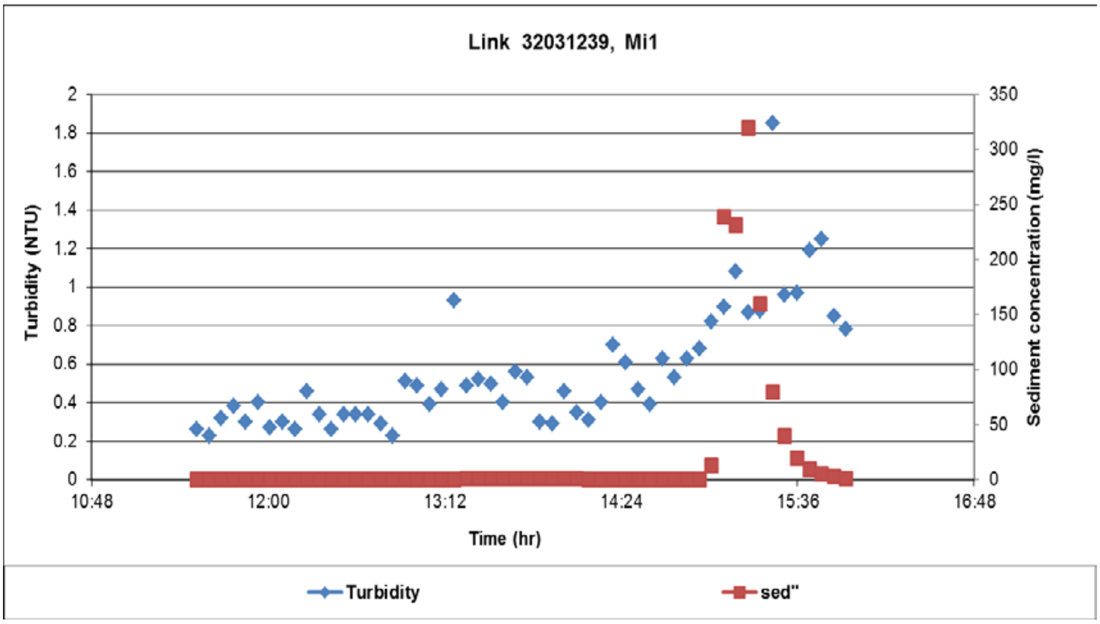


Figure C.6: EPAnet-PSM prediction for the sediment concentration in the Mi1 pipe using resuspension velocity equal to 0.4 m/s, compared with fieldwork turbidity results.

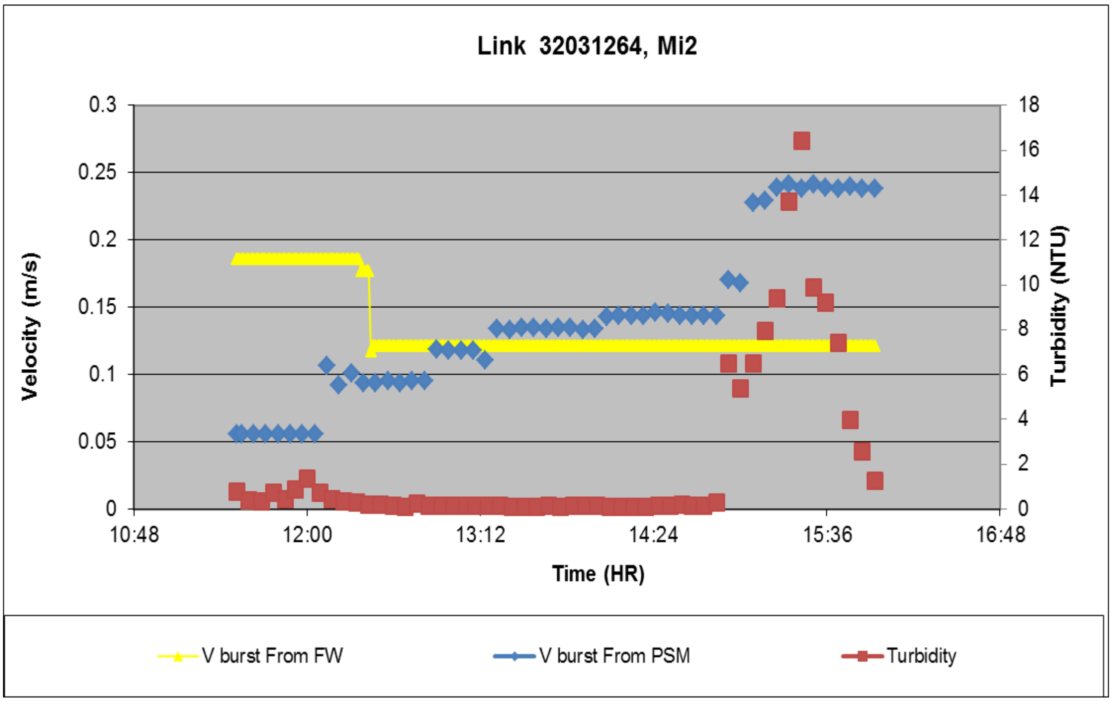


Figure C.7: EPAnet-PSM prediction for the velocity at burst pipe situation in the pipe Mi2 compared with fieldwork turbidity and velocity results.

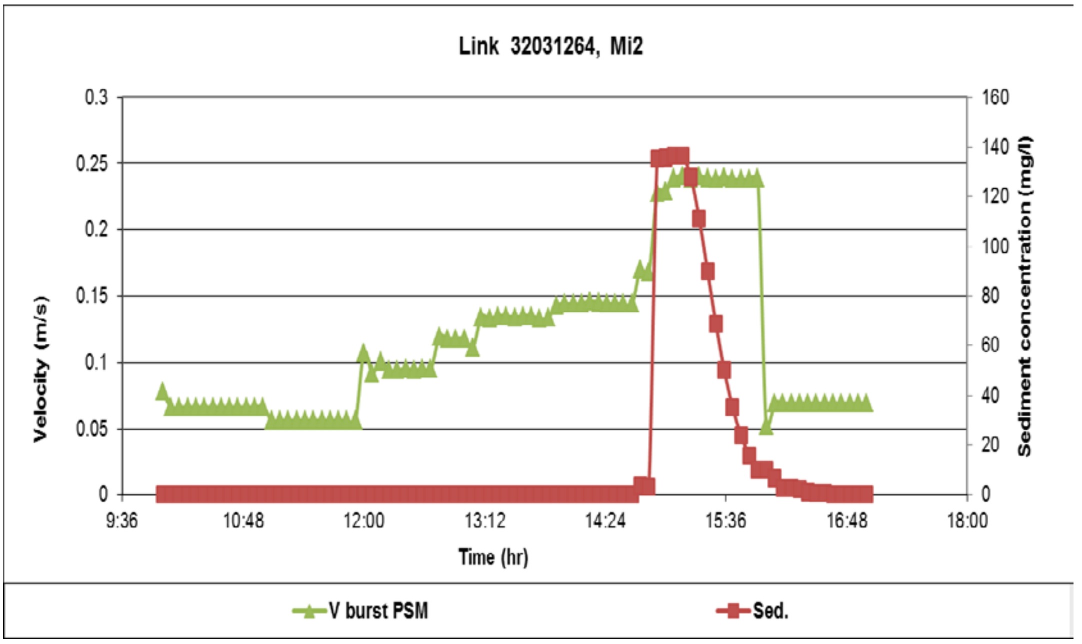


Figure C.8: EPAnet-PSM prediction for the velocity and sediment concentration in the Mi2 pipe using resuspension velocity equal to 0.4 m/s.

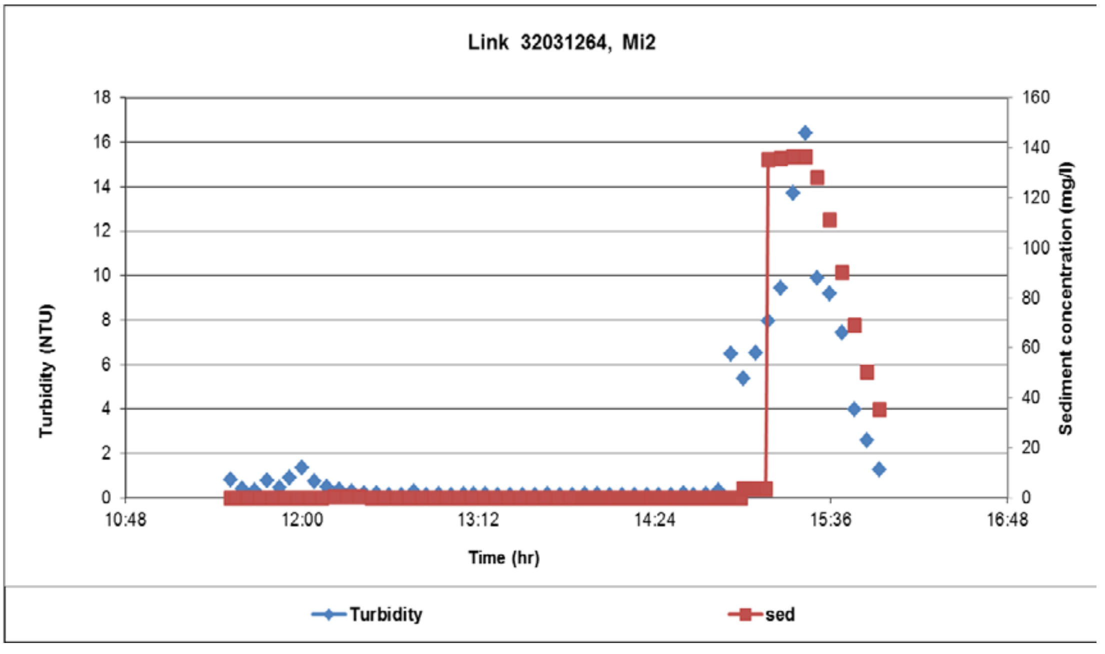


Figure C.9: EPAnet-PSM prediction for sediment concentration in the Mi2 pipe using resuspension velocity equal to 0.4 m/s, compared with fieldwork turbidity results.

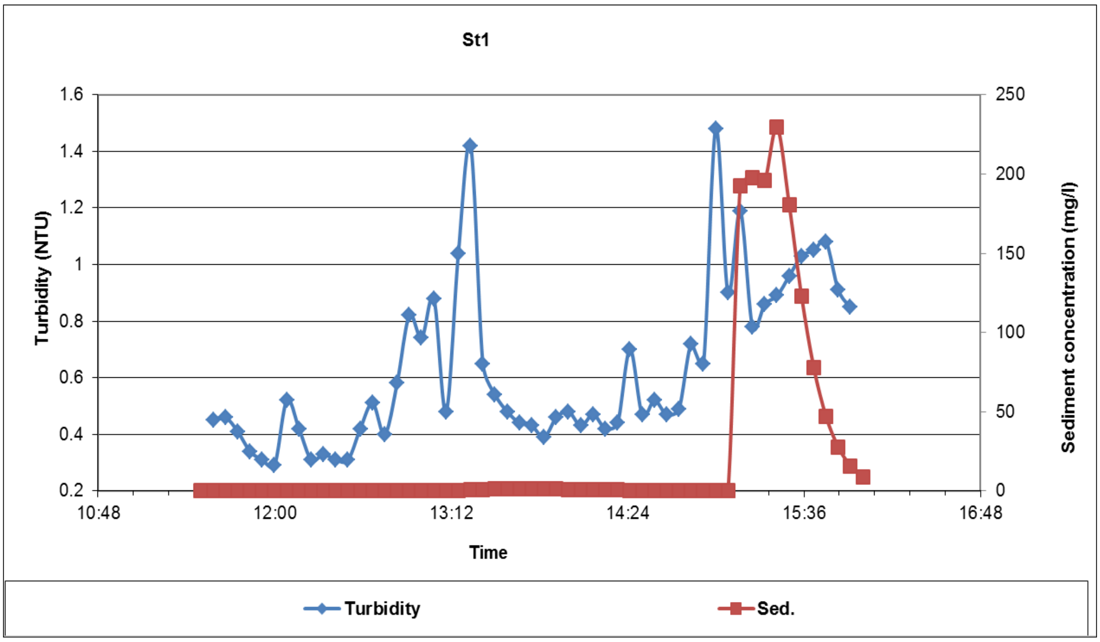


Figure C.10: EPAnet-PSM prediction for the velocity and sediment concentration in the St1 pipe compared with fieldwork results with resuspension velocity equal to 0.4 m/s.

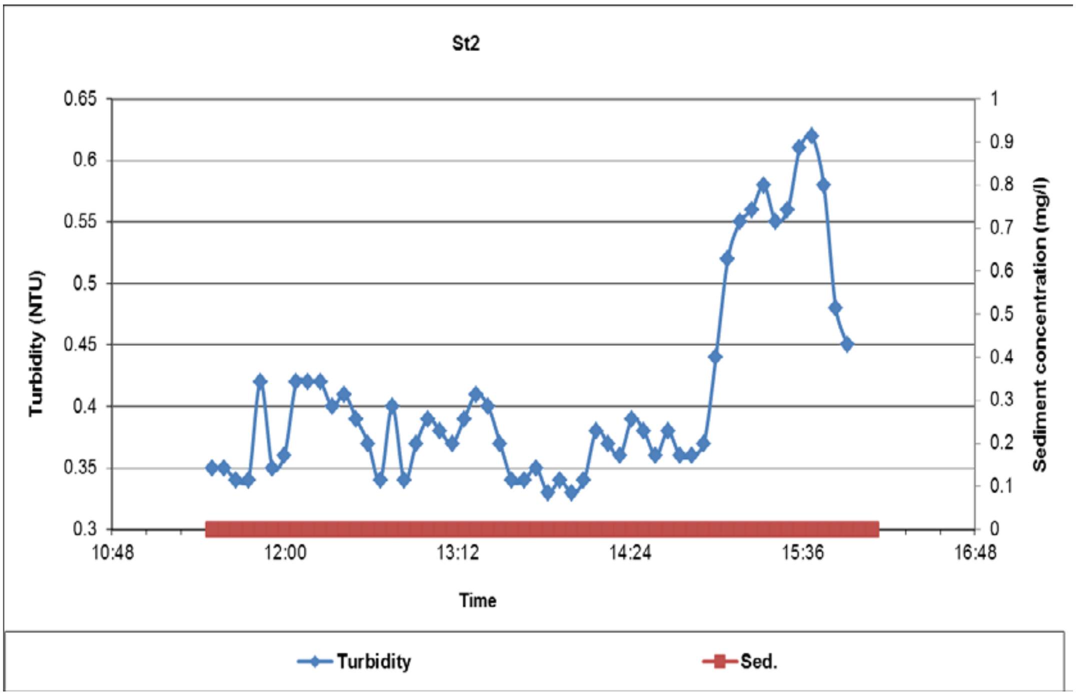


Figure C.11: EPAnet-PSM prediction for the velocity and sediment concentration in the St2 pipe compared with fieldwork results with resuspension velocity equal to 0.4 m/s.

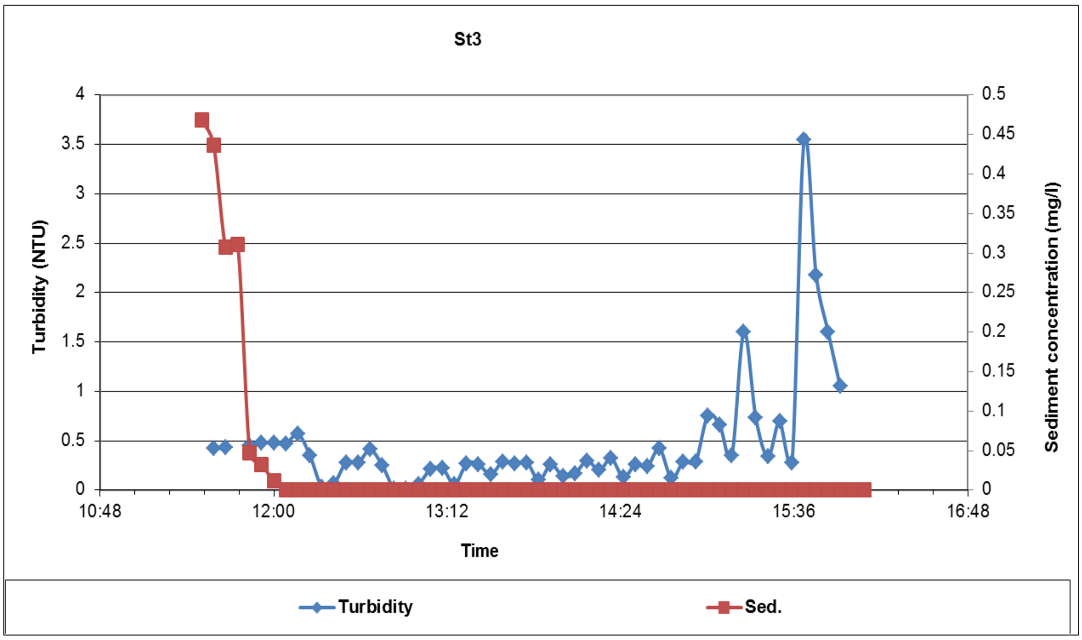


Figure C.12: EPAnet-PSM prediction for the velocity and sediment concentration in the St3 pipe compared with fieldwork results with resuspension velocity equal to 0.4 m/s.

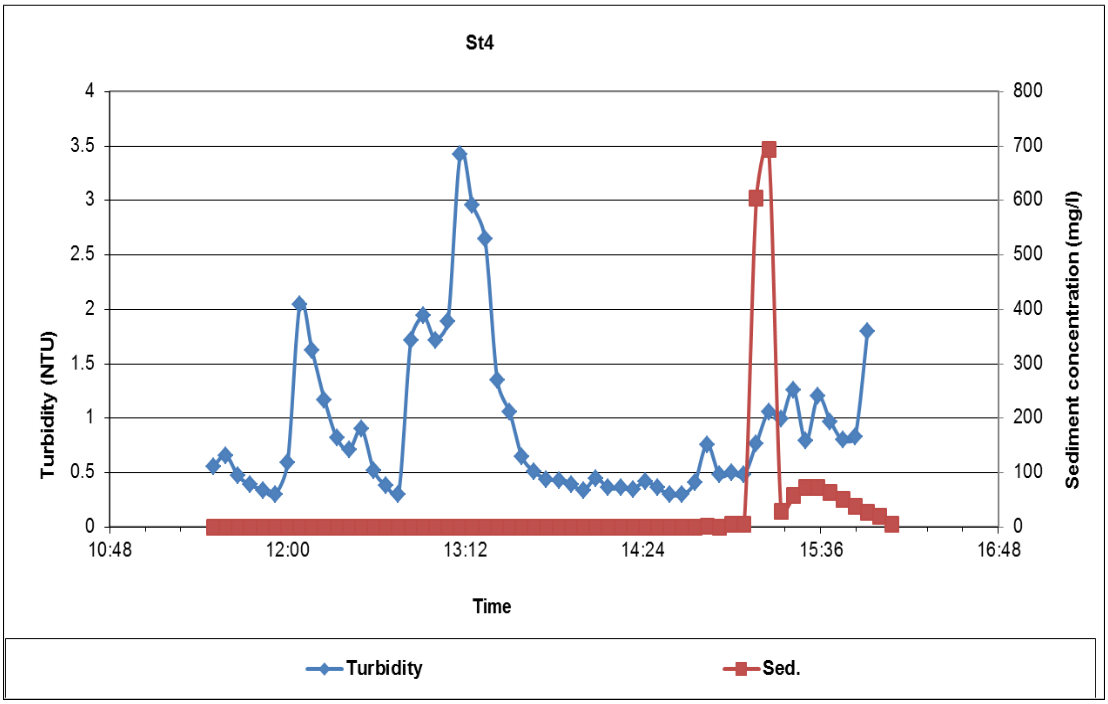


Figure C.13: EPAnet-PSM prediction for the velocity and sediment concentration in the St4 pipe compared with fieldwork results with resuspension velocity equal to 0.4 m/s.

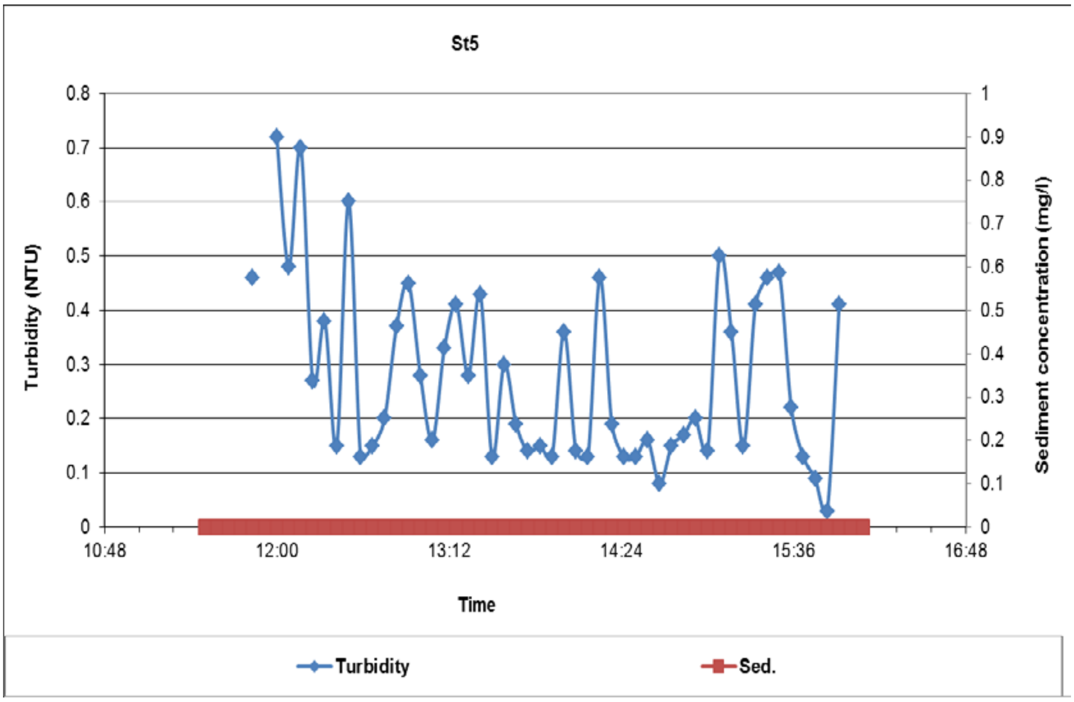


Figure C.14: EPAnet-PSM prediction for the velocity and sediment concentration in the St5 pipe compared with fieldwork results with resuspension velocity equal to 0.4 m/s.

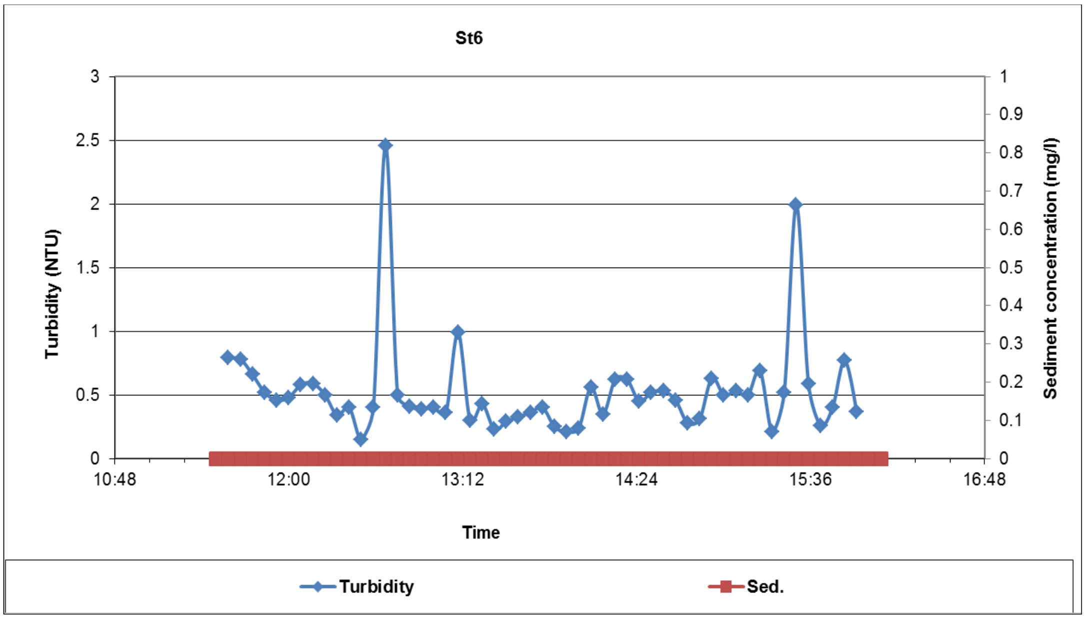


Figure C.15: EPAnet-PSM prediction for the velocity and sediment concentration in the St6 pipe compared with fieldwork results with resuspension velocity equal to 0.4 m/s.

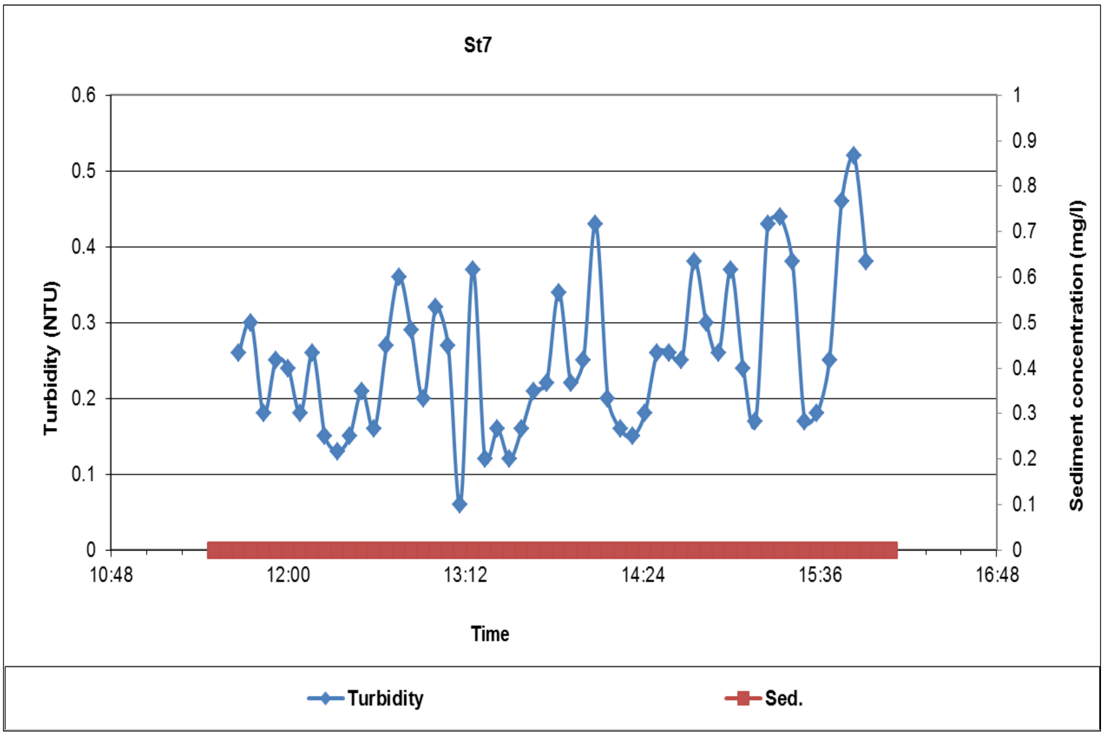


Figure C.16: EPAnet-PSM prediction for the velocity and sediment concentration in the St7 pipe compared with fieldwork results with resuspension velocity equal to 0.4 m/s.

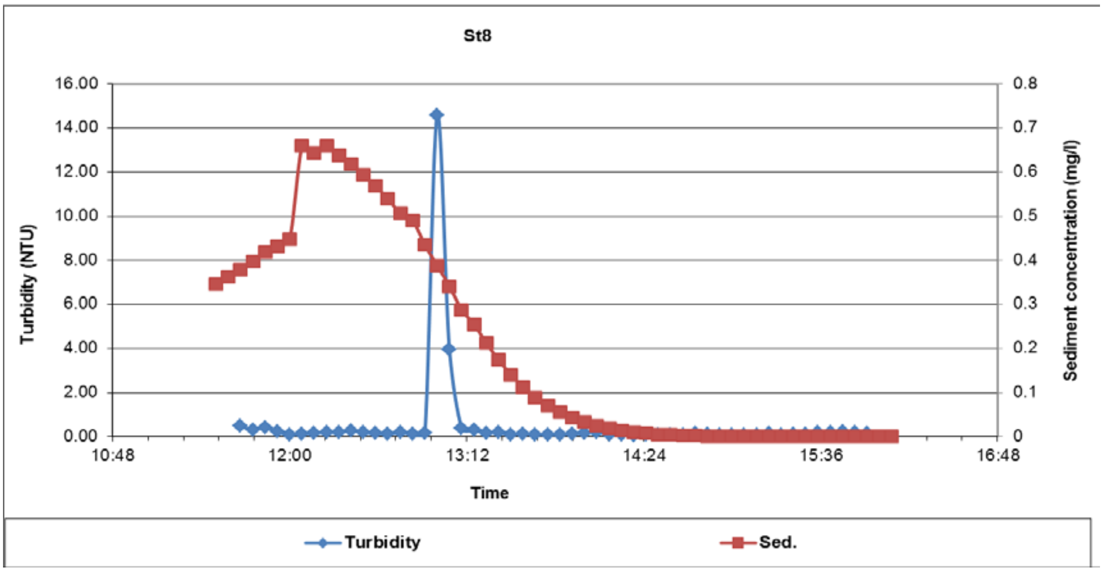


Figure C.17: EPAnet-PSM prediction for the velocity and sediment concentration in the St8 pipe compared with fieldwork results with resuspension velocity equal to 0.4 m/s.

As illustrated before in Figure 9.24) there are differences between the EPAnet-PSM predicted velocities and those obtained from the fieldwork measurements, especially those measurements taken starting from 14:50 hrs (the time at which the flushing from Ma2 started) until the end of fieldwork. The velocity predicted from PSM (V_{PSM}) matched with the turbidity values from the fieldwork (T_{FW}) at major sites. The sediment concentration predicted (S_{PSM}) had a maximum value that matched with the maximum $T_{FW,}$ as illustrated in Figures C.1 to C.3.

Figure 9.25 shows the velocities from both fieldwork (V_{FW}) and (V_{PSM}) in Mi1. They have the same pattern as that found during fieldwork except the time which the flow meter "takes off" from Ma1 to then be installed in Ma2. The T_{FW} values almost match with the V_{PSM} on the Mi1, as illustrated in Figure C.4. In addition, the S_{PSM} has a maximum the same as the highest recorded T_{FW} in Mi1 as shown in Figure C.6.

Figure 9.26 shows the great difference between the V_{FW} and V_{PSM} in Mi2 before the fieldwork started and at end of fieldwork. However the velocities were not matching but the maximum value of T_{FW} was recorded with maximum V_{PSM} and there was no relation at all with V_{FW} velocity, as shown in Figure C.7 where the velocity was 0.12 m/s. The T_{FW} recorded a maximum value of 16.4 NTU while it was recorded as 0.9 NTU when the velocity was 0.18 m/s. Figure C.8 shows that there was a sound relationship between the S_{PSM} and V_{PSM} in Mi2. Figure C.9 also shows very sound relationship between the T_{FW} and the S_{PSM} in Mi2.

Figures C-.10 to C.17 show the relationship between S_{PSM} and T_{FW} for all the eight sites St1, St2, St3, St4, St5, St6, St7 and St8. The results were reasonable, especially for sites St2, St3, St5, St6 and St7 where the maximums recorded (T_{FW} (NTU), S_{PSM} (mg/l)) were (0.62, 0), (3.5, 0.46), (0.72, 0), (2.4, 0), (0.52, 0) respectively. The predictions did not match for sites St1, St4 and St8 where the maximums recorded (T_{FW} (NTU), S_{PSM} (mg/l)) were (1.48, 229.4), (3.4, 692.3) and (13, 0.8) respectively.

The analyses of all results with 0.2 m/s resuspension velocity are illustrated in Figures C.18 to C.31.

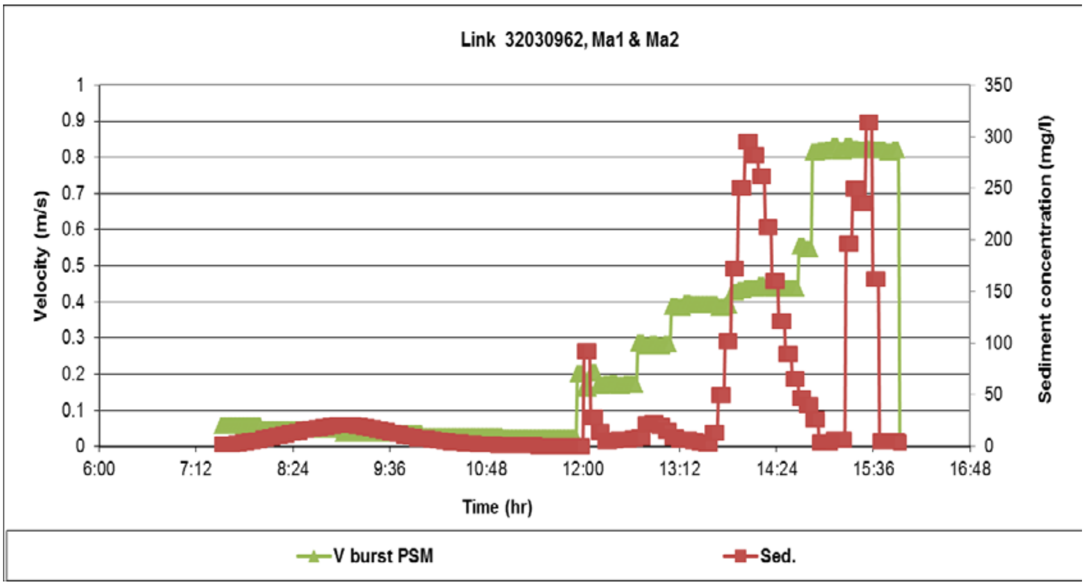


Figure C.18: EPAnet-PSM prediction for the velocity and sediment concentration in the major sites (Ma1 and Ma2) pipe using resuspension velocity equal to 0.2 m/s.

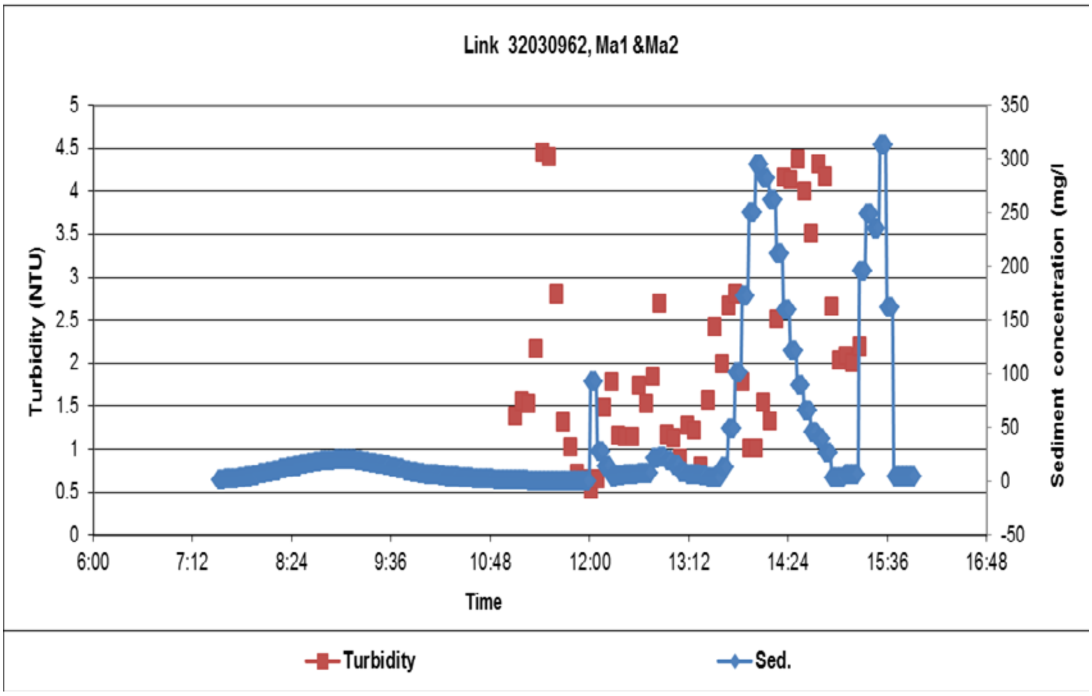


Figure C.19: EPAnet-PSM prediction for the sediment concentration in the major sites (Ma1 and Ma2) pipe using resuspension velocity equal to 0.2 m/s, compared with fieldwork turbidity results at Ma1.

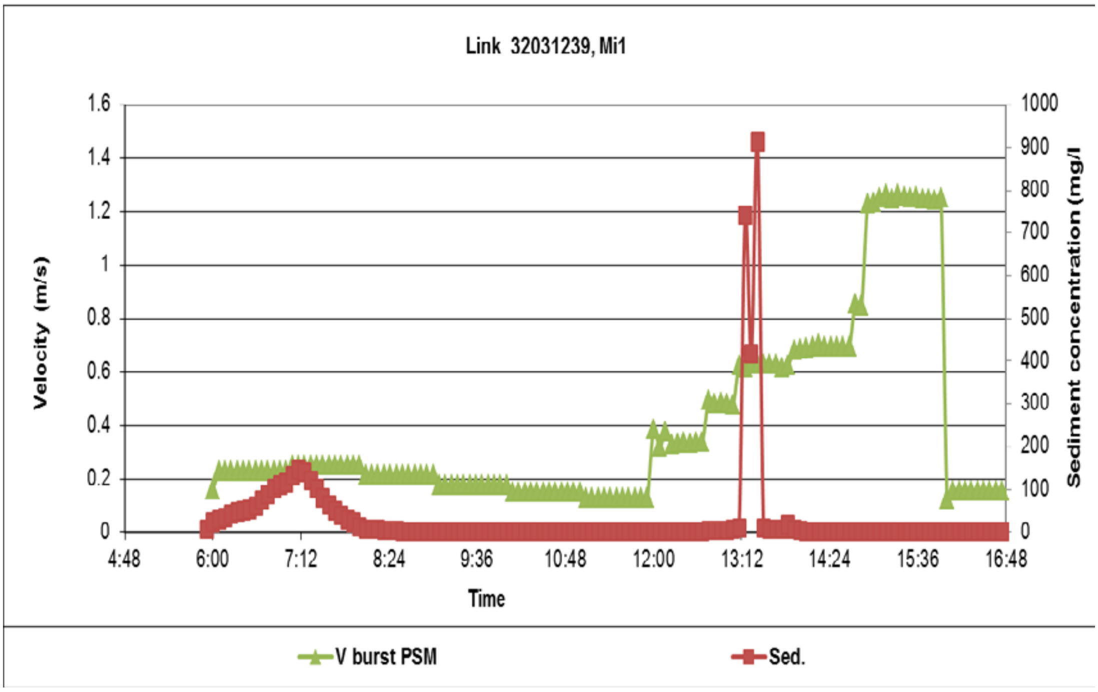


Figure C.20: EPAnet-PSM prediction for the velocity and sediment concentration in the Mi1 pipe using resuspension velocity equal to 0.2 m/s.

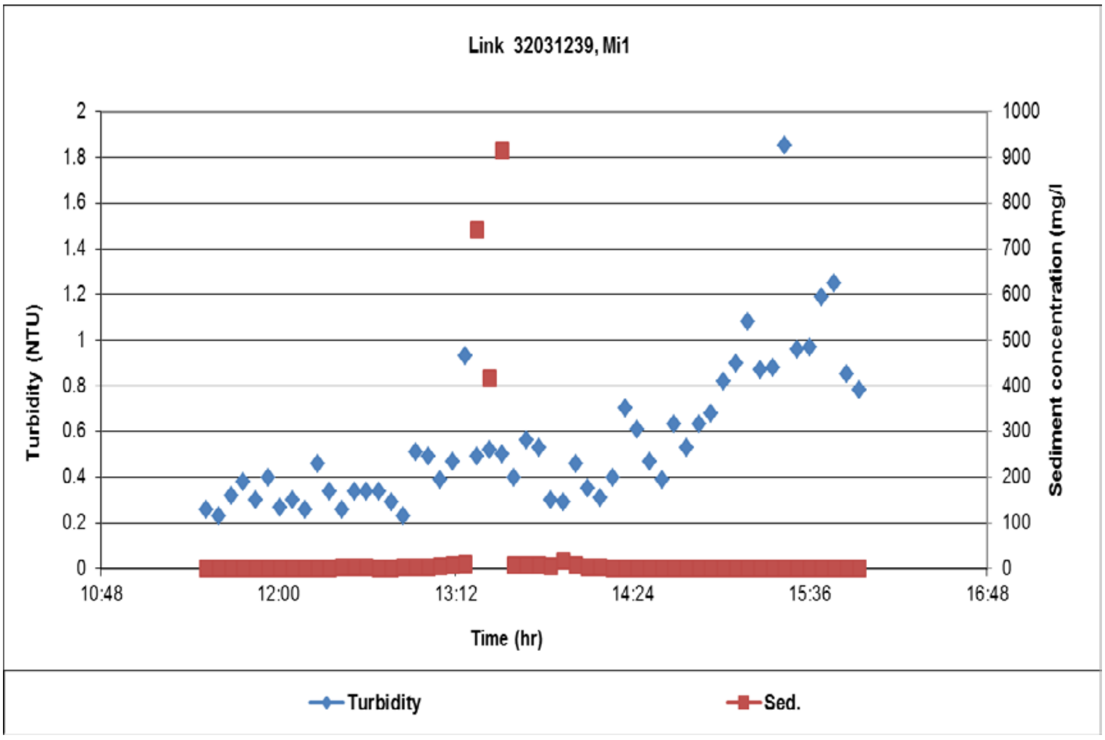


Figure C.21: EPAnet-PSM prediction for the sediment concentration in the Mi1 pipe using resuspension velocity equal to 0.2 m/s, compared with fieldwork turbidity results.

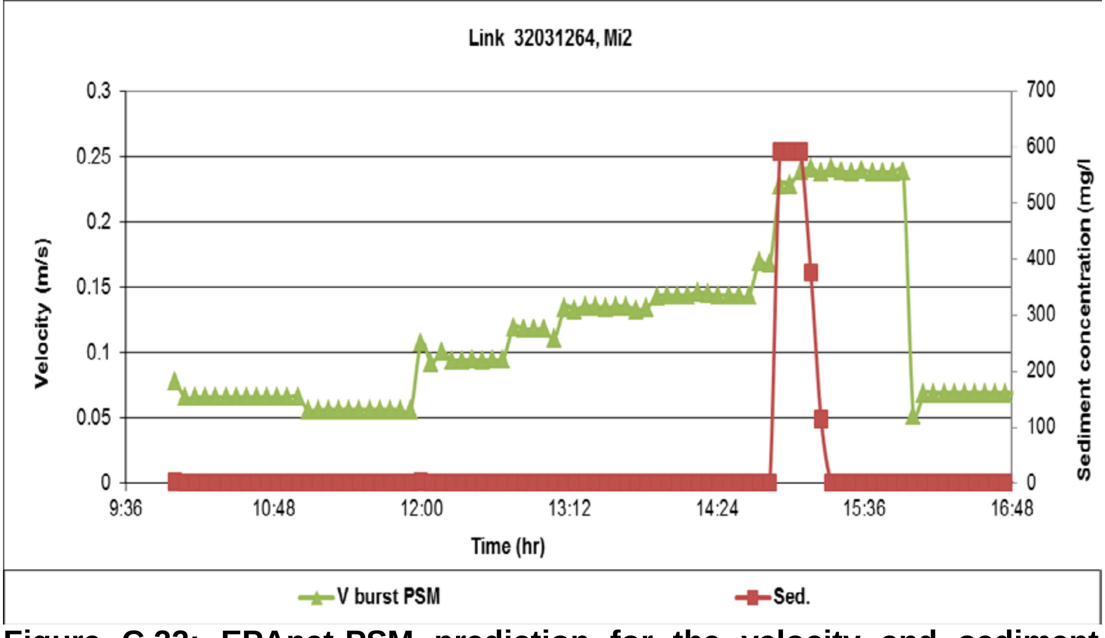


Figure C.22: EPAnet-PSM prediction for the velocity and sediment concentration in the Mi2 pipe using resuspension velocity equal to 0.2 m/s.

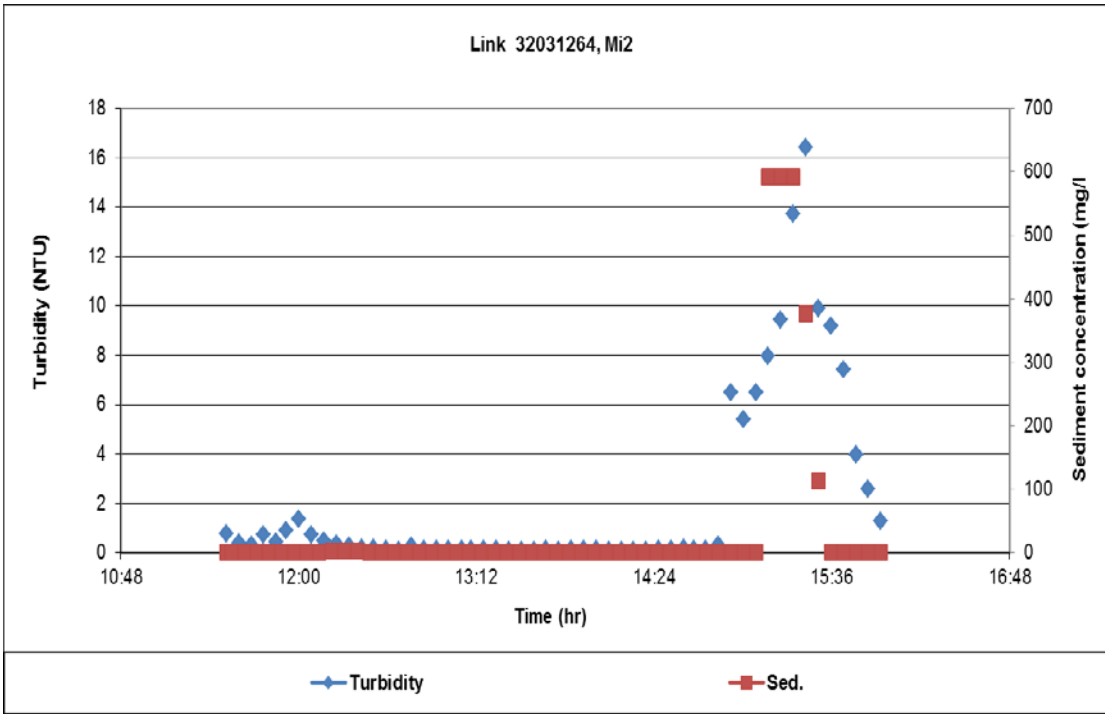


Figure C.23: EPAnet-PSM prediction for the sediment concentration in the Mi2 pipe using resuspension velocity equal to 0.2 m/s, compared with fieldwork turbidity results.

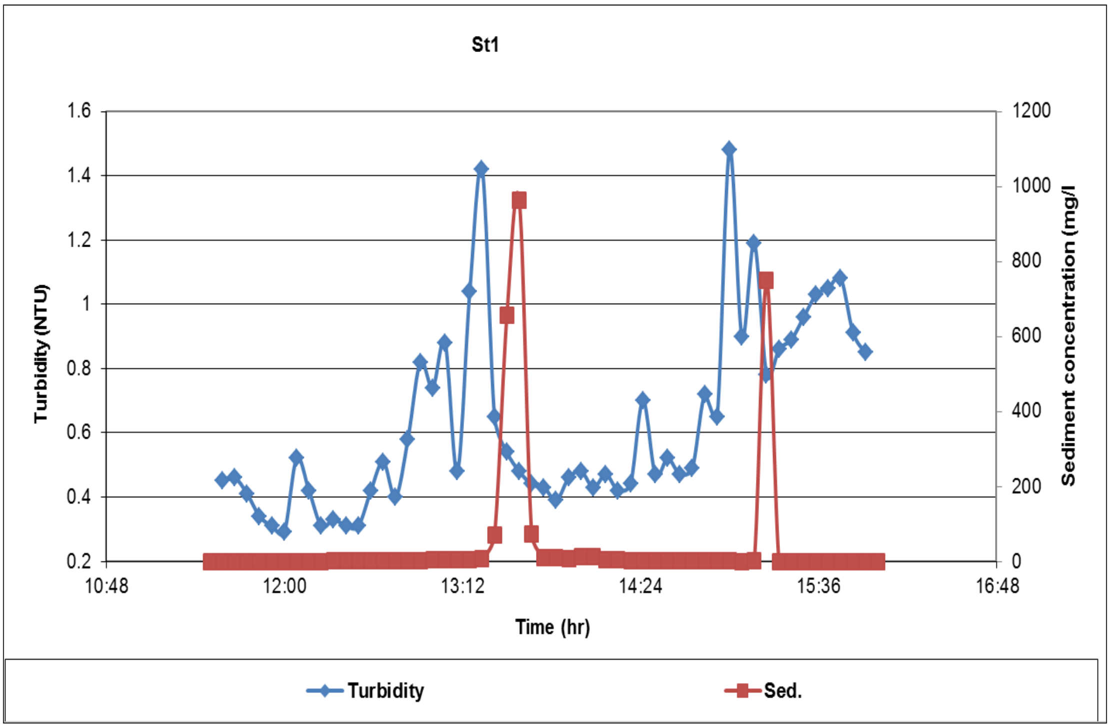


Figure C.24: EPAnet-PSM prediction for the velocity and sediment concentration in the St1 pipe compared with fieldwork results with resuspension velocity equal to 0.2 m/s.

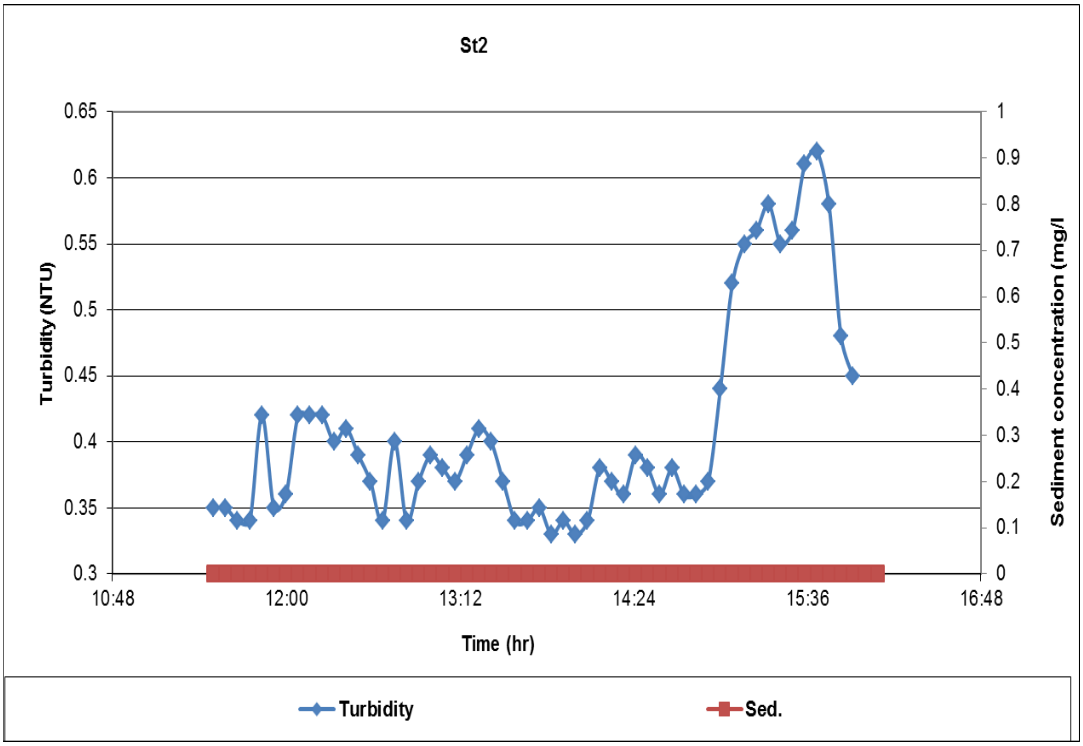


Figure C.25: EPAnet-PSM prediction for the velocity and sediment concentration in the St2 pipe compared with fieldwork results with resuspension velocity equal to 0.2 m/s.

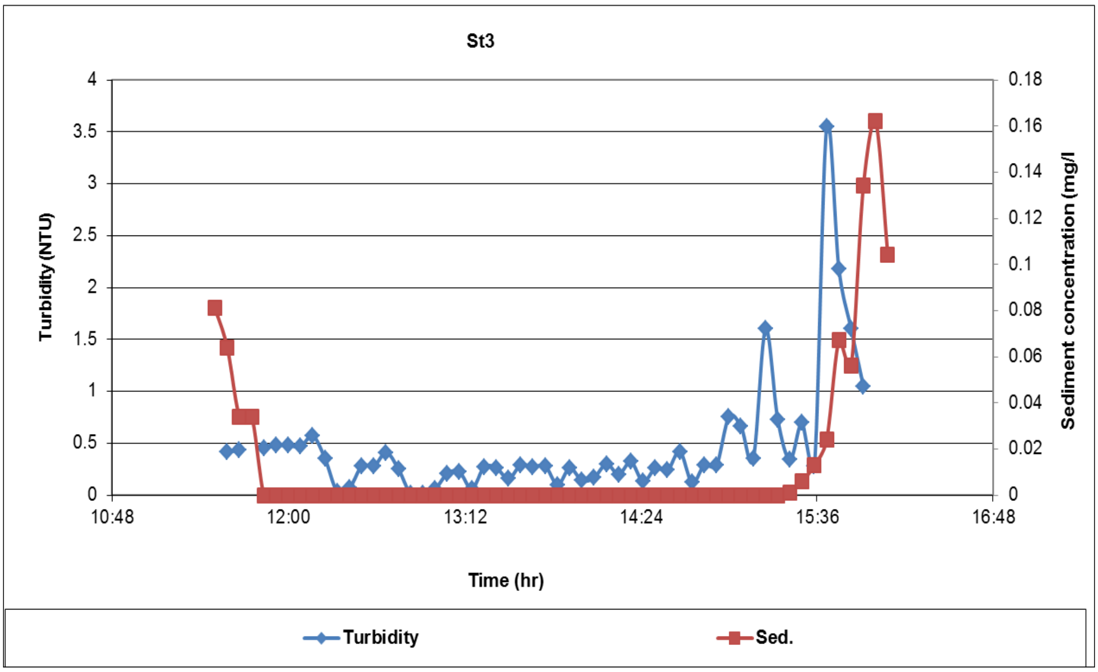


Figure C.26: EPAnet-PSM prediction for the velocity and sediment concentration in the St3 pipe compared with fieldwork results with resuspension velocity equal to 0.2 m/s.

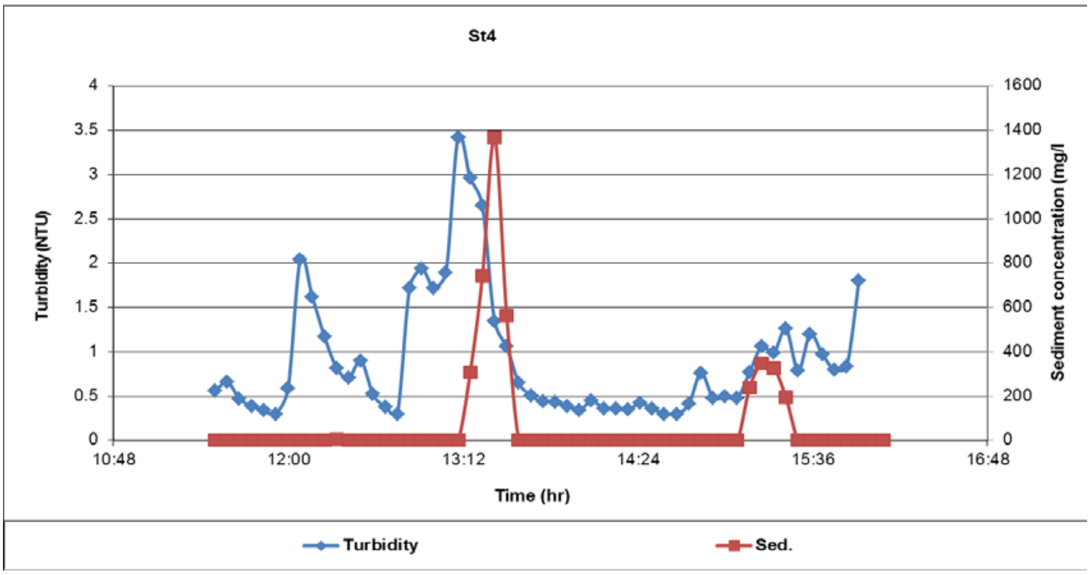


Figure C.27: EPAnet-PSM prediction for the velocity and sediment concentration in the St4 pipe compared with fieldwork results with resuspension velocity equal to 0.2 m/s.

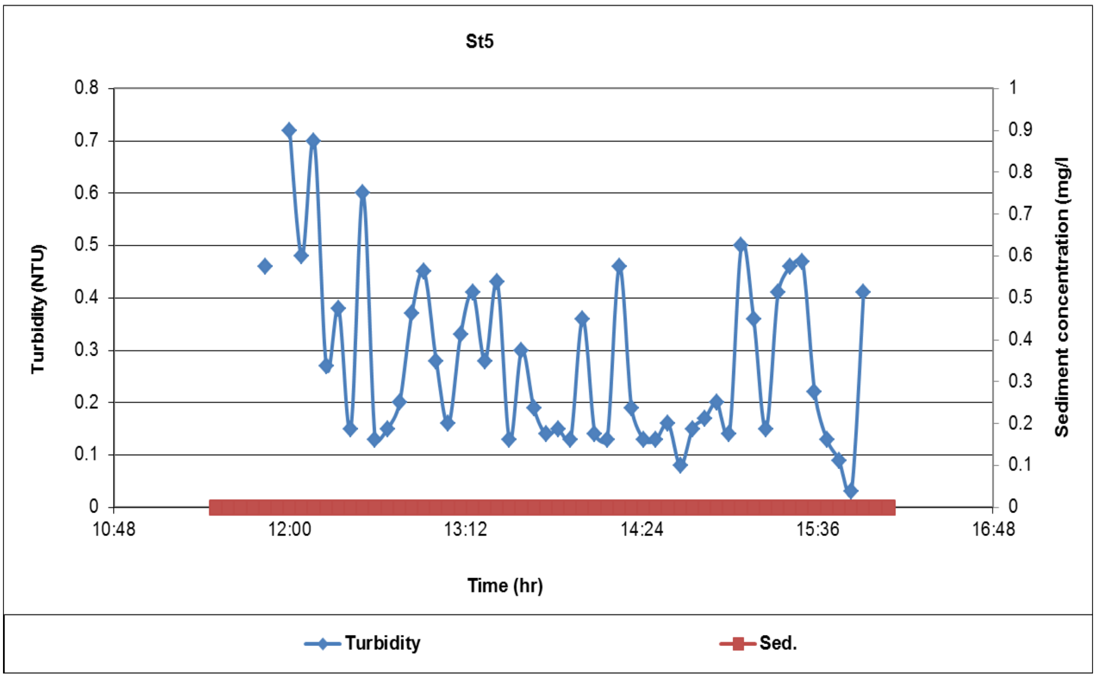


Figure C.28: EPAnet-PSM prediction for the velocity and sediment concentration in the St5 pipe compared with fieldwork results with resuspension velocity equal to 0.2 m/s.

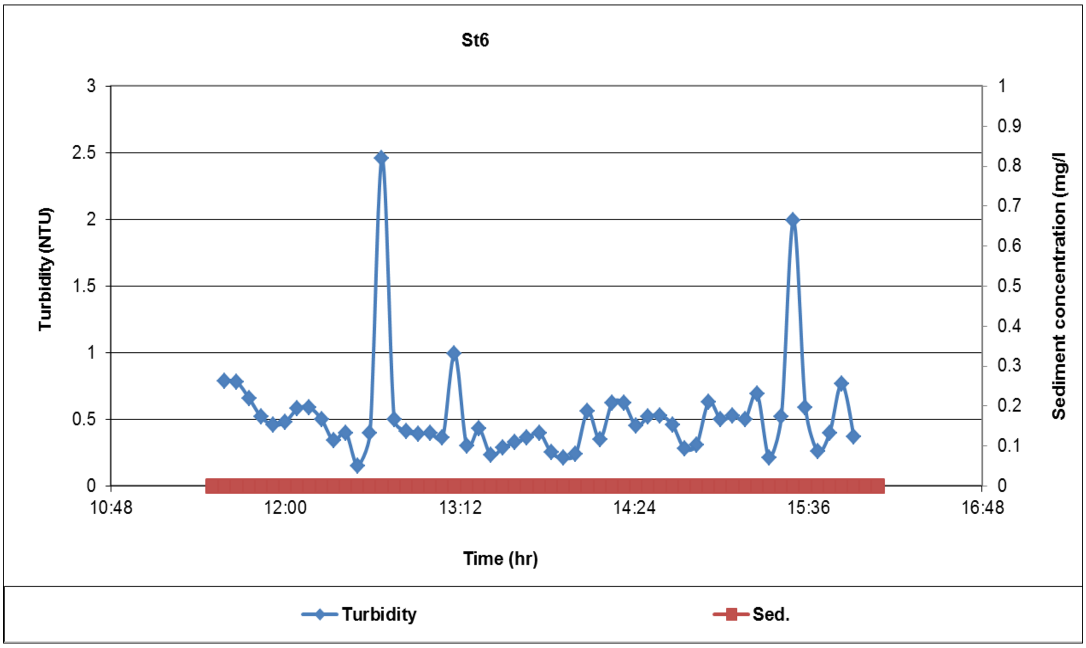


Figure C.29: EPAnet-PSM prediction for the velocity and sediment concentration in the St6 pipe compared with fieldwork results with resuspension velocity equal to 0.2 m/s.

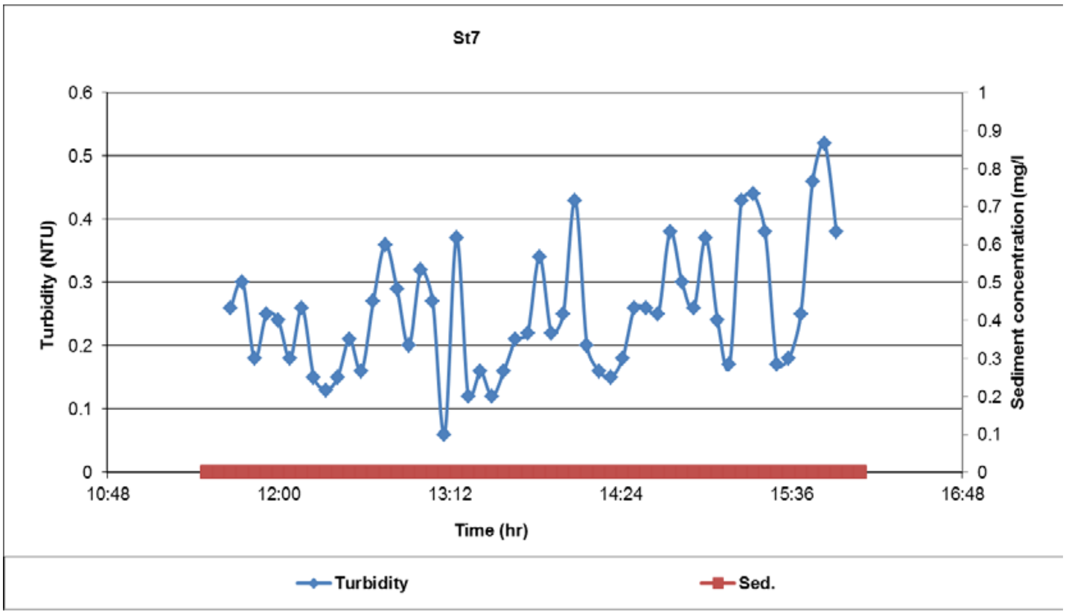


Figure C.30: EPAnet-PSM prediction for the velocity and sediment concentration in the St7 pipe compared with fieldwork results with resuspension velocity equal to 0.2 m/s.

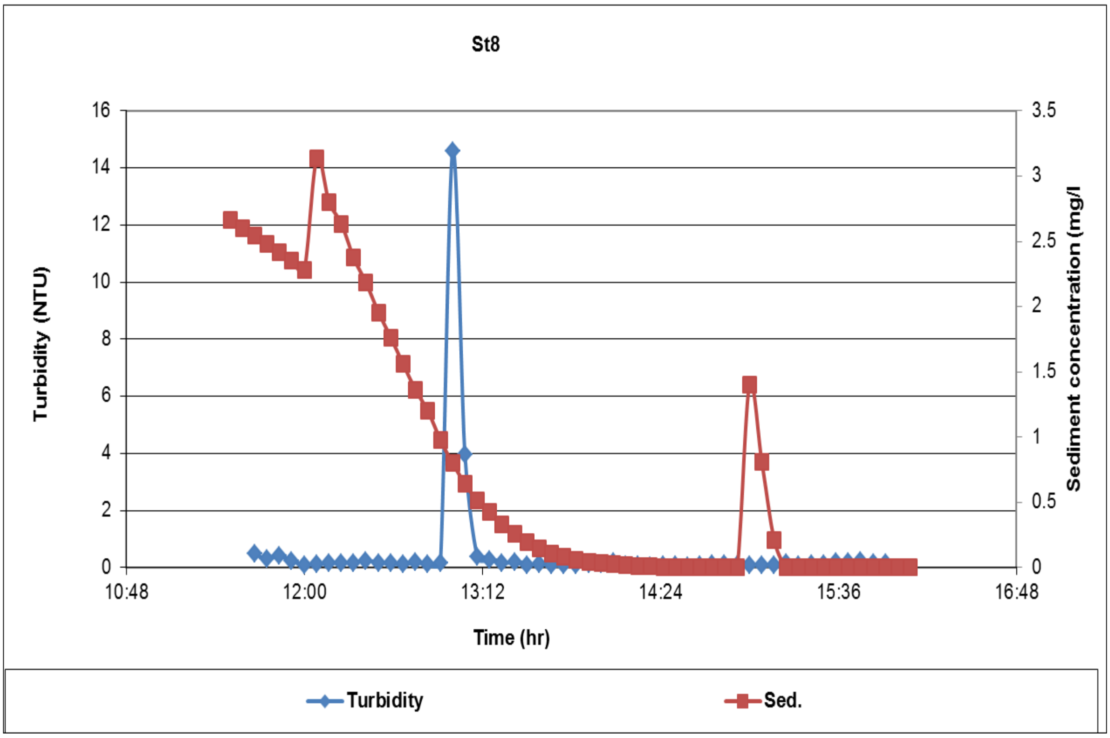


Figure C.31: EPAnet-PSM prediction for the velocity and sediment concentration in the St8 pipe compared with fieldwork results with resuspension velocity equal to 0.2 m/s.

Figure C.18 shows the S_{PSM} and the V_{PSM} at major sites with 0.2 m/s resuspension velocity. The sediment concentration predicted (S_{PSM}) at major sites has a maximum value matching with the maximum $T_{FW,}$ as illustrated in Figure C.19.

Figure C.20 shows the S_{PSM} and the V_{PSM} at site Mi1. There is no relation between T_{FW} values and S_{PSM} at Mi1 as illustrated in Figure C.21.

Figure C.22 shows the S_{PSM} and the V_{PSM} at site Mi2. The velocities V_{FW} and V_{PSM} in Mi2 were not matching as shown previously in Figure 9.25. However, the maximum value of T_{FW} was recorded as the same as the maximum S_{PSM} as shown in Figure C.23 where the velocity was 0.12. The T_{FW} recorded a maximum value of 16.4 NTU and the S_{PSM} 592 mg/l.

Figures C.24 to C.31 show the relationship between S_{PSM} and T_{FW} for all the eight sites St1, St2, St3, St4, St5, St6, St7 and St8 with 0.2 m/s resuspension velocity. The results were reasonable, especially for sites St2, St3, St5, St6 and St7 where the maximums recorded (T_{FW} (NTU), S_{PSM} (mg/l)) were (0.62, 0), (3.5, 0.16), (0.72, 0), (2.4, 0), (0.52, 0) respectively. The predictions did not match for sites St1, St4 and St8 where the maximums recorded (T_{FW} (NTU), S_{PSM} (mg/l)) were (1.48, 962), (3.4, 1366) and (13, 3.2) respectively. However, the results were reasonable for all the eight sites except for site St8. At St8 there is no relation between T_{FW} and S_{PSM} in pattern and value, as the site location was far away from major sites and this could be another reason for the cause of the high turbidity.

The flows predicted by PSM (normal flow) are different from those calculated in the fieldwork before the burst flushing occurred. A hydraulic model is a simplified version of the reality, and as such, a lot of assumptions are made.

Furthermore, in the fieldwork, flushing was carried out at two hydrant points, while the above EPAnet-PSM was simulated by increasing the demand at a single downstream node. Therefore another two PSM runs were carried out with nodes created at the middle of pipe 32030962; major sites pipe (Ma1 and Ma2 pipe). Two situations were created, one node and two nodes. The two nodes were created to resemble the real situation as closely as possible but the results for both situations were not as expected. A sample of the results (for one node at middle) is illustrated in Figures C.32 to C.36.

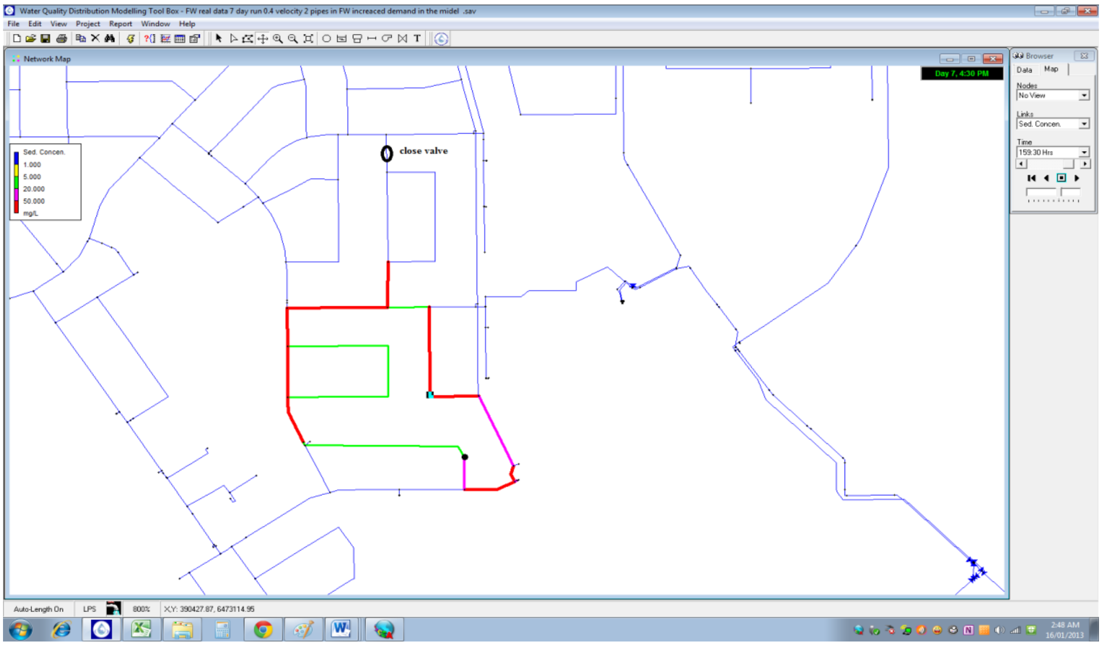


Figure C.32: Create node at middle of major sites pipe and close one of partially closed valves near Mi2.

Figure C.33: EPAnet-PSM prediction for Ma1 with runs of 5 days dirty reservoir, one node at middle.

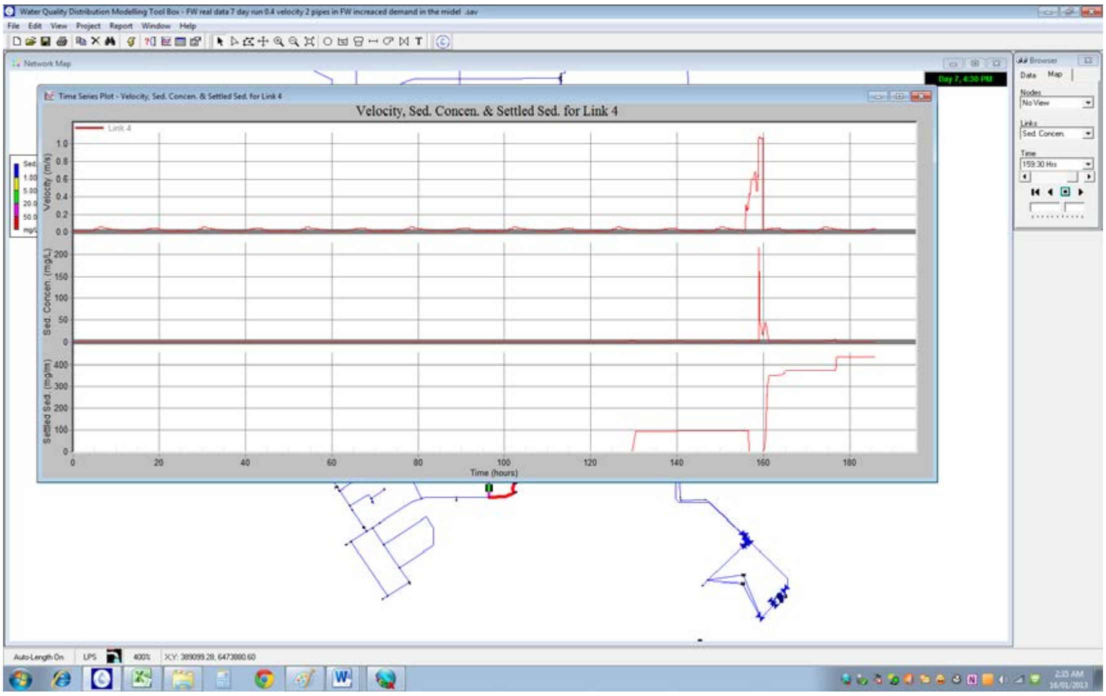


Figure C.34: EPAnet-PSM prediction for Ma2 with runs of 5 days dirty reservoir, one node at middle.

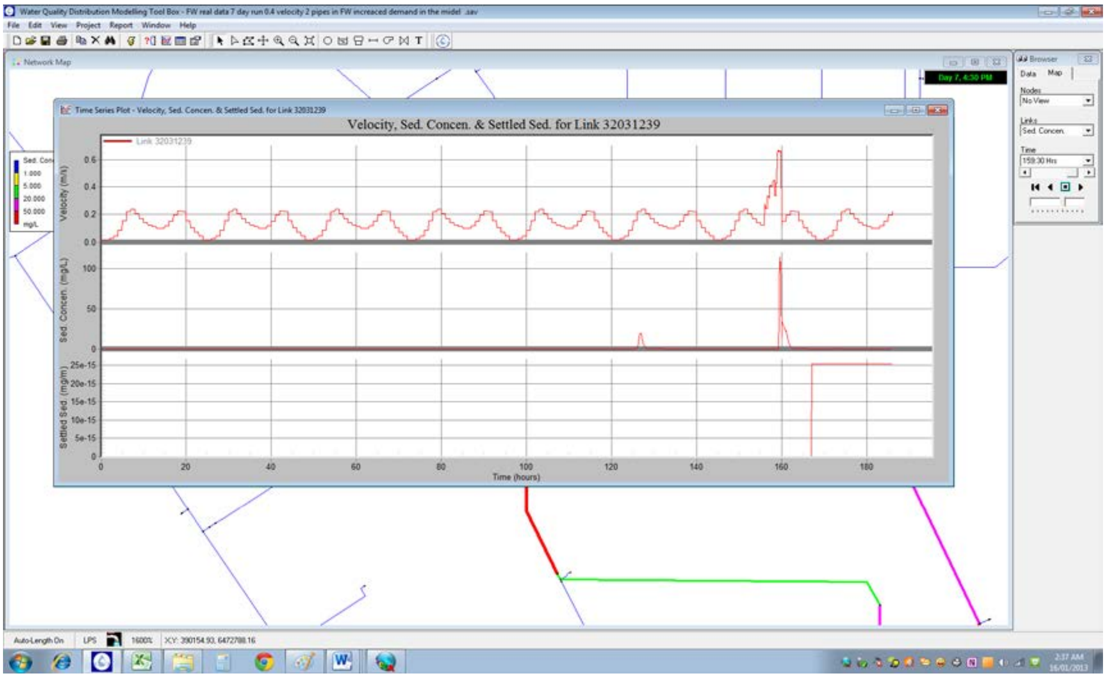


Figure C.35: EPAnet-PSM prediction for Mi1 with runs of 5 days dirty reservoir, one node at middle.

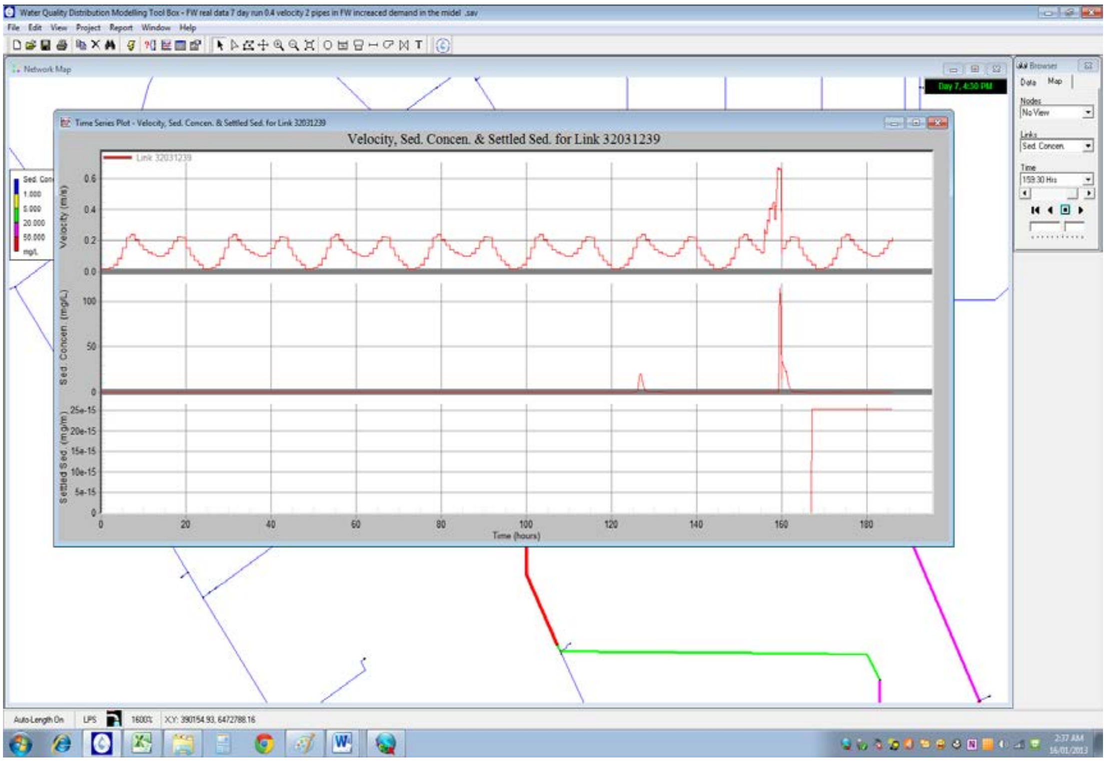


Figure C.36: EPAnet-PSM prediction for Mi2 with runs of 5 days dirty reservoir, one node at middle.

The PSM could be used to understand the potential risks associated with a hydraulic event but not in predicting exactly where complaints will or will not occur. The program requires modification that will take all problems into consideration and another investigation then undertaken to test the reliability of EPAnet-PSM. For this reliability test, the collected data could be used.