Formation of discoloured water and turbidity in an unfiltered water distribution system

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ABSTRACT

Despite current management practices discoloured water events in both filtered and unfiltered water distribution systems continue to be a major issue for the water industry worldwide. Limited research has taken place into the formation and prediction of discoloured water events in unfiltered water distribution systems.

The most widely adopted measuring techniques currently used by the majority of water companies to identify and measure discoloured water events, namely, discoloured water customer complaints and water quality grab samples, severely underestimate the extent to which discoloured water events occur. Customer complaints and grab samples also give little information as to the cause, time or magnitude of a discoloured water event. It is recommended that water companies not use discoloured water customer complaints or water quality grab samples for the prediction of areas at risk of forming discoloured water in unfiltered water distribution systems with lined or PVC pipes. This study demonstrates that monitoring sites for continuous on-line testing of turbidity and flow rate in series within the water supply network can be used effectively to investigate the operating environment of the system and understand the steady state hydraulics that cause discoloured water events in an unfiltered system. This new understanding can be used in preventative management of discoloured water events.

This study investigated discoloured water formation in a 450 mm transfer main in Wantirna water quality zone of South East Water in Melbourne, Australia, as an example of an unfiltered water distribution system with few unlined ferrous pipes. The study found that the majority of discoloured water events could be explained by the erosion of cohesive layers of particles formed on the internal pipe wall when a critical shear stress was exceeded in the pipe. For the system investigated, the critical shear stress was variable and could be estimated from the maximum applied shear stress reached in a particular section of pipe in the preceding 24 hours.

It is therefore recommended that operational procedures, particularly isolated flushing procedures, be modified to reduce the occurrence of unplanned incidences of
discoloured water when the critical shear stress of a pipe is exceeded. A hydraulic model and the method for estimating the critical shear stress outlined in this thesis could be used to test scenarios of operational procedures to identify pipes with increased likelihood of producing discoloured water.

The cohesive layers which contribute to discoloured water events appear to form in less than 1 week. It is therefore also recommended that the mains cleaning techniques using flushing currently employed to remove material causing discoloured water events appear to have no medium or long term benefits for the system investigated and further investigation into the effectiveness of routine flushing programs for the prevention of discoloured water events is required.

When the causes of discoloured water are understood, a system can be proactively managed to prevent discoloured water events by managing those causes. This philosophy fulfils contemporary water system management approaches such as the Framework for the Management of Drinking Water Quality in the 2004 Australian Drinking Water Guidelines.
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DECLARATION OF AUTHENTICITY

I declare that this thesis:

- Contains no material which has been accepted for the award of any other degree or diploma, except where due reference is made in the text of thesis;
- To the best of my knowledge contains no material previously published or written by another person except where due reference is made in the text of thesis; and
- Where the work is based on joint research or publications, discloses the relative contributions of the respective workers or authors.

Signed by Rachael Prince
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CHAPTER 1 : INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Management of the quality of drinking water comprises two key issues; those related to health and those related to aesthetics. Historically, the primary focus of the water industry, and the research community in general, has been on the health aspect of water quality. This emphasis is not unexpected, as poor drinking water quality has a significant role in the transmission of infectious disease (Tebbutt 1992; and The Institution of Engineers Australia and GHD Pty Ltd 1999).

However, to focus purely on the health aspect of water does not take into account how humans “assess” the safeness of water (Jones 1996; and Walski and Parker 1974). Not unexpectedly, customers evaluate water by their senses, taste, smell, and sight (Walski and Parker 1974; World Health Organisation 1984; Deb and Hasit 1995; Fairley and Sinclair 1999; and Bernal et al. 1999). Marketing literature describes these evaluation processes by the customer as ‘expectation measures’. Knowing the relative importance of each of these expectation measures assists greatly in determining the point at which a customer will be dissatisfied with a particular level of service (Boyd et al. 1998).

It is somewhat ironic that the greatest health risk from water is usually associated with substances that are not perceived by humans through taste, sight or smell (for example, micro-organisms or dissolved organics), while substances that contribute to making water appear unattractive or unhealthy are often, in themselves, harmless, for example, suspended inorganic material or colour (Department of Human Services and Department of Natural Resources and Environment 2000; and Walski 1991). As a result, a paradox exists between health and aesthetic aspects, where potable water may be rejected as dangerous based on a sensory perception even if, in fact, it is safe (Jones and Tuckwell 1993; World Health Organisation 1984; and Jones 1996).
Fairley and Sinclair (1999) explain this phenomenon of customer rejection of water as being fundamentally a result of most people evaluating acceptable water quality as water that “tastes and looks good”. In this way the customer may complain when the level of expected service in terms the expectation measures of appearance, smell or taste is not reached. For example, water could be rejected and the customers complain if the water smells “musty” or the appearance is “brown” (Males et al. 1992). It is therefore important that water companies address both the health and aesthetic issues of water, as both are important to customer satisfaction (Fairley and Sinclair 1999).

This research investigates the appearance aspect of water quality as, although occurring rarely, events of ‘discoloured’, or ‘dirty water’, are reported as the major aesthetic issue in many parts of the world: in the USA and Canada (Deb and Hasit 1995; Ellison 2003), United Kingdom (Childs 1987; De Rosa 1993; and Boxall et al. 2001), the Netherlands (Slaats 2002), France (Gauthier et al. 1999), and Australia (Yarra Valley Water 1999 and Sydney Water 2001). For example, between 60 and 90% of customer complaints received by water retail companies in Australia relate to discoloured water (Polychronopoulos et al. 2001; and Sydney Water 2001). Furthermore discoloured water complaints are a Key Performance Indicator (KPI) for the unfiltered water distribution system investigated in this study. Customer complaints are used as a KPI because the customer charter of the water company managing the system requires delivery of water that is aesthetically pleasing, and the Safe Drinking Water Act (2003) requires the water not cause widespread complaints and requires reporting of all customer complaints.

1.2 What is discoloured water and where does it come from?

The appearance of the discoloured water in water distribution systems can range from red, yellow, brown and black depending on the spectrum colour and concentration of the particles (De Rosa 1993; and Gauthier et al. 1996). Many authors have identified particulate material, not true colour, as being responsible for the majority of discoloured water and therefore discoloured water customer complaints (Childs 1987; De Rosa 1993; Deb and Hasit 1995; Gauthier et al. 1999; Boxall et al. 2001; Grainger et al. 2002; Slaats 2002; Ellison 2003; and Ekanayake et al. 2003). Logically, the type of
particles causing discoloured water will depend on their origin. The various origins of particles causing discoloured water are discussed in the following sections.

1.2.1 Source water

Drinking water supplies (source waters) may contribute particles and colour that lead to discoloured water, particularly if they are unfiltered. Source water may introduce naturally occurring particles and colour (Ellison 2003; Yarra Valley Water 1999; and Lin and Coller 1997) including sediment, silt, sand, turbidity, tastes, odours, colour, and organisms (Kirmeyer et al. 2000), algae and organic matter (Reilly and Kippin 1983; Donner and Kirner 1985; Gauthier et al. 2001; and Slaats 2002). Surface waters have also been attributed to introducing clays and silts to drinking water supplies (Lin and Coller 1997; South East Water 1998; van der Walt et al. 1999; and Ekanayake et al. 2003), airborne dust and sand (Ellison 2003), and tannin colour (Lin and Coller 1997).

A statistical analysis of water quality results collected from hydrants in 56 supply zones in the United Kingdom reported by De Rosa (1993) suggested that surface water sourced from lowland reservoirs and rivers is likely to contribute more deposits in the water distribution system than water sourced from upland reservoirs and borehole water supplies. It has also been suggested that wells may introduce sands and silts (Ellison 2003). Groundwater on the other hand has been identified as a potential source of dissolved elements such as iron, manganese and calcium that can precipitate and cause discolouration when they travel through the water distribution system (De Rosa 1993; Sly et al. 1990; Kirmeyer et al. 2000; and Slaats 2002).

1.2.2 Treatment

Not unexpectedly, unfiltered source water has generally been found to have a higher mass load of particles than filtered water (Kirmeyer et al. 2000;). A reduced number of customer complaints in filtered systems, as compared to unfiltered systems, in Melbourne, Australia, also support this position (Yarra Valley Water 1999).

However, even with filtration, particles may enter the system through treatment breakthrough (Gauthier et al. 2001) and incomplete removal of particles, such as iron colloids, from source water (Gauthier et al. 1999; and Slaats 2002). The treatment
process itself may also introduce particles, such as alum or iron coagulates (Ellison 2003; and Slaats 2002), aluminium microflocs (Gauthier et al. 2001), filter material (Gauthier et al. 2001; and Ellison 2003), powdered activated carbon particles (Gauthier et al. 2001), and bio-particles grown within biofilters if proper backwashing procedures are not carried out (Gauthier et al. 2001). However, Boxall et al. (2001) argue that when appropriate control and monitoring techniques are employed in water treatment, the treatment process should rarely contribute directly to discoloured water events.

The same argument applies to the unfiltered water supply in Melbourne, Australia, where protected catchments, long detention times and selective withdrawal of source water in reservoirs are used to reduce the risk of significant direct allochthonous particle release into the water distribution system. However, significant direct allochthonous events aside, both filtered and unfiltered water may indirectly contribute to discoloured water by supplying a low concentration of particles to the water distribution system which settle on the pipes, gradually accumulating over time to be released autochthonously during high flow events or disturbances (Kessler et al. 1998; Gauthier et al. 1999; Yarra Valley Water 1999; Gauthier et al. 2001; Grainger et al. 2002; Slaats 2002; and SE Water 2003). [This indirect method of forming discoloured water is discussed further in Section 1.3.]

1.2.3 Water distribution system

Processes within the water distribution system can also contribute to the types of particles present in a discoloured water event. The contribution of each process will depend on the supply of dissolved substances from source water, the treatment type and the materials of the asset components in the pipe network.

Sources of particles formed within the water distribution system include:-

- The corrosion of ferrous pipes and fittings. This is reported to be a dominant source of particles in systems with unlined ferrous pipes (Stephenson 1989; De

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* Allochthonous particles are defined as those that are derived from outside the water distribution system such as those that occur direct from source water.

† Autochthonous particles are defined as those that are entrained from within the water distribution system.
Rosa 1993; Gauthier et al. 2001; Boxall et al. 2001; Clement et al. 2002; and Smith et al. 1997). The quantity of particles created by the corrosion process can be increased by microbiological activity when chlorine residuals are low (Meches 2001). Lindley and Davies (1995) claim that unlined ferrous pipes are the only source of particles from within the system causing discolouration. However, this is clearly not the case, as particles are still found in systems not containing unlined ferrous pipes (Sly et al. 1990; Goold et al. 1991; Lin and Coller 1997; van der Walt et al. 1999; and Ekanayake et al. 2003). Furthermore, chemical analyses of deposits accumulated in systems containing unlined ferrous pipes have found elements other than iron (De Rosa 1993; Gauthier et al. 1996; Gauthier et al. 2001; and Carriere et al. 2002). These studies, however, agree that the main component of deposits in systems containing unlined ferrous pipes is iron, indicating the importance of corrosion for these types of systems (Smith et al. 1997; Boxall et al. 2001; and Seth et al. 2004). The chemical composition of deposits from systems with few unlined ferrous pipes has less iron than unlined systems (Lin and Coller 1997; van der Walt et al. 1999; and Ekanayake et al. 2003);

- Erosion of pipe linings such as cement can introduce sand and aluminium (Gauthier et al. 1996; and Lin and Coller 1997);

- Precipitation of dissolved elements such as iron, magnesium and calcium with changes in pH (Stephenson 1989; Gauthier et al. 1996; Lin and Coller 1997; Sly et al. 1990; Walski 1991; Kirmeyer et al. 2000; and Slaats 2002). Chlorine and chlorine dioxide used for disinfection can also cause the oxidation of dissolved manganese to form particulate material (Sly et al. 1990). Boxall et al. (2001) report that blending of water sources has also been found to cause precipitation of dissolved elements;

- Biological growth (biofilm) and subsequent stripping due to changes in chlorine levels and/or flows (Katz 1986; Le Chevallier et al. 1987; Stephenson 1989; Clark et al. 1993; Gauthier et al. 1996; Brunone et al. 2000; Meches 2001; Gauthier et al. 2001; and Slaats 2002). Some bacteria that live in biofilms may also cause aesthetic problems, including objectionable tastes, odours, and colour (Meches 2001).
• Microbial deposition of manganese and iron into biofilm (Sly et al. 1990; and O'Connor and O'Connor 2000);
• Backflow problems, where potable water is contaminated by water flowing back into the water distribution system from domestic water tanks, factories, hospitals, and other premises during low-pressure events. This may introduce organic or inorganic particles depending on the source of the contamination;
• External contamination such as main repairs introducing backfill material such as sand (Gauthier et al. 1996; and Slaats 2002) and intrusion of silts, clays or micro-organisms from ground water during negative pressure events (Gauthier et al. 1999; and Kirmeyer et al. 2000); and
• Animals such as invertebrates and protozoa (Stephenson 1989; and van Lieverloo et al. 2002).

1.2.4 Internal house plumbing
Internal plumbing can markedly change aesthetic water quality and lead to discoloured water emerging at customer taps (Ruta 1999; and Slaats 2002). Galvanized iron plumbing is well known in the water industry for causing brown water complaints, and copper pipes may corrode to cause blue water complaints (South East Water 1998).

1.2.5 Identification of the source of discoloured water
Linking the characteristics and composition of particles found in the water distribution system to a specific cause can be very difficult due to the number of possible sources of particles and the complexity of the pipe network (Gauthier et al. 1999). This may lead to the situation where deposits found in a particular pipe may not have formed in that pipe but may have travelled quite a distance through the system (Gauthier et al. 1996; and Seth et al. 2004). For example, Gauthier et al. (1996) found iron oxide particles in a number of samples taken from PVC pipes where they could not have originated.

Furthermore, high total iron concentrations may be the result of corrosion of assets within the water distribution system, precipitation of solute metals, and/or derived from iron rich clays which have been transported from the surface water catchment. The relative contributions of each of the possible particle sources are often not investigated, with a single origin often assumed to be the dominant contributor based on system
characteristics (Smith et al. 1997; Boxall et al. 2001; Ackers et al. 2001; and Seth et al. 2004).

It is important to understand the way in which particles are transported from a source and are concentrated to create discoloured water that the customer sees. The common mechanisms used to describe the creation of discoloured water in water distribution systems are described in the following section.

1.3 Discoloured water formation

1.3.1 General mechanisms of discoloured water formation

Acute discoloured water formation, also called the “problematic effect” by Smith et al. (1997) is defined as a single origin supplying particles to the water distribution system at a concentration that a customer could see. Particles originating from the origins discussed in Section 1.2 would rarely be acute. However, a number of studies have concluded that low concentrations of particles enter or are generated in the water distribution system and that these particles accumulate in pipes, forming “sediment reservoirs” of deposits (Walski 1991; Gauthier et al. 1997; Ackers et al. 2001; Grainger et al. 2002; and Boxall et al. 2001). These deposited particles are subsequently released into the bulk water stream when the forces imposed on the deposits by the fluid movement which creates applied shear, lift and drag forces, exceed the gravitational, friction, cohesion and/or adhesion forces holding the deposits at rest (Walski 1991; De Rosa 1993; Ackers et al. 2001; and U.S. Army Corps of Engineers 2002). This process can be described as the chronic or “passive effect” (Smith et al. 1997).

Importance of particle characteristics

Under the processes for the generation of discoloured water described in the previous paragraph, knowing the characteristics of the particles that occur within a water distribution system is vital in understanding the deposition and re-suspension mechanisms that can take place. These particle characteristics can be broadly categorised as cohesive/non-cohesive and discrete/flocculent.
Discrete particles do not change size, shape or mass with transport in the water distribution system, while flocculent particles are those that cluster during movement, changing in size, shape and relative density (Tebbutt 1992). Cohesive particles are those that tend to “stick” together due to electro-chemical or biological forces between particles (U.S. Army Corps of Engineers 2002; and Raudkivi 1990). Non-cohesive particles on the other hand exist as loose deposits. Non-cohesive material generally consists of large (greater than 30 µm) discrete particles. The movement of this type of particles is dependent on the physical properties of size, shape, specific gravity and concentration (Gauthier et al. 1996; Cheng 1998; Raudkivi 1990; Walski 1991; Boxall et al. 2001; and van den Boomen et al. 2004).

Non-cohesive particles tend to settle out from the water column primarily due to gravity. Entrainment of non-cohesive particles occurs when the applied forces on the settled material exceed gravitational and friction forces. The physical properties of non-cohesive discrete particles can be used with one of the versions of Shield’s function to determine settling time, the maximum velocity required to allow for sedimentation, and the scouring velocity required to entrain loose deposits (Stephenson 1989; Raudkivi 1990; Walski 1991; Tebbutt 1992; NHMRC and ARMC 1996; Gauthier et al. 2001, 1999, 1996; and Friedman et al. 2004).

Discrete particles, or clusters of particles larger than 50 µm, will settle readily under gravitational forces, at rates depending on their density. Smaller particles, however, have very long settling velocities so that sedimentation may not occur in the water distribution system (Tebbutt 1992). Particle shape can also have an impact, with flat particles taking longer to settle than round particles due to the affect of surface charge (Raudkivi 1990). Higher concentrations of particles can also change the way in which particles settle because of inter-particle interactions. Particles can be “naturally” flocculent because of particle charges or they may ‘floc’ due to the addition of coagulants (Tebbutt 1992). Flocculating particles exhibit increased settling velocity (Tebbutt 1992).

The behaviour of cohesive sediments is mainly dependent on the strength of the attractive forces (electro-chemical and/or biological forces) between particles, rather than the physical properties of the individual grains (U.S. Army Corps of Engineers
This phenomenon means that the attractive forces dominate gravitational forces in preventing entrainment. At present no general analytical theory for cohesive sediment re-suspension (or deposition) is available and empirically based field and laboratory experiments are recommended (Black et al. 2002).

The division between cohesive and non-cohesive particles is related to particle chemistry, mineralogy and size (Christian 1998). Some general guidelines (for fresh water) are that particles will act cohesively when the grain size of the particle is less than 20 – 30 µm (Delleur 2001; and Friedman et al. 2004) or if over 10 % of the material is less than 2µm (clay) (Raudkivi 1990).

A number of different theories have been used by authors to describe discoloured water formation based on assumptions of particle characteristics and observations of particle movement. However, there is general agreement that the exact mechanism for how these particles form discoloured water is little understood (Walski 1991; Boxall et al. 2001; and Grainger et al. 2002). Brief descriptions of the four key mechanisms which have been used to describe discoloured water formation are discussed in the following sections. This section is followed by an analysis of these mechanisms based on the characteristics of particles found in water distribution systems. [A major review of the first three mechanisms and existing sediment modelling in water distribution systems can be found in Ackers et al. (2001).]

**Deposition and re-suspension mechanism**

Deposition and re-suspension of particles is a key concept used to describe the process involved in the formation of discoloured water in water distribution systems. This process is shown in Figure 1-1. The mechanism is based on discrete, non-cohesive particle movement in river systems where the following cycle occurs: transport - sedimentation - erosion of deposits - transport - sedimentation.

The mechanism is based on relatively large particles (gravels (60 mm) to sands (0.2 mm)), which are non-cohesive, discrete and for which gravitational forces are dominant. The movement of these particles in this cyclical process depends on the physical properties of size, shape, specific gravity and the concentration of particles (Gauthier et al. 1996; Cheng 1998; Raudkivi 1990; Walski 1991; Boxall et al. 2001; and van den
Boomen et al. (2004). As noted previously, these properties can be used in one of the versions of Shield’s function to determine settling time, the maximum velocity required to allow for sedimentation, and the scouring velocity required to entrain loose deposits.

**Generation and mobilisation mechanism**

Figure 1-2 describes the formation of discoloured water from observations of corrosion of unlined cast iron pipes in Thames Water and other United Kingdom systems (Boxall et al. 2001; and Smith et al. 1997). This process involves fine particles which are ‘generated’ at the location of the discoloured water from the corrosion of iron or copper pipes. It was observed in these United Kingdom studies that the particles are so small (colloidal) that the rate of iron particles formation through corrosion can be greater than the deposition rate, such that turbidity increases in dead ends (Smith et al. 1997). These deposits have also been described as forming discrete loose deposits (Smith et al. 1997) and cohesive layers (Boxall et al. 2001). Both cases assume that the deposits and suspended colloids are transported when flow is increased and do not re-settle so that the following occurs: generation - mobilisation - transportation and no re-deposition.
**Adhesion and stripping mechanism**

The adhesion and stripping mechanism for movement of particles applies to the formation of biofilm, iron and manganese oxide coatings, or corrosion scales and the subsequent absorption of loose particles and composites into that biofilm/coating at low wall shear stresses. This process is shown schematically in Figure 1-3. The biofilm/coating and absorbed particles are mobilised when the biofilm/coating is stripped from the pipe wall as a result of applied shear stresses exceeding the adhesive forces. Discussions on these mechanisms can be found in Sly *et al.* (1990), Smith *et al.* (1997) and Brunone *et al.* (2000).

![Figure 1-3: Cross section of pipe showing adhesion and stripping mechanism of discoloured water formation.](image)

**Cohesion and erosion mechanism**

The cohesion and erosion mechanism for particle movement relates to the formation of cohesive layers of particles on the circumference of the pipe wall due to electro-chemical and biological forces (Sethi 1996). Erosion or stripping of the cohesive layer occurs when the applied shear stress on the cohesive layer exceeds the electro-chemical and/or biological forces holding the particles in place (Shrestha *et al.* 2001; Ackers *et al.* 2001; Delleur 2001; Black *et al.* 2002; U.S. Army Corps of Engineers 2002; Seth *et al.* 2004; and Boxall and Saul 2005). This leads to a cyclical process of collection of particles onto the inner wall of the pipe by van der Waals forces, erosion due to shear stress, transport of particles and then recollection back onto the pipe wall as shown in Figure 1-4.

Each of these mechanisms may be complicated by the flocculation of particles within the water distribution system due to chlorine and lime oxidising particles (Gauthier *et
and general mixing within the pipe during low turbulence flows (Tebbutt 1991).

![Figure 1-4: Cross section of pipe showing cohesion and erosion mechanism of discoloured water formation](image_url)

### 1.3.2 Mechanism of discoloured water formation in an unfiltered and lined water distribution system

#### Particle characteristics in water distribution systems

Most studies characterising particulate matter have been conducted on filtered water supply systems. As shown in Table 1-1, few studies have been conducted on lined pipes or unfiltered systems, which are the systems of interest for this study.

Although authors such as Walski (1991) have requested characterisation of sediment in water distribution systems, only a few papers have been published on the topic. A summary of the limited number of these studies is given in Table 1-2. The studies indicate that a wide range of particle sizes occur within a water distribution system, a situation which indicates that a number of the discoloured water formation mechanisms described in the previous section may occur simultaneously.

The method in which the particle samples were collected should also be taken into account when comparing particle characteristics. The majority of papers have used samples collected by mains flushing. Collecting samples by mains flushing is not recommended by Walski (1991), as the method may draw particles from an area within the region, not just a specific pipe. Particles may be drawn from beyond the specific pipe because the particles are transported from surrounding pipes during the induced hydraulic disturbance. In addition, the high shear stresses experienced during a pipe
Flush may break up conglomerates of particles and therefore the effective particle size might be smaller than would have occurred under normal conditions within the water system.

Table 1-1: Type of systems in which investigations of particulate characteristics causing discoloured water have been conducted.

<table>
<thead>
<tr>
<th>Papers investigating particulate characteristics</th>
<th>System Type</th>
<th>Unfiltered</th>
<th>Filtered</th>
<th>Lined</th>
<th>Unlined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melbourne, Australia (Grainger et al. 2002; Ekanayake et al. 2003; Ryan et al. 2004)</td>
<td></td>
<td>4</td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Downstream of Sugarloaf Reservoir, Melbourne, Australia (Lin and Coller 1997)</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Yarra Valley Water system, Australia (van der Walt et al. 1999)</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Adelaide, Sydney, Brisbane, Australia (Ryan et al. 2004)</td>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Gold Coast, Australia (Sly et al. 1990)</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Kansas City, USA (Goold et al. 1991)</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Nancy, France (Gauthier et al. 1999; 2000; and 2001)</td>
<td></td>
<td>3</td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Thames Water System, United Kingdom (Smith et al. 1997)</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>North England, United Kingdom (Seth et al. 2004; and Boxall et al. 2001)</td>
<td></td>
<td>2</td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>United Kingdom (De Rosa 1993)</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Canada (Gauthier et al. 2001; and Carrière et al. 2002)</td>
<td></td>
<td>2</td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>6</strong></td>
<td><strong>14</strong></td>
<td><strong>11</strong></td>
<td><strong>9</strong></td>
</tr>
</tbody>
</table>

Note: /  
Unfiltered = system where water is not treated by filtration  
Filtered = system where water is treated by filtration/micro-filtration  
Lined = system has predominately PVC or lined pipes  
Unlined = system has unlined ferrous pipes

In addition, Grainger et al. (2003) found that some larger particle sizes settled out in water tankers used to transport water samples from the sample site to the laboratory where particle size testing occurred. This problem introduces errors in the upper limit of particle sizes reported for those samples transported in this way.

**Particle accumulation in water distribution systems**

Understanding the mechanisms for accumulation of particles in water distribution systems is important because, excluding acute allochthonous discoloured water events from source water or corrosion of ferrous pipes, discoloured water events will only occur when particles have accumulated and are subsequently mobilised.
Table 1-2: Comparison of studies involving weight averaged particle size ranges and specific gravity of particulate matter.

<table>
<thead>
<tr>
<th>System characteristics</th>
<th>Reference</th>
<th>Sample location</th>
<th>Common particle size</th>
<th>Range of particle sizes</th>
<th>Specific Gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unfiltered, lined system Melbourne, Australia</td>
<td>Grainger et al. 2002</td>
<td>Within distribution system</td>
<td>11 µm</td>
<td>0.9 to 280 µm</td>
<td>1.39 – 2.04</td>
</tr>
<tr>
<td>Unfiltered, lined system Melbourne, Australia</td>
<td>Grainger et al. 2003</td>
<td>Service reservoir**</td>
<td>8 – 27 µm</td>
<td>0.8 – 400 µm</td>
<td>Not reported</td>
</tr>
<tr>
<td>Filtered, lined system Melbourne, Australia</td>
<td>Grainger et al. 2003</td>
<td>Service reservoir**</td>
<td>18 µm</td>
<td>0.5 – 300 µm</td>
<td>1.92</td>
</tr>
<tr>
<td>Unfiltered, lined system Melbourne, Australia</td>
<td>Ekanayake et al. 2003</td>
<td>Within distribution system</td>
<td>5 – 10 µm</td>
<td>Majority less than 50 µm</td>
<td>Not reported</td>
</tr>
<tr>
<td>Unfiltered, lined system Melbourne, Australia</td>
<td>Ryan et al. 2004</td>
<td>Within distribution system</td>
<td>15 µm</td>
<td>2 – 200 µm</td>
<td>Not reported</td>
</tr>
<tr>
<td>Filtered, lined system Adelaide, Australia</td>
<td>Ryan et al. 2004</td>
<td>Within distribution system</td>
<td>19 µm</td>
<td>4 – 120 µm</td>
<td>Not reported</td>
</tr>
<tr>
<td>Filtered, lined system Perth, Australia</td>
<td>Ryan et al. 2004</td>
<td>Within distribution system</td>
<td>13 µm</td>
<td>9 – 120 µm</td>
<td>Not reported</td>
</tr>
<tr>
<td>Filtered, lined system Sydney, Australia</td>
<td>Ryan et al. 2004</td>
<td>Within distribution system</td>
<td>20 µm</td>
<td>12 – 84 µm</td>
<td>Not reported</td>
</tr>
<tr>
<td>Filtered, unlined system United Kingdom</td>
<td>Boxall et al. 2001</td>
<td>Within distribution system</td>
<td>10 µm</td>
<td>70 % &lt; 50 µm</td>
<td>1 – 1.3</td>
</tr>
<tr>
<td>Filtered, unlined system United Kingdom</td>
<td>Ackers et al. 2001</td>
<td>Within distribution system</td>
<td>2 - 5 µm</td>
<td>&lt; 0.75 µm to &gt; 500 µm</td>
<td>2.6 – 3.1*</td>
</tr>
<tr>
<td>Unfiltered, lined system Melbourne, Australia</td>
<td>Van Der Walt et al. 1999</td>
<td>Service reservoir**</td>
<td>Not reported</td>
<td>70 % &lt; 3 mm (3000 µm)</td>
<td>3.1</td>
</tr>
</tbody>
</table>

Note:/
* Specific gravity calculated using samples that were collected in 57 µm nets.
** Note these samples were not taken within the water distribution system, but from a service reservoir supplying a water distribution system.

The majority of the research for sedimentation has been conducted for rivers and Raudikivi (1990) provides a detailed account of work done in this area. Ackers et al. (2001) and Friedman et al. (2004) discuss the application of the sedimentation mechanisms to water distribution systems. However, the implications of particle sizes typically found in water distribution systems on the collection processes to pipe walls are not well treated by these authors because, as described in Section 1.3.1, the deposition-re-suspension mechanism assumes that the particles are comparatively large (greater than 60 mm), non-cohesive and discrete and that gravitational forces are dominant (Raudikivi 1990; Ackers et al. 2001; and Friedman et al. 2004). A large proportion of the particles found in water distribution systems are, however, less than 50
µm (Table 1-2) and consequently the majority of particles in water distribution systems are in the size range that does not settle quickly, assuming that flocculation does not occur.

This conclusion is supported by sedimentation studies conducted in both filtered and unfiltered systems (De Rosa 1993; Ackers et al. 2001; van der Walt et al. 1999; and Grainger et al. 2003). These studies simulated sedimentation in a 100 mm pipe and found that the majority of particles took 2 hours (for filtered, unlined systems) to 6 hours (for unfiltered and lined systems) to settle in the pipe in totally quiescent conditions. The remaining material was found to take in excess of 20 hours to settle. In addition, Grainger et al. (2002), in a study using particles from an unfiltered and lined system, found that sedimentation occurred slower than predicted by Stokes settling of spherical particles, where gravitational forces are assumed to be dominant. The extended sedimentation time found by Grainger et al. (2002) can be explained by the small flat, clay like particles, found in the same system by van der Walt et al. (1999) using an Electron Scanning Microscope. Electrochemical forces are dominant for particles with these characteristics.

Sedimentation times in actual water distribution systems are likely to be even longer than those recorded in these laboratory sedimentation studies which were conducted under quiescent conditions. These longer sedimentation times are due to the effect on sedimentation rates of the small particles present (shown as approximately 10 µm in Table 1-2) and the almost continuous flows present in the water distribution system due to water demand. Boxall et al. (2001) used Stokes Laws to suggest that, once particles of this size are entrained, they will stay in suspension and not re-deposit onto the pipe wall due to sedimentation because of turbulence at the pipe wall.

It might therefore be concluded that sedimentation is not the dominant accumulation mechanism in water distribution systems. However, this conclusion does not explain how material in a system becomes attached to the pipe wall, as found by Grainger et al. (2002) and Ekanayake et al. (2003) and why corrosion products have accumulated in PVC pipes in unlined systems, as found by De Rosa (1993) and Gauthier et al. (1997).
Post flocculation of particles within the water distribution system must therefore be considered. Grainger et al. (2003) note that samples taken from a service reservoir tank in an unfiltered water distribution system required sonification to disperse conglomerates before particle size measurements were made. Modal particle size moved from 25 µm to 12 µm with sonication (Grainger et al. 2003). It must be noted, however, that even a particle of 25 µm will take 10 hours to settle at flow rates well below those experienced in a water distribution system for this length of time. Therefore, another mechanism for deposition must exist for the majority of particles.

Sethi (1996) conducted a review of literature on deposition of particles under turbulent and laminar conditions. Based on his review, Sethi (1996) proposed that deposition of fine particles in water distribution systems would actually increase with increasing Reynolds number. This increased deposition takes place because, with increased turbulence, more of the particles will achieve effective transfer into the laminar sub-layer at the pipe wall through ‘turbulent bursts’. Once in the laminar sub-layer, the particles will adhere to the pipe wall due to van der Waals forces. These particles could collect on the full circumference of the internal surface of the pipe (Sethi 1996). These findings of Sethi (1996) are supported by laboratory test rig experiments by Grainger et al. (2002) who found that, when a steady state high velocity, well above a velocity that would prevent sedimentation was created, particle numbers in the bulk flow decreased over time.

Based on the experimental results of Grainger et al. (2002), Wu et al. (2003) derived an equation to model the transfer of particles from the bulk flow to the pipe wall. This equation is based on Fick’s Law of diffusion, calculating the mass flux of particles from the bulk flow to the pipe wall. Results showed that the particle wall deposition equation could be calibrated to experimental results under different flow conditions using a mass wall coefficient. Once the mass wall coefficient is known the particle mass at the wall could be calculated under steady state conditions. Although these results increase the level of confidence in the mechanism of particles collecting on the pipe wall due to van der Waals forces, more development is needed before it can be practically used by water companies. This further work is required because, based on the preliminary data presented, the mass wall coefficient appears to vary with particle concentration, particle characteristics and water velocity.
Adhesive or cohesive layers

Cohesive sediments are those in which the attractive forces (electro-chemical and biological forces) between particles are stronger than the force of gravity (US Army Corps of Engineers 2002). Adhesive materials are those where different types of substances, such as biofilms, particles and the pipe wall, have attractive forces (electro-chemical and/or biological). In both cases van der Waals forces are dominant and both can occur simultaneously.

The cohesion-erosion mechanism theory may have relevance to drinking water pipes through research conducted in sewers and estuarine mud flats. The U.S. Army Corps of Engineers (2002) and Black et al. (2002) provide a substantial review of the behaviour of cohesive sediments in estuarine coastal environments. Pisano et al. (1998) and De Sutter et al. (2000) provide a similar review of behaviour of cohesive sediments in sewers and stormwater drains. However, there has been limited direct research on cohesive sediments in water distribution systems.

The research into cohesive layers in other areas, such as rivers, needs careful interpretation when applied to water distribution systems, as there are significant differences between the environments. Firstly, the electrochemical interactions between particles increase with salinity (U.S. Army Corps of Engineers 2002). Secondly, conditions in pipes are different from those in channels and rivers due to the different cross-sectional shapes, significant variations in hydraulic conditions and limited supply of sediment influencing the flow (Raudkivi 1990; Ekanayake 2003; and Delleur 2001). Thirdly, the cohesive and/or adhesive properties of sewers and stormwater systems tend be due to fats, grease, tars and electrochemical forces in organics (Delleur 2001) which are not likely to be present in water distribution systems. Nevertheless, some conclusions can be drawn from these studies on the likely behaviour of cohesive sediments in water distribution systems.

As previously indicated (Section 1.3.1 under ‘Importance of particle characteristics’), particles will act in a cohesive manner in fresh water when the grain size of the particle is less than 20 – 30 µm (Delleur 2001; and Friedman et al. 2004) or if over 10 % of the material is clay (< 2 µm) (Raudkivi 1990). Much of the material found in water
distribution systems is in this size range and therefore would be likely to act in a cohesive manner (see Table 1-2). In addition, particles from an unfiltered and lined water distribution system in Melbourne, Australia, have been found to be dominated by clay (van der Walt et al. 1999; Grainger et al. 2003; and Ekanayake et al. 2003). These particles have also been observed to act in a cohesive manner in laboratory experiments (van der Walt et al. 1999; Johnson and Gianchino 2000; and Grainger et al. 2003). The cohesion-erosion process was thus adopted as the most likely underlying mechanism for the formation of discoloured water formation in the unfiltered and predominately lined water distribution system used in this study.

**Entrainment of particles**

A key parameter in the entrainment of cohesive particles is shear stress. Applied shear stress at the interface between the cohesive layer and the water arises from the hydraulics of the water in the pipe. Shear stress is comprised of two components, a dynamic component caused by the acceleration of the water and a steady state component related to the steady state velocity of the water. Work by van den Boomen et al. (2002) and van den Boomen (2004) suggests that the dynamic component is small compared to the steady state component for large potable water pipes with a diameter greater than 400 mm. [The theory of shear stress in pipes can be found in basic texts such as Crowe et al. (2001).]

It is generally accepted within the literature that a critical shear force at the cohesive layer and water interface must be exceeded for significant particle entrainment and re-suspension to occur (Ackers et al. 2001; and Black et al. 2002). Entrainment then occurs at an erosion rate which is equal to the rate of particle suspension with time (Ravisanger et al. 2001; Black et al. 2002; and U.S. Army Corps of Engineers 2002).

Black et al. (2002) report that the following factors were used in other fields to deduce functional relationships between major physical sediment properties, critical shear stress and the erosion rate: “dry and bulk density mineralogy, clay fraction, electrochemical properties, water content, vane shear strength, elastic and plastic properties, biochemical properties”. However, even with this theoretical framework, no universal relationship or predominant property has been identified. Black et al. (2002) therefore
suggest that laboratory experiments, where factors can be controlled, are the best means of investigating erosion rates.

Ravisanger et al. (2001), Black et al. (2002) and U.S. Army Corps of Engineers (2002) discuss the various studies that have been conducted to determine erosion rate formulae in rivers and estuarine mudflats. All the equations considered in those studies suggest that the erosion rate is dependent on the amount by which the critical shear stress is exceeded by the applied interfacial shear. This difference is defined as the excess shear stress $\tau_{xs}$ and expressed by Equation 1-1.

$$\tau_{xs} = \tau_0 - \tau_c$$  \hspace{1cm} (1-1)

Where:

$\tau_{xs} = $ excess shear stress;

$\tau_0 = $ shear stress at water and cohesive layer interface; and

$\tau_c = $ critical shear stress of entrainment.

Erosion occurs when $\tau_{xs} > 0$.

According to Black et al. (2002), for freshly deposited cohesive layers in sewers in the process of an initial self-weight consolidation, the erosion rate is a function of the excess shear stress, as shown by the commonly used Partheniade’s equation, shown in Equation 1-2.

$$\ln(\varepsilon/\varepsilon_f) = \alpha((\tau_0 - \tau_{c(z)}))^{\beta}$$  \hspace{1cm} (1-2)

Where:

$\varepsilon = $ erosion rate;

$\varepsilon_f = $ floc erosion rate;

$\tau_{c(z)} = $ critical shear stress for entrainment at distance toward the pipe wall $z$, (sometimes referred to as the bed shear strength);

$\beta = $ exponent coefficient; and

$\alpha = $ rate coefficient.

For consolidated or mechanically emplaced cohesive layers in sewers that are comparatively uniform over the uppermost few centimetres, the erosion rate is
proportional to a dimensionless excess shear stress as indicated by the commonly used Partheniade’s equation in Equation 1-3.

$$\varepsilon = \varepsilon_M \left(\frac{\tau_0 - \tau_c}{\tau_c}\right)^{\delta}$$

Where:

- $\varepsilon$ = erosion rate;
- $\varepsilon_M$ = rate coefficient; and
- $\delta$ = exponent.

An erosion rate proportional to a dimensionless excess shear is also reported for mudflats (U.S. Army Corps of Engineers 2002) and clays in rivers (Ravisanger et al. 2001). However, these equations have not been applied to water distribution systems.

A number of empirical studies have, nevertheless, been conducted in both sewer and water distribution systems to determine the critical shear stress. Using a 100 mm clear PVC pipe test rig and particles collected from an unfiltered system, Johnson and Gianchino (2000) and Grainger et al. (2002) found that significant suspension began at 0.12 – 0.13 m.s$^{-1}$, equating to a critical shear stress of 0.05 N.m$^{-2}$. The only field trials found in literature to determine the critical shear stress specifically in a water distribution system were by Polychronopoulos et al. (2001). In those field experiments, Polychronopoulos et al. (2001) consistently found that the critical shear stress required to entrain material in an unfiltered water distribution system was below the minimum hydraulic conditions that could be generated by a hydrant disturbance (0.12 m.s$^{-1}$) for small pipe sizes tested. They therefore concluded that induced hydraulic disturbances using hydrants in the field could not be used to accurately determine the critical shear stress for small pipe sizes.

The erosion rate and critical shear stress can be affected by biological activity, consolidation, and concentration of cohesive additive. Black et al. (2002) indicate that biological activity could strengthen or weaken a cohesive layer, raising or lowering the critical shear stress and decreasing or increasing the erosion rate. However, Grainger et al. (2003) found that, for particles collected from within a number of water distribution systems in Australia, the increase in strength of the cohesive layer was due to
consolidation and van der Waals forces. Biological activity was not found to have an effect.

The greatest rate of strength increase in the cohesive layer found by Grainger et al. (2003) occurred in the first day after the material was left to consolidate. No significant additional strength increase occurred over the period of a week. This increase in cohesive strength, due to consolidation, increases the critical shear stress and reduces the erosion rate. The critical shear stress and erosion rate can also be altered by several orders of magnitude depending on the concentration of a cohesive additive, such as clay (Delleur 2001). The critical shear stress and erosion rate may also change with both time and location due to the combined effect of consolidation and cohesive additive.

The erosion rate has been described as being either constant or decreasing with depth through the cohesive layer depending on the bed structure (Black et al. 2002; and Shrestha et al. 2001). A constant erosion rate indicates that the sediment layer will maintain the same strength through the layer. A decreasing erosion rate indicates that the strength of the sediment layer increases with distance toward the pipe wall. Laboratory experiments using test pipe rigs with material collected from the an unfiltered system (Grainger et al. 2002) and field experiments in an unfiltered system (Polychronopoulos et al. 2001) both concluded that the cohesive layer strength increased with distance toward the pipe wall.

Delleur (2001) observed that when the critical shear stress is exceeded in sewers a sudden collapse of the cohesive bed structure can take place so that material is “stripped” from the pipe wall in clumps larger than the underlying particle size. This phenomenon indicates that the cohesive forces between particles in the sewer system are greater than forces between the cohesive layer and the pipe wall. This sudden collapse of the bed structure leads to clusters of varying size being carried down the stream similar to the process for non-cohesive particles. In contrast to these sudden breakout results in sewers, visual inspection by Grainger et al. (2002) in potable water test rig laboratory experiments using material collected from a number of water systems in Australia placed in the pipe, indicated that erosion of the cohesive layer occurs over a long period of time.
However, using a test rig and particulate material from an unfiltered potable water system, Johnson and Gianchino (2000) and van der Walt et al. (1999) observed that laboratory experiments using potable water displayed a mixture of both the time dependent erosion and the sudden stripping mechanism. The particles at the pipe wall were eroded over time by the “stripping off” of conglomerates that then broke up as they travelled along the pipe. This type of mechanism is supported by findings of Grainger et al. (2002) who found that sonication and turbulence reduced the particle size of material collected from a water distribution system in Melbourne.

This type of mixed erosion/stripping process is also reported by Grainger (Grainger 2003) who noted that in potable water laboratory experiments erosion of the cohesive layer occurred to a particular depth toward the pipe wall followed by a collapse of bed structure. This observation may again indicate that the cohesive bonds between particles in unfiltered water systems are stronger than the adhesive bonds between particles and the pipe wall, in this case a PVC pipe. Differences in pipe material and particle chemistry would therefore seem to affect adhesive and cohesive bonds and should be investigated further.

**VARIANCES IN CRITICAL SHEAR STRESS RESULTING FROM VARIATIONS IN THE COHESION - EROSION CYCLE**

The basic cohesive layer theory noted earlier indicates that when a shear stress greater than the cohesive layer surface strength is applied, the cohesive layer will erode until equilibrium between the applied hydraulic forces and the resisting cohesive forces is again realised. The cohesive layer surface strength is dependent on past shear stresses that have been applied to the layer and the rate of particle accumulation (Boxall et al. 2001). In addition, the surface strength is dependent on the rate of consolidation (Grainger et al. 2002). Thus, the critical shear stress is not a constant figure, but varies with flow, and therefore location and time. The overarching conclusion from this prior work is that there is no single “magic number” for critical shear stress of entrainment for water distribution systems.

The discoloured water prediction model described by Boxall et al. (2001) and Boxall et al. (2004) proposes that, provided the cohesive layer has not been recently disturbed, the cohesive layer surface strength can be modelled as the peak shear stress experienced
under normal demand. However, as it is not known how quickly particles accumulate, or in this case are generated by corrosion, it is not known how distant in time an event must be before it does not affect the critical shear stress. Theoretical equations are proposed by Boxall et al. (2001) to determine the way in which a cohesive layer ‘regenerates’ after an excess shear stress event, so that this effect can be modelled. However, the parameters required for cohesive layer regeneration are not fully known and the regeneration equations have not been verified. Therefore, further research is required to determine the speed in which cohesive layers regenerate and consolidate so that a means to estimate the variable critical shear stress under all conditions can be developed.

1.3.3 Causes of hydraulic disturbance

Operational procedures create hydraulic disturbances in the water distribution system, which may result in water velocities which exceed the critical shear stress, and cause discoloured water. A literature survey could locate only a few articles that directly referred to the type of activities such as operational changes within the system that may cause discoloured water (van den Hoven and Vreeburg 1992; Gray 1994; Chambers 2000; Brunone et al. 2000; and Boxall et al. 2001). Most articles describe these occurrences as “abnormal hydraulic events”, without being more specific.

Chambers (2000) also comments on the lack of published data and literature on this topic. To derive some understanding of the types of events causing discolouration, Chambers (2000) surveyed selected staff from United Kingdom water utilities. The operational activities that the water utility staff indicated may lead to discoloured water include:

- High risk - burst and main repairs;
- Medium risk - operation and maintenance of valves, step tests for leakage control, operation of hydrants (for fire fighting, sample collection or filling of tankers), recommissioning of out-of-service pipes, pipe recharging, change of supply;
- Low risk - pump switching and poor service reservoir maintenance.
Other operations work mentioned in literature include: hydrant operations (van den Hoven and Vreeburg 1992), repair and maintenance work (Gray 1994), and bursts, rezoning and annual peak demand (Boxall et al. 2001).

Periods of transient flow (such as water hammer), which create a dynamic component of shear stress, have been reported to lead to discoloured water (Brunone et al. 2000). These dynamic events have been documented as causing biofilm stripping and efficient re-suspension of particulates. However no studies that determined the relative contribution of water hammer in comparison to steady state shear stress in creating discoloured water events in water distribution systems could be found.

1.3.4 Locations of accumulated particles in water distribution systems

It appears from the literature that in both unfiltered and filtered water distribution systems particles accumulate in all pipes. However, a larger volume of particles have been found in dead ends, smaller diameter pipes and behind joints in both types of systems. For example, a number of studies in filtered systems found a larger volume of particles collect in dead ends where lower flows than in ‘through mains’ can be reasonably expected to occur in the distribution system (De Rosa 1993; Gauthier et al. 1999; Barbaeu et al. 2000, and Gauthier et al. 2001). De Rosa (1993) and Smith et al. (1997) also found a greater volume of particles in small diameter pipes (< 20 inch) than large diameter pipes (>20 inch). Smith et al. (1997) and Maier (1998) noted that particles can accumulate behind valves. Work by Yarra Valley Water (1999) and unpublished studies by South East Water suggest that unfiltered water distribution systems also experience a greater build-up of particles in small and dead end mains. This conclusion is reached because there was a higher proportion of complaints (as an indicator of discoloured water) from customers serviced by dead end mains (which are also typically small pipes) than those serviced by through mains.

The additional volume of particles present in dead ends, small pipes and joints has typically been attributed to sedimentation during periods of laminar or stagnant conditions (De Rosa 1993, Gauthier et al. 1996; and Yarra Valley Water 1999). However, as discussed in Section 1.3.2, sedimentation due to gravity is not expected to be the dominant deposition mechanism for the majority of particles due to the small
particle size. As previously established, the particles in the size range found in water distribution systems are likely to collect due to van der Waals forces during low turbulent flow and form cohesive layers.

Cohesive layer theory accounts for the greater volume of particles removed from dead ends and small pipes. Significant erosion of the cohesive layer will only occur when a critical shear stress is exceeded. Cohesive layers are conditioned by pipe hydraulics so that, assuming no abnormal hydraulic events have occurred, the critical shear stress will be in equilibrium with peak shear stresses. Therefore cohesive layer theory suggests that the cohesive layers in areas of low flow (such as dead ends) will have a lower critical shear stress than mains (such as ‘through mains’) that typically experience regular higher flows. This hypothesis means that, for a hydraulic disturbance with the same shear stress, more material would be eroded from a pipe that typically experiences low shear stresses, than from a pipe that typically experiences high shear stresses.

Smith et al. (1997) observed that joints promoted the accumulation of deposits and hypothesised the cause to be local low velocities in flow patterns near the joint. Localised turbulent flow will also actively transfer particles to laminar sub-layers behind a joint increasing deposition due to van der Waals forces, as discussed in Section 1.3.2. If the valve is closed, it would act like a dead end main and the processes discussed above for dead end mains would occur.

There is a greater probability of ‘through mains’ experiencing atypical events, as they service a greater area of the network than dead end mains and are impacted by flow changes across a wider area of the network. As a result, particles collected in the cohesive layer in ‘through mains’ may also be exposed to a greater number of events where the critical shear stress is exceeded. Frequent and regular occurrences of high shear stress may cause the main to be self-cleaning, preventing the build up of particles and resulting in no situations where sufficient particles are entrained at a significant concentration to cause a discoloured water event. The concept of self-cleaning velocities was developed in van den Boomen et al. (2002), and van den Boomen et al. (2004). The self-cleaning concept also suggests that the greater volumes of particles in dead ends, relative to ‘through mains’, are due to a lower critical shear stress and low incidence of
critical shear stress being exceeded rather than increased rate of accumulation (through sedimentation theory).

Many particle-sampling studies have found that not all particles accumulate in the area in which they are formed but may originate from further upstream. For example, Gauthier et al. (1996) and Smith et al. (1997) found iron oxide particles in a number of samples taken from PVC mains where they could not have originated. Some trends have been found linking the likely origin of particles and the pattern of particle accumulation in the water distribution system. A major study undertaken in the United Kingdom involving 71 supply zones reported by De Rosa (1993) found that, if the treated water was of poor quality, particles would accumulate to a greater extent in dead end mains. De Rosa (1993) also found that, when the deposits were likely to have been a result of corrosion products, then the locations of the deposits were more evenly distributed between dead-end and ‘through’ mains. Barbeau et al. (2000) agree, and found that for unlined systems with the same source water, main material, hydraulic configuration and approximate detention time, there was variability in the volume of material found in dead ends and other parts of the system. Barbeau et al. (2000) also concluded that corrosion might have the dominant effect on the total amount of deposits collected during flushing for unlined systems.

However, the relationship between the volume of particles collected in a main and water quality seen by the customer seems to be complex. De Rosa (1993) found no clear correlation between the volume of particles in the main and the water quality at customer premises during an induced hydraulic disturbance. Although the entrainment of deposits usually caused severe problems at houses near a hydraulic disturbance, some properties appeared to be more affected by a discoloured water event than others situated on the same main, without an obvious cause. De Rosa (1993) also notes that in some cases the discoloured water event lasted 3 or 4 hours and effected areas of up to 300 metres from the point of disturbance.
1.3.5 Limitations of laboratory and field trials for discoloured water formation in unfiltered potable water systems

The limitations of major studies that have been conducted on the unfiltered water system in Melbourne, Australia to determine the mechanism of discoloured water formation are discussed below. Many of their results are referred to previously in the above sections.

The experiments of Johnson and Gianchino (2000) and van der Walt et al. (1999) were conducted with sediment collected from a service reservoir tank of an unfiltered system supplying South East Water (SE Water) in Melbourne, Australia. Ekanayake et al. (2003) found that the characteristics of the particles in sediments collected from service reservoirs in the same system were comparable to those in the water distribution system, validating the use of these sediments and eliminating corrosion as the dominant particle source. However, the collected particles were continuously reused in the laboratory test rig, which introduced potential unknown effects of particle changes with age. Van der Walt et al. (1999) used non-cohesive theory to describe the behaviour of particles that were found to be mainly clay and clearly acting in a cohesive manner. Their conclusions are therefore weakened by not having considered cohesive aspects of the particle behaviour.

Particles used in laboratory based experiments to develop the Particle Sediment Model (Grainger et al. 2002 Grainger et al. 2003, Wu et al. 2003 and Ekanayake et al. 2003) were collected from water distribution systems using hydrant flushing and water service reservoirs (tanks) during tank cleaning. Collecting particles by hydrant flushing may introduce two types of errors:

1. Particles may be drawn from further upstream and therefore the sample may not accurately represent the deposits in the main being tested (Walski 1991); and
2. The magnitude and duration of the shear stress created by the hydrant flush was not reported and may affect the volume of material resuspended from the pipe wall if the layer is cohesive, and the size range mobilised if the particles are non-cohesive.
There is therefore no way to link the hydraulic conditions generated in the sample collection to those usually experienced in the system. Particles for laboratory experiments for the Particle Sediment Model that were collected from water service reservoirs were transported to the laboratory in tankers. Grainger et al. (2003) observed that some larger particle sizes settled out in the tankers and were not able to be analysed.

All three of those laboratory experiments were conducted on 100 mm diameter clear PVC main. Only Wu et al. (2003) compared the effects of PVC relative to the commonly used cement lined, cast iron (CLCI) mains on accumulation mechanisms or rates. As many mains within water distribution systems are not of PVC, this is an important shortcoming of those experiments. Also, none of those laboratory experiments replicated the diurnal flow profiles found in live systems (Grainger et al. 2002 Grainger et al. 2003, and Wu et al. 2003).

Polychronopoulos et al. (2001) conducted field studies in dead end mains (< 100 mm diameter) in the unfiltered and lined water distribution system of SE Water. In that study, hydrant flows were increased in steps and turbidity measured continuously. The point at which turbidity increased was used to indicate the point at which material was being resuspended from the main. However, the velocity to resuspend material in the main was found to be consistently below the minimum velocity that could be achieved by a hydraulic disturbance using the hydrant configuration (0.12 m.s$^{-1}$), limiting the usefulness of results. This critical velocity of entrainment is consistent with results of Grainger et al. (2002) who established that particles began to be entrained at 0.07 m.s$^{-1}$ in the same diameter pipe (100 mm).

1.3.6 Existing discolouration prediction models based on particle behaviour

Ackers et al. (2001) report that the equations for many of the commercially available particle transport models in water distribution systems have been derived from research on slurry transportation using the Ackers-White formula. The Ackers-White formula is inappropriate for water distribution systems because it considers only a single characteristic sediment size and a high concentration of particles (Ackers et al. 2001).
Particle behaviour changes when a range of particle sizes are present, such as indicated in Table 1-2, and settling times can alter with different concentrations of particles (Tebbutt 1992; and Raudkivi 1990). Therefore application of the Ackers-White formula to water distribution systems with their quite different particle characteristics to those of slurry flows is likely to result in erroneous conclusions (Ackers et al. 2001).

Two models which are not based on the Ackers-White formula are currently under development: (1) the Prediction Of Discoloration events in Distribution Systems (PODDS) Model (Boxall et al. 2001 and 2004); and (2) the Particle Sedimentation Model (Wu et al. 2003).

The empirical PODDS model outlined in Boxall et al. (2001) is a computer model for prediction of discoloured water from cohesive sediments in water distribution systems. This model is derived from sewer research and was validated for the United Kingdom water distribution systems dominated by iron corrosion (Boxall and Saul 2005). It is based on the fundamental principle that the material causing discoloured water is held to the pipe wall in stable cohesive layers. The model is coded into EPANET (Rossman 2000).

Within the PODDS model, the cohesive layers are described as having a profile of discoloration potential related to layer strength, with an increase in discoloration potential corresponding to a decrease in layer strength. The ultimate strength of the layers is theorised as being determined by the shear stress imposed within each main at the time of a relatively constant peak daily flow. Thus peak daily flow that typically occurs in the main is assumed to control the potential for discoloured water. The model is based on the assumption that disequilibria hydraulic conditions (burst, re-zoning, increased daily flow etc.) may expose the cohesive layers to forces in excess of their conditioned cohesive strength, leading to a mobilisation of the layers and the generation of a discoloration event.

In practice the model is applied by calibrating a measured flow rate and turbidity response of a system to a predicted flow rate and turbidity response. The measured turbidity response of the system is collected using a short duration of continuous on-line testing of flow rate and turbidity when a hydrant is opened (to ascertain the system
reaction under atypical conditions). A number of parameters that are used to describe the relationship between the strength of the cohesive layer and its potential to cause discoloured water, as described by a stored turbidity volume, are optimised to achieve this calibration (Boxall et al. 2001). Predictable values for the parameters of the PODDS model have been found to be dependent on pipe sizes, material and age for a number of English potable water systems. To use the model effectively in Australia a table of these values needs to be developed by conducting a range of field trials.

As noted above, the conditioned strength of the cohesive layer in the PODDS model is assumed to be equal to the shear stress at an assumed typical peak daily flow. Peak daily flow is usually ascertained by a combination of system knowledge and optimisation of the model parameters and not through direct measurement. If the modelled cohesive layer strength is very different to that which would be anticipated from the peak daily flow it is assumed that a recent event of high shear strength has occurred in the system which has eroded the cohesive layer and that there has not been sufficient time for the layer to regenerate.

The PODDS model has provision for a layer regeneration parameter to simulate the growth of the layer from any material source, although these equations have not yet been incorporated or validated. The model also has no provision for the loss of concentration of particles from the bulk flow as they re-accumulate onto the pipe wall during regeneration of the cohesive layer.

PODDS runs as a water quality element within the EPANET substance tracking and transport algorithms. As such the model is subject to the assumptions of quasi-steady state modelling within EPANET, so that effects from dynamic shear stress are not considered. Furthermore, the model does not directly address how material collects in the cohesive layers and assumes that particles will stay in suspension after they are entrained. Although this assumption of no re-accumulation of particles appears to be appropriate during the short term modelling of a discoloured water event (i.e. when flow rates are high), in reality particles do not appear to stay in suspension (even from corrosion) based on the empirical evidence of particle accumulation discussed in Section 1.3.2.
The Particle Sedimentation Model of Wu et al. (2004) predicts the accumulation of sediment based on an average settling rate of particles, average velocity of flow necessary to begin re-suspension and an average velocity to resuspend all particles. The model is developed for the Australian water industry for both filtered and unfiltered water distribution systems.

The settling and re-suspension rates of the Particle Sedimentation Model are based on particle analysis and investigation reported by Grainger et al. (2002) and Grainger et al (2003). They are therefore subject to the limitations of these studies as discussed in Section 1.3.5. Although a theoretical basis is presented for the collection of particles onto the pipe wall via van der Waals forces, the only published application of this theory that could be found was a preliminary test, using the model, for settling of particles by gravitational forces only (Wu et al. 2004). Cohesive forces preventing entrainment are taken into account in re-suspension rates, as the re-suspension rates are based on measurements in laboratory test rigs where particles were noted as forming cohesive layers.

This model is currently undergoing validation on real systems. Limitations of the model are the need for laboratory testing to determine particle behaviour parameters and the fact that the tests have been conducted mainly on 100mm diameter PVC and cast iron cement lined (CICL) mains. Average deposition and re-suspension rates are also used, where a range of particles are actually present in the live water distribution system. The effect of particle characteristics on the transport of particles when scaling up from the laboratory to a whole water system is not presented.

Short term modelling of turbidity that is directed at modelling a system during water mains flushing has been successfully conducted by authors such as Walski and Draus (1996). In that study Walski and Draus (1996) hypothesised that the amount of turbidity generated was related to the velocity generated in the water main by the flushing procedure through an empirical relationship between velocity and turbidity. EPANET was used to conduct the modelling using field measurements of turbidity taken every 10 minutes. In the filtered and unlined system modelled, discolouration consisted of an initial period in which turbidity values were high. These turbidity values then taper off, consistent with the findings of other authors in both filtered and unlined systems.
(Boxall et al. 2004) and unfiltered and lined systems (Grainger et al. 2002 and Grainger et al. 2003). However, Walski and Draus (1996) rightly point out that, notwithstanding these results, the relationship between turbidity and velocity is likely to be dependent on the nature of the solids and the amount of material that has collected in the pipes since the last sufficiently high flushing velocities.

1.4 Current methods for measuring and predicting discoloured water

Prediction of areas in which discoloured water will be created for the purpose of optimising mains cleaning operations of water companies has been attempted for many years. This prediction has typically been driven by the desire to reduce customer complaints, as the number of complaints are a Key Performance Indicator and/or regulatory reporting requirement for many water companies. For example, the water retail companies in Melbourne, Australia, ‘compete by comparison’ using these Key Performance Indicators. The aim of the comparison of the three retail water companies on the basis of discoloured water complaints, is to encourage continual improvement of the service provided and the identification of the optimum way of reducing the occurrence of discoloured water, while containing expenditure.

To reduce customer complaints, methods have been developed to predict discoloured water events, or areas likely to experience events, and to clean these areas. However, most current discoloured water prediction methods are derived from measurement techniques that are based on data that can be sourced at the least cost or, alternatively, anecdotal evidence from field observations, rather than targeted investigations. These approaches have led to historical records of customer complaints and required regulatory water quality grab samples being the dominant ‘measurement’ techniques used by water companies worldwide to assist in predicting areas at risk of discoloured water events (Prince 2003; and Ellison 2003). As a result, research has tended to focus on the optimal use of these existing measurements or their augmentation, with only limited studies evaluating how appropriate these measurements actually are.

The use of other measurement methods, such as empirical measurements in the field and water quality models, is relatively new. The acceptance of these new specific
measurements techniques by the international water industry is patchy and the evaluation variable. The only country with significant publications that does not employ customer complaints and grab samples as primary measuring techniques is the Netherlands. In the Netherlands the primary method used is a repeatable insitu measurement called the Re-suspension Potential Method (RPM) which is used to determine the water quality response of a system to a hydraulic disturbance which is then used to predict mains cleaning rates (Prince 2003; and Slaats 2002). The nature and use of these and other techniques are reviewed in the following sections.

1.4.1 Customer complaints

A customer complaint is defined as the record of a customer complaining directly to a water company regarding water quality. Analysis of historical customer complaint data (location, time and/or frequency) is currently the primary way in which water companies worldwide identify areas of high risk of future discoloured water events (Goold et al. 1991; Deb and Hasit 1995; Jones 1996; Prince 2003; and Ellison 2003). The predominance of this technique is probably due to complaints being a freely available data source, as long as good records are kept (Chadderton et al. 1992).

The underlying assumption for using customer complaints is that a complaint will only occur when discoloured water has been created, so that long-term trends may indicate areas with recurrent problems (Clement et al. 2002). However, this base assumption is not in agreement with other results in the literature. The literature tends to support the use of customer complaints only when they are used in conjunction with other parameters (Evins et al. 1990; Davis and Smith 1993; Schaap et al. 1999; and Clement et al. 2002). One of the reasons for the need to use parameters additional to actual customer complaints is because customers tend not to complain about every incident of discoloured water they receive. The reasons behind a customer not complaining are discussed below.

Factors affecting whether a customer will complain

Survey results in both Australia and the United Kingdom have found that the majority of customers do not complain even when they are dissatisfied with the appearance of drinking water. The proportion of customers that complain when they observe incidents of discoloured water varies from region to region. Sydney Water, in a survey of its
customers, found that only 7% of customers that had observed aesthetically unpleasing water over a 12 month period complained (Roseth 2002). In the predominately unfiltered SE Water system in Victoria, only 16% of customers who observed discoloured water complained (Roseth and Rock 2003). Ewan and Williams (1986), in a survey of water customers in the United Kingdom, found that on average 30% of customers who observed discoloured water complained.

This result is comparable to research in the general corporate retail sector where it is expected that only a third of those who have experienced ‘performance worse than expected’ will complain to the company, while the remainder are more likely to complain to others or boycott the company (Engel et al. 1990). In the water industry, boycotting as a response to water worse than expected is relatively limited in scope but could take the form of drinking bottled water (this has occurred to a greater degree in Sydney, Australia since the cryptosporidium incident in 1998) or installing home filters (Barnett 1998; and Roseth 2002).

Results based on customer surveys, such as those discussed above, should be treated with an additional degree of caution. The need for this increased caution arises from the fact that customer questionnaires or surveys are subjective and the answers sometimes misleading and inaccurate, which may lead to poor data (Engel et al. 1990; Evins et al. 1990; and Ellison 2003). For example, because of the way in which the human memory deals with time, surveys relying on a customer recalling the number of incidences that they have noticed in a preceding period can overestimate the number of incidences received. For example, it is hard for customers to remember if an incident occurred, say, 12 or 15 months previous (Engel et al. 1990; Evins et al. 1990). This aspect of human memory is well documented in the sociology field. Other objections are that the selection of customers for surveys can be biased, and the collection process expensive (Lindley and Davies 1995).

Even when the inherent inaccuracies of customer surveys are taken into account, survey findings demonstrate that not all customers complain about every incident of discoloured water that they receive. Therefore, complaints are at best an indirect measure of customer satisfaction.
Factors affecting whether or not a customer will complain when dissatisfied include human behaviour, demographic variations and water company awareness. These factors are discussed more fully below.

**Customers solving the problem themselves**

Lawrence and Stratton (1999), in a major customer survey, found that customers in the water sector will usually only complain when their own actions to remedy the situation do not work. Before complaining most customers will try and solve the problem by: (1) running the tap; (2) letting the water settle; and (3) waiting for the discoloured water to disperse in its own time. Only as a final step, will the customer contact the water company.

**Water use**

The frequency that a customer actually sees and implicitly examines the water, which can be interpreted as the frequency of measurement, is dependent on the pattern of water use (Williams and Ewan 1987) and logically the type of water use. It is likely that considerably less water is used in ways in which discoloured water is readily observable (for example, 2 litres/person/day is directly drunk out of an average usage of 331 litres/person/day of potable water in Melbourne, Australia, in 2006) than uses in which a discoloured water event would not be observed (for example out door use of 66 litres/person/day) (water use figures from Central Region Sustainable Water Strategy 2006). Therefore, customers are not a continuous measurement of water quality and there is a relatively high probability that a customer will not see a discoloured water event.

**Geographic and demographic variances**

Customer expectations of the level of service for water supplied to their home can vary quite considerably from region to region (Owen *et al.* 1999). For example, customer surveys conducted by Ewan and Williams (1986) found that the number of customers who actually complain when they receive discoloured water was highly variable with location, varying from 0 to 70 %. This geographical variance can been linked to a number of factors; (1) the water quality that the customer usually receives (Ewan and Williams 1986); and (2) demographics of the community. This spatial variability of the conversion of customer dissatisfaction to customer complaints indicates assumptions of
the proportion of discoloured water incidences that will cause complaints cannot be transferred from one location to another.

In cities, such as Melbourne, Australia, with high living standards, the level of expected service is very high (McCarthy et al. 1997). Although Melbourne has historically been labelled one of the best water supplies in the world its water companies still receive regular customer complaints (Melbourne Water 2001; and South East Water 2003). By contrast, Ewan and Williams (1986) found that in a certain United Kingdom water system that supplied persistently discoloured water, no customer complaints were recorded. One explanation for this situation is that customers grow used to the quality of water supplied, and therefore come to expect a poor quality system to have a discoloured appearance (Ewan and Williams 1986). Therefore the complaint rate may not be a reflection on the amount of discoloured water events that occur but more related to the expected level of service of the customer.

Thurman et al. (1999) conducted a phone study of rural water customers in the state of Victoria, Australia, and found that the age, level of education and type of occupation of the customer influenced expectations. The higher the education or more skilled the occupations of customers, the more likely the customer was to be dissatisfied with the quality of water supplied. The older the person the more tolerant they were in regards to the quality of water supplied. This may relate to the expectation levels as described by Ewan and Williams (1986).

**Awareness of the water company**

Jones (1996) attributed an increase in water quality customer complaints in the United Kingdom to the public becoming more aware of the water industry after it was privatised. This phenomenon has lead to a need to invest in identifying and meeting customers’ expectations regarding the aesthetic level of water quality supplied, irrespective of the fact that a water supplier has a regional monopoly and is not in direct competition with another provider (Jones 1996). This was also the experience of Sydney Water, Australia. Customer complaints of water quality increased dramatically after a ‘boil water alert’ was issued due to a major cryptosporidium incident (Roseth 2002). However, this phenomenon was not found to occur in the USA. Customer surveys in the
USA found no change in customer satisfaction with water quality when Water Quality Reports began to be issued by the water providers (Johnson 2003).

**The level of water quality at which a customer will complain**

There is limited research published in relation to an objective technique for determining the level of discolouration at which a customer will complain, defined as the complaint threshold. It is, however, important to know this ‘complaint threshold’ in order to determine the level of service that is needed to prevent customer complaints.

The World Health Guidelines (1984), Australian Drinking Water Guidelines (1996) and many other guidelines and regulations suggest that a customer will complain when discolouration is just visible in a glass of water. Panel surveys to determine the complaint threshold have also been conducted in the Netherlands (Slaats 2002). [The aesthetic limits of water quality parameters are discussed further in Section 1.4.2.]

The factors discussed above support statements by Lindley and Davies (1995) that customer complaints can significantly underestimate a problem with discoloured water. In other words, a lack of complaints does not necessarily imply that the water quality is acceptable (Evins *et al.* 1990). In spite of the limitations of customer complaints as a means of assessing the occurrence of discoloured water, water companies and researchers have developed a number of methods to most effectively use customer complaints. These are discussed in the following sections.

**Methods of using complaints**

There are two primary ways customer complaints are used by water companies: (1) as a trigger for immediate investigation and remedial action in a small area where the complaint occurred (Ellison 2003); and (2) for the optimal planning of systematic system-wide mains cleaning (Evins *et al.* 1990; Chadderton *et al.* 1992; South East Water 1998; and Yarra Valley Water 1999).

Methods for the use of complaints for prediction of areas experiencing discoloured water include:
**Ranking**

Ranking essentially involves identifying, through complaints, those areas where discolouration problems are the worst, in order to determine a priority listing for potential remedial action. Many water companies use the frequency of complaints to identify problem areas (Evins et al. 1990; Chadderton et al. 1992; South East Water 1998; and Yarra Valley Water 1999). The complaints per 1000 properties are used to remove bias from differences in population figures in time and location before applying a ranking procedure (Evins et al. 1990; Yarra Valley Water 1999; South East Water 1998). This approach suffers from the shortcoming of assuming that customers in all areas of the system have the same complaint threshold, the same conversion rate from observing discoloured water to complaining, and the same sensitivity and water usage patterns. This aspect is clearly in conflict with other evidence from the literature.

Chadderton *et al.* (1992) suggest that ranking areas of highest complaints to lowest complaints has disadvantages. These disadvantages arise because multiple complaints may occur as a result of a single event, such as a pipe break, that produced only localised discolouration. This situation could result in the whole of a zone being cleaned, when only a small area was actually affected. To alleviate this bias, Chadderton *et al.* (1992) advocate a system where a single point or score is assigned to each month in a particular zone that has a complaint and an extra point is given if more than one complaint occurred in the zone. The points accumulated in one year for each zone are added and the zones ranked.

Chadderton *et al.* (1992) also suggest filtering out complaints associated with fire fighting and hydrant testing as they do not indicate systemic long-term deterioration in the distribution system. However, if an area is susceptible to continual collection of deposits then multiple complaints, including complaints associated with fire fighting and hydrant testing, may represent a long-term deterioration that is evident only during times of higher flows in the area. The exclusion of fire-fighting or hydrant testing causes incidences from the complaint base may therefore not be appropriate.

*Geographic clusters and seasonal repetition*

Geographical clustering and seasonal repetition of customer complaints within hydraulic areas of the same source water have been used to identify problematic
hydraulic configurations and seasonal causes of discoloured water (Males et al. 1992; Yarra Valley Water 1999; Polychronopoulos et al. 2001; and Crowe et al. 2001).

The usefulness of complaints for identifying problematic hydraulic configurations and seasonal variances is limited by the location of customer connections. For example, Williams and Raphael (1997) suggest that customer complaints are not a good indicator of the need to clean transfer mains as few, if any, customers are supplied directly from transfer mains. However, logically, clustering of complaints downstream of a transfer main may indicate a fouled transfer main, but this type of analysis requires subjective interpretation of the customer complaint data.

Spectrum Colour

Water companies in Melbourne, Australia, divide discoloured water customer complaints into five categories based on how the customer would describe the appearance of the discoloured water. These categories are: Brown Water Complaints, Yellow Water Complaints, Black Water Complaints, Blue Water Complaints and White Water Complaints (South East Water 1998; and Yarra Valley Water 1998). The definitions for each of these categories are as follows:-

- Brown water emerges from the tap with a brown, red-brown or yellow-brown colour and has historically been attributed to clay, silt and rust particles (De Rosa 1993; South East Water 1998; and Yarra Valley Water 1998);
- Yellow water emerges from the tap with a yellow or yellow-brown colour and is usually a light version of brown water (Hearn 1999);
- Black water has been attributed to biofilm stripping (South East Water 1998; and Yarra Valley Water 1998) and manganese (Sly et al. 1990; and De Rosa 1993). (This categorisation should not be confused with the title “black water” used to describe sewerage effluent);
- Blue water emerges from the tap with a blue or green-blue colour and has been attributed to copper corrosion (South East Water 1998; and Yarra Valley Water 1998); and

Transfer mains (sometimes called trunk or transmission mains) are large pipes used to ‘transfer’ water from one area to another. Reticulation mains, which do have customer connections, branch off the transfer main and are typically of much smaller diameter.
- White water has been attributed to air bubbles and saturated air (South East Water 1998; and Yarra Valley Water 1998), chlorine (Johnson 1999), and high levels of zinc (Malina 1996);

Systems that have predominately unlined mains, such as those in the United Kingdom, have another category – red water. In this case the water emerges from the tap with a red colour, with the colour being attributed to the abundance of corrosion products from iron mains (Smith et al. 1997).

No studies were found that evaluated the effectiveness of techniques attempting to correlate customer complaints with the actual occurrence of discoloured water events. All techniques appeared to assume a correlation between discoloured water events and complaints, without verification.

### 1.4.2 Water quality grab sample analysis

A grab sample (sometimes called ‘still sampling’ or ‘spot sampling’) is a single sample of water taken for a quantitative measure of water quality without creating a large hydraulic disturbance within the main. In this way, test results of the grab sample measures the water quality of a system under typical operating conditions at a specific point in time and space (Chadderton et al. 1992; van den Hoven and Vreeburg 1992; and Evins et al. 1990).

Sampling under typical conditions is achieved by drawing from randomly selected customer taps, rather than from a hydrant which may produce water velocities large enough to disturb particulate material. The sampling is typically taken on a routine but infrequent basis, often based on compliance sampling frequency rates (NHMRC and ARMC 1996; and Lindley and Davies 1995). For example, in Australia routine grab sampling is usually conducted at rates suggested by the Australian Drinking Water Guidelines (NHMRC and ARMC 1996). Grab samples are typically analysed by determining the number of sample results that exceed regulatory or indicator limits.

Grab samples are often used by water companies for discolouration assessment as they are an existing source of information requiring no additional expenditure (Prince 2003;
There is, however, debate on the value of water quality grab samples for identifying areas of high risk of discoloured water formation. The central issue in this debate is whether the frequencies and timing of sampling are adequate as the sampling is generally specified by guidelines for determining base level water quality, not episodic discolouration. Some specially designed sampling programs have been proposed to better identify infrequent water quality issues (Kirmeyer et al. 2000; Chadderton et al. 1992; and Liebeschuetz and Hulsmann 1990). However the practical application and evaluation of these sampling programs have not been documented.

**Ways in which the results of grab sample analysis are used**

There are two ways in which water quality test results of grab samples are used by water companies to identify areas requiring cleaning or changes to treatment processes: (1) the frequency that grab sample test results exceed the aesthetic guideline limits are used to rank water systems in terms of failure of compliance (Ellison 2003); and (2) using changes in grab sample test results to identify both spatial and temporal trends in water quality deterioration to identify origins of particles and predict the risk of discolouration (Ewan and Williams 1986).

**Aesthetic parameters tested with grab samples**

The relevant guidelines during the time period over which the analysis in this study was conducted are the 1996 Australian Drinking Water Guidelines (ADWG 1996) and the 1984 World Health Organisation Drinking Water Guidelines (WHO 1984) which set levels that ensure water will be aesthetically pleasing and safe. A parameter is considered to have exceeded the aesthetic guideline when the concentration or amount is “just noticeable in a glass of water” (ADWG 1996).

A variety of parameters can be used to measure aesthetic water quality. These include spectrum colour, apparent colour, true colour, turbidity, particle counts, and suspended solids (Walski and Parker 1974; Ewan and Williams 1986; Bernal et al. 1999; and Gauthier et al. 1999). These parameters are often called organoleptic parameters. Such parameters are readily observable by the customer but have little health significance in themselves (World Health Organisation 1984; and Tebbutt 1992). Total iron,
manganese and aluminium are also used (Ewan and Williams 1986; Bernal et al. 1999; and Gauthier et al. 1999).

However, Evan and Williams (1986) argue against using total iron, aluminium and manganese to test for aesthetics, as typical measurements cannot distinguish between the soluble (colourless) form and particulate (visible) forms. The actual parameters used to determine discoloured water are usually limited to turbidity and colour (ADWG 1996, Bernal et al. 1999; and Gauthier et al. 1999) due to the ease in their measurement and interpretation. Colour and turbidity are discussed further in the following section.

**True colour and apparent colour**

The scientific measure of colour is either true or apparent. True colour is measured after the water is filtered, while apparent colour is measured before filtration and is thus a combination of the colour of solute substances and suspended particles (Mays 1996; and ADWG 1996). True colour is not an appropriate parameter to monitor the deterioration of water quality in distribution systems, because, as Ewan and Williams (1986) show, true colour results mainly from organic acids which are rarely affected by passage in the distribution system. Similarly Boxall et al. (2001) report that discoloured water is due to particulates, not true colour. Apparent colour is therefore a more appropriate parameter as it also takes into account the effect of particulates. ADWG (1996) suggests an aesthetic guideline level for apparent colour of 25 PCU (Platinum Cobalt Units) as the point at which a customer is likely to be able to see discolouration.

**Turbidity**

Turbidity is a measure of the extent to which a beam of light is scattered by the suspended matter within water (Gippel et al. 1991; Mays 1996; Malina 1996; and Sadar 1998). Turbidity is therefore not explicitly quantitative in terms of concentration, because it does not determine the number of particles present. It is however, a strong qualitative measure, indicating the extent of cloudiness or muddiness of the water. As human perception of discolouration is also based on the scattering of light (Thomas 1986), turbidity provides an indication of the visual impact on the customer of the particulate nature of water quality. [A history of the origin of the turbidity measurement can be found in Sadar (1998).]
Turbidity instruments are typically calibrated using a formazin standard. However caution is still required in comparing readings from different instruments, because, when particles other than formazin are tested, the turbidity measurement may differ (Slaats 2002; Gippel 1988; and Burlingame et al. 1998). This problem occurs because turbidity is highly dependent on the nature of particles, the wavelength of the light source used, and importantly the construction of the turbidity meter (Slaats 2002; and Burlingame et al. 1998). Slaats (2002) recommends that the type of turbidity meter be specified when turbidity results are given and that the same type of turbidity meter be used when comparisons are needed.

Turbidity may be reported as nephelometric turbidity units (NTU), formazin turbidity units (FTU), formazin nephelometric units (FNU), or formazin attenuation units (FAU). All these measurements are based on the same formazin primary standard. For example, 1 FTU is equal to 1 NTU when measuring formazin (Sadar 1998). It is generally accepted that NTU and FTU are equivalent when turbidity is greater than 1 NTU (for example, Sadar 1998; and Culligan of Canada Ltd 1997). However, there is some disagreement about the reliability of these measurements when using non-formazin solutions at low turbidity (The Clean Archives 2003).

NTU has been found to be the most stable measurement of turbidity because: (1) it is more stable when measuring different types of particles (Gippel 1998); (2) NTU values have been found to be less affected by dissolved colour (ADWG 1996) because colour in water from dissolved substances will absorb the diffused light and can reduce the signal in some turbidity meters (Slaats 2002); and (3) the nephelometric meter is very sensitive to particle light scatter and thus more accurate at low turbidity (Sadar 1998).

The ADWG (1996) and WHO (1994) recommend turbidity be kept below the aesthetic guideline level of 5 NTU, the level assumed to be the point at which a customer will see turbidity in a glass of water. However, neither guideline references studies from which the turbidity guideline value was derived. Kiwa Water Research found that, in the Netherlands, the mean level at which customers would complain was 10 FTU (approximately 10 NTU), although responses varied from 2.5 FTU to 25 FTU (Slaats 2002). Based on the Kiwa results, 75 % of customers would not complain if turbidity levels were kept below 5 FTU (approximately 5 NTU).
Spatial and temporal trends

Ewan and Williams (1986) give some general guidelines in interpreting variations in quality with distance from source water.

- Decrease in iron, aluminium or manganese in grab samples with distance from the source may indicate deposition of particles from the bulk water flow, or precipitated solutes from treated water that are then deposited on to the pipe wall, and removed from the bulk flow at the point from where the sample is collected;
- Increase in aluminium, or manganese may indicate re-suspension of deposits;
- Increase in iron and turbidity may indicate internal corrosion of mains or re-suspension of deposits; and
- Decrease in dissolved oxygen with increase in heterotrophic plate counts\(^\text{§}\) may indicate microbiological activity associated with loose deposits.

Objections to use of grab samples

Although there is little debate that grab samples can be utilised as a quantitative technique for assessing water quality, there is considerable debate over whether grab samples can indicate the potential of a system to produce discoloured water. Van den Hoven et al. (1992) argue that samples taken under normal flow conditions do not necessarily represent the water quality at times of atypical flow (when discoloured water is assumed to occur), and thus do not always indicate the risk of the system. Van den Hoven and Vreeburg (1992) concur and give specific examples of single samples, which did not indicate what was actually occurring in a system, thereby causing the approach to yield insufficient, and even incorrect, information. A typical example of these problems is when the samples are not taken during the short time of a discoloured water incident that was observed by customers, reported to be only hours by De Rosa (1993). Ewan and Williams (1986) also support this concern, saying that it is difficult to capture the transient nature of discoloured water with grab samples. Thus the basis of most objections to the use of grab sample data are that the frequency required to get an accurate representation of the water quality in all mains, or to capture a poor water

\[^\text{§}\] The measure of the number of heterotrophic micro-organisms in the water supply is an indicator of microbial water quality (ADWG 1996)
quality event, is very labour and time intensive (Chadderton et al. 1992; and van den Hoven and Vreeburg 1992).

In response to this problem Evins et al. (1990) have suggested random grab sampling in time and location to reduce the number of samples required to achieve an adequate capture rate. However, this approach may also prove to be too expensive as it is unclear what frequency of random samples would be needed to accurately represent the infrequent and short duration of discoloured water events. Another approach suggested by Chadderton et al. (1992) is that water quality data should emphasise time series data at carefully selected locations, rather than scattered, random locations, to control spatial variability.

In both these cases, studies determining the effectiveness of these methods have not been published. Research into the actual frequency and severity of discoloured water events and evaluation of sampling programs is therefore needed. [The effectiveness of a random sampling program as suggested by the ADWG (1996) and an increased grab sampling program at set locations in capturing discoloured water events is explored further in Chapter 3.] The use of continuous on-line testing to achieve time series data is discussed in the following section.

1.4.3 Continuous on-line testing

Continuous on-line testing (COLT) is an insitu water quality measurement technique where a device continuously, or very frequently, monitors the water parameters. The frequency of measurement may range from a few seconds to daily. Continuous monitoring of water quality is most often used to establish time series of water quality parameters. In this way, the water quality and hydraulics during typical conditions and non-typical flows may be obtained (Chadderton et al. 1992). Typical parameters measured by COLT are turbidity, chlorine, flow rate and pressure.

Turbidity is the most utilised aesthetic water quality parameter measured by COLT. The major issues in using COLT to measure turbidity are stray light, accumulation of particles or algae in the sample cell, lamp and detector deterioration (Burlingame et al. 1998). Burlingame et al. (1998) recommend maintenance and calibration programs to
prevent variation between instruments. As discussed in Section 1.4.2 the same type of instrument should also be used within a particular water distribution system because different turbidity meters can give different responses.

Interpreting and managing the huge volume of data that COLT produces can be a challenge to using these instruments (Burlingame et al. 1998). Some techniques can be borrowed from the use of COLT for monitoring filters in treatment plants. The on-line data from monitoring filters is often interpreted in terms of the height and width of peaks (also called spikes) in turbidity, with this information linked temporally to operational changes (Burlingame et al. 1998). An alternative to plotting the temporal pattern of turbidity is to plot turbidity against the cumulative volume of water passing the meter. This second approach is suggested because flow rate in the main being monitored may change significantly, whereas the rate at which COLT sampling is recorded typically is set to a specific time interval (Burlingame et al. 1998). This would apply to the use of COLT in water distribution systems where flow rate changes throughout the day due to changes in water demand (Walski et al. 2001).

While COLT is often used in water treatment plants, it has rarely been used for investigation of water quality within the water distribution system itself (Prince 2003). Insitu research studies and interpretation of this type of data are still developing. In the discoloured water research studies that have been undertaken, COLT has been used to monitor changes in water quality in specialist short-term projects, mainly during induced hydraulic disturbances (Boxall and Saul 2005; Schaap et al. 1999; Schaap and Mesman 2000; and Polychronopoulos et al. 2001).

The main disadvantages of using COLT are the expense of installation and maintenance (Brazos and O'Connor 1990) and the lack of a method to optimally select monitoring site locations (Brazos and O'Connor 1990; and Lindley and Davies 1995). The key factors that lead to these disadvantages are that a COLT site only tests water quality at a set location and discoloured water events appear to be quite localised (De Rosa 1993). Hence, determining the minimum number of COLT sites and their optimum location to measure a system is critical.
The selection of location and number of monitoring sites depends on the objectives of the monitoring program. Only limited guidelines have been provided by regulations such as the Safe Drinking Water Act (Kessler et al. 1998). There has been research on and guidelines developed for the optimal placement of water quality monitoring sites for detecting the decay or growth of non-conservative constituents (typically for chlorine); to a lesser extent, the accidental intrusion of pollutants; and to provide data needed for model calibration (Clark et al. 1993). However, most literature refers to the optimum selection of sites for collecting grab samples through routine sampling programs for determining typical water quality. No publications were found for the optimum placement of turbidity and flow rate COLT sites for the investigation of the formation of discoloured water. [The effectiveness of COLT for long-term monitoring of the water distribution system for discoloured water research is investigated in Chapter 4.]

1.4.4 Use of induced hydraulic disturbances

This approach involves the deliberate creation of a hydraulic disturbance in a water distribution system and the measurement of the water quality response that occurs. The hydraulic disturbance is used to simulate the flow conditions for which discoloured water is likely to occur. The flow and water quality changes in the system are measured at one or more locations.

The induced disturbance is usually introduced by turning on a hydrant to create a large flow in the main under investigation. The aesthetic water quality response is then measured. The amount of control placed on the generation of this type of hydraulic disturbance varies. Some measuring techniques do not specify any type of control on how the disturbance is initiated and managed. Other measuring techniques place vital importance on the conditions of the disturbance, for example the velocity and duration of the disturbance (Slaats 2002; and Polychronopoulos et al. 2001).

The variety of methods by which the water quality is monitored in conjunction with an induced hydraulic disturbance include:

1. Filter paper colour (Evins et al. 1990; and Ewan and Williams 1986);
2. Clarity assessment using:
a. Continuous measurement of turbidity with an on-line meter (Grayson et al. 1996; Schaap et al. 1999; Slaats 2002; and Polychronopoulos et al. 2001);
b. A series of samples testing for turbidity, iron, or colour taken from the hydrant (Schaap et al. 1999; and Slaats 2002);
c. Visual inspection (Lindley and Davis 1995; Schaap et al. 1999; Ellison 2003; and Abate and Lim 2000);
3. Sediment sampling (Schaap et al. 1999; and Lindley and Davis 1995); and
4. Time for the water to run clear (Chadderton et al. 1992; and Ellison 2003).

The literature tends to support the use of induced disturbance measuring techniques for identifying areas at risk of causing discoloured water (Evins et al. 1990; Williams and Raphael 1997; Schaap et al. 1999; and Carrière et al. 2002). However, Chadderton et al. (1992) note that the method is labour intensive. Lindley and Davis (1995) concur, arguing that it is difficult to conduct, disruptive to customers and inconclusive. However, the legitimacy of these objections will depend on how the measurement is taken.

The Re-suspension Potential Method, a standardised reproducible disturbance method developed by Kiwa Water Research, solves many of the objections so that results can be meaningfully compared both spatially and temporally (Slaats et al. 2002; and Schaap et al. 1999). The Re-suspension Potential Method stipulates both the magnitude of velocity in excess of typical flow conditions and the period of induced disturbance. This means that repeat visits to the same site can be compared to determine the potential of the main to produce discoloured water and how this potential is changing. Equipment has been developed to enable quick deployment of the method, making it easy and relatively quick to use (Slaats et al. 2002). The Re-suspension Potential Method is well accepted in the Netherlands water industry (Schaap et al. 1999; and Slaats et al. 2002), but is not widely used elsewhere (Prince 2003).

Chadderton et al. (1992) are cautious about whether an induced disturbance accurately represents customer experience. This concern is valid, because no studies that have measured the actual hydraulic conditions that typically or operationally cause discoloured water in a water distribution system and related such conditions to those
caused by induced hydraulic disturbances could be found. Hydraulic conditions that typically cause discoloured water events are investigated in this study.

1.4.5 Other system characteristics and approaches

Prediction of discoloured water formation has also been performed by means of a matrix of system characteristics such as pipe material, configuration, source water, or treatment type correlated to customer complaints or water quality grab samples (Kirmeyer et al. 2000; Ellison 2003; Davis and Smith 1993; Yarra Valley Water 1993; and Williams 2001). The method is not widely used within the water industry (Prince 2003; and Ellison 2003) but is supported by studies conducted by Davis and Smith (1993), Yarra Valley Water (1993), and Williams (2001).

SE Water identified areas that require cleaning using a matrix of historical data such as frequency of customer complaints, water quality grab samples, coliform counts, and time since the system was last cleaned. However, the largest weighting in their approach was given to customer complaints.

1.4.6 Hydraulic and water quality models

A hydraulic model is a computer simulation of the hydraulic performance (velocities, pressures etc) of a complete pipe network or portion of a network. While hydraulic models cannot in themselves be used to measure discoloured water, in combination with other parameters, they can be used to predict water quality.

Ackers et al. (2001) discuss how a hydraulic model can be used to determine the risk of collection and entrainment of sediment if the hydraulic conditions for particle sedimentation and re-suspension causing discoloured water are known. Ellison (2003) agrees, recommending that by comparing calculated velocities with customer complaints, mains at high risk of biofilm and sediment accumulation can be determined. However, neither Ellison (2003) nor Ackers et al. (2001) refer to studies that have verified these propositions nor the calibration limitations of hydraulic models, particularly at the extremity of the water distribution system, considered to be a significant area of particle accumulation.
Ellison (2003) suggests that a comparison of modelled hydraulic performance with actual hydraulic performance can also be used to determine areas of restricted flow from corrosion incrustations. This is of some value to the problem of predicting discoloured water as these incrustations have been attributed to \textit{insitu} discoloured water formation in water distribution systems with unlined ferrous mains.

Water quality modelling has been used to determine areas at high risk of water quality issues such as low chlorine residual and water age. Water quality models for the prediction of discoloured water are relatively new, because the way in which discoloured water is formed in the pipe network is only beginning to be understood (Boxall \textit{et al.} 2001). Ackers \textit{et al.} (2001) noted that no currently commercially available models are appropriate for the purpose of predicting discoloured water. Discoloured water models under development include the PODDS model (Boxall \textit{et al.} 2001) and the Particle Sediment Model (Wu \textit{et al.} 2003) described earlier in Section 1.3.6. These two discolouration models use a hydraulic model platform to determine water quality changes.

**1.5 Key knowledge gaps**

Research into the prediction of areas at high risk of experiencing discoloured water is relatively new and not well developed. The majority of the research is fragmented, focusing on only one aspect of the issue, such as particle chemical composition, without evaluating the impact of the results on the mechanisms of discoloured water formation. The gaps in knowledge can be discussed broadly under two banners; (1) verification of the effectiveness of existing methods for measuring discoloured water events; and (2) understanding of the mechanisms that cause discoloured water events.

The majority of the water industry worldwide has relied on analysis of historical data collected for other purposes to indicate problem areas for discoloured water formation. This analysis has been conducted without a robust understanding of the causes of discoloured water and no information specifically to measure or predict discoloured water has been collected. Historical records of customer complaints and grab samples have been the main measuring techniques used. Determining the usefulness and effectiveness of the data derived from these types of techniques is vitally important.
Customer complaints are an easily collected source of information and, subject to customer perception and water use patterns, monitor the majority of the water distribution system simultaneously. Seasonal patterns and the geographic location of customer complaints may provide insight into areas in which discoloured water is formed and even into the causes of discoloured water. A high frequency of complaints per 1000 properties would indicate areas with past water quality problems. However, a lack of complaints does not mean that no water quality problems are present because complaints are likely to underestimate the number of discoloured water events that have occurred.

This underestimation arises because: (1) complaints are a subjective process; (2) there is variability among customer responses to a discoloured water incident; (3) evidence that customers do not report all discoloured water events they experience; and (4) the customer does not notice all discoloured water that occurs. Complaints should therefore only be used in conjunction with other measuring techniques when predicting the likelihood of future discolouration events. Studies that link customer surveys and customer complaints have been conducted in an attempt to capture a high percentage of events seen by customers. However, it is recommended that these results be verified, as these approaches have subjective elements and their own limitations in capturing all events.

Use of water quality grab samples is a quantitative approach that provides data but only at the time and point of collection. They are generally collected for other water quality monitoring purposes, generally to meet regulatory and guideline requirements for monitoring water quality under typical conditions.

Geographical and temporal trends in grab sample data may indicate areas with constant problems and give an indication of the cause of discolouration. However, the sampling frequency required to detect discolouration is unknown because the location, frequency and duration of naturally occurring discoloured water events is not known and is sporadic and episodic.
The frequency of data collection, reliability and system coverage of customer complaint data and grab samples is a severe limitation in their use in predicting the likelihood of discoloured water events. The actual percentage of discoloured water events that both customer complaints and grab samples identify are not known, as no comprehensive study that accounts for all discoloured water incidences has been conducted. In addition, the subjective and variable response from customers in relation to complaints of discoloured water makes them an unreliable indicator when taken in isolation.

A study to determine how well customer complaints and water quality grab samples collected by current methods correlate with discoloured water events is needed. From this study the usefulness of customer complaint data will be evident and improvements in collection and analysis may be apparent. In the same way, the optimal frequency of grab sampling to measure discoloured water is not known, as the frequency of discoloured water events has not been well characterised in live water distribution systems.

A study that measures all discoloured water events that have occurred in a system would therefore be beneficial to determine how well customer complaints and grab samples can be used for the prediction and management of discoloured water events. In the same way, knowing how often discoloured water actually occurs within a system would help identify the scope of the issue that is being managed and ideally lead to operational practices to reduce the scope of the problem.

COLT of water quality is a technique of measuring the time series variance of water quality at a point within the water distribution system. COLT can therefore be used to objectively measure the frequency, time and severity of all discoloured water events at a point in the water distribution system. Monitoring all mains within a water distribution system to gain a system wide indication of discoloured water would, however, be expensive and impractical. The determination of the optimum configuration of monitoring equipment to gain an accurate and reliable indication of the occurrence and distribution of discoloured water in the system is needed. The optimal configuration of monitoring equipment will also require some idea of the processes leading to discoloured water formation.
COLT of turbidity and flow rate as frequently as every minute has been successfully used for short-term studies during induced disturbances (Schaap et al. 1999; Polychronopoulos et al. 2002; and Boxall and Saul 2005). However, no long term monitoring of “naturally occurring” conditions in the water distribution system for the purpose of discoloured water research has occurred. This absence of long term monitoring means that no study can conclusively determine the type of hydraulic and operational events that typically create discoloured water “naturally” within the system. It is proposed that COLT could be used to identify these “naturally occurring” discoloured water events and, through retrospective analysis, determine the effectiveness of using customer complaints and grab samples to measure discoloured water.

The material causing discoloured water in water distribution systems appears to come in part, or in some systems, from cohesive layers of particles on the pipe wall. Cohesive layer theory based on rivers, mudflats and sewers would suggest that erosion of the cohesive layer begins when a critical shear stress for entrainment, greater than that predicted by Shields function, is reached. However, cohesive layer theory for water distribution systems is not well defined and the shear stress criteria for collection and entrainment of particles for use in a hydraulic or water quality models in water distribution systems has had only limited laboratory investigation. The effect of sampling and transporting particles from the water distribution system to the laboratory is also not known. Neither is the effect of changes to particles within the water distribution system understood.

It has also been shown that the critical shear stress is variable with location and time. Thus, there is a need to develop a method for determining the critical shear stress in situ. The focus of this thesis is to develop such an in situ method and the approach used is described in the following section.

1.6 Problem statement

The aim of the research described in this thesis is to develop a method of predicting the occurrence of discoloured water events in an unfiltered water distribution system, based on an understanding of the causes of discoloured water.
To fulfil this aim, the following hypotheses are tested:

1. That customer complaints and water quality measurements taken by grab samples have a low correlation to discoloured water events and are therefore an inadequate indicator of the likelihood of discoloured water.

2. That the majority of discoloured water events in an unfiltered water distribution system are formed through an ongoing cyclic mechanism of antecedent accumulation of particles in cohesive layers and the erosion of the cohesive layer when a critical shear stress is exceeded and therefore:
   a. That the majority of the discoloured water events are formed within the water distribution system.
   b. That operational events causing high shear stress within water distribution systems are the most common contributors to triggering discoloured water.
   c. That the critical shear stress is variable in location and time and can be estimated through the peak shear stress experienced by a main over a specific preceding period of time.
   d. That the predicted critical shear stress can be used to determine the likelihood of an operational procedure causing a discoloured water event.

The following chapters develop these hypotheses further. Chapters 2 and 3 investigate the effectiveness of using customer complaints and grab samples, respectively, for identifying discoloured water events. Chapter 4 examines the effectiveness of using both COLT and historical data to increase understanding of the type of events that may create discoloured water. Chapter 5 discusses the detailed analysis of COLT data to understand, and then predict, the hydraulic conditions that create discoloured water. Chapter 6 draws together the key findings on what causes discoloured water and shows how these findings can be integrated into current proactive management strategies.
2.1 Introduction

As noted in Chapter 1, complaints regarding discoloured water, henceforth referred to as Discoloured Water Customer Complaints (DWCCs), have been used by many water companies as a primary indicator of system performance in relation to the occurrence of discolouration. In addition, the number and location of DWCCs have been used as the basis for the application of prevention strategies against future discoloured water events. As the largest proportion of complaints received by water companies in many parts of the world continue to be in regard to discoloured water, it would appear that current strategies in monitoring and managing discoloured water adopted by water companies need further development.

In approaching this problem it is important, as a first step, to determine if use of customer complaints are an adequate technique for monitoring discoloured water in unfiltered water distribution systems. This chapter begins that exploration by determining the information that can be gained about the causes of discoloured water events in unfiltered water distribution systems when using customer complaints as the primary indicator. An investigation is then undertaken into the influences and adequateness of customer complaints as an indicator of discoloured water, an issue which is explored in further detail in later chapters.

The analysis in this chapter uses DWCC historical records sourced from the unfiltered system operated by SE Water, in Melbourne, Australia. Based on the studies reviewed in the Chapter 1, the types of operational procedures, flow patterns and hydraulic configurations that may cause discoloured water complaints are also investigated.
To use historical records of DWCCs for these purposes a number of assumptions need to be made as there is no guarantee that customers will always complain when they observe a discoloured water event. As discussed in Chapter 1, a customer’s response to exposure to a discoloured water event may vary with demographics, location, past experiences, water use, and awareness of the water company. As historical records of complaints are used, it is difficult to identify the specific demographics or past experiences of a particular customer. The assumption is made that these influences will have a uniform impact on complaint rates over the whole of the water company area. In this way, complaints are assumed to be a reasonable approximate sample of the population of discoloured water events that have occurred. This same assumption was also made by Roseth and Rock (2003). The validity of this assumption, and the actual conversion rate of customer complaints to discoloured water events, is explored in later chapters. The significance of public exposure of the water company during billing time and water use in producing variability in customer complaints is also explored in this chapter.

The water distribution system operated by SE Water is described in the following section. The subsequent sections describe the acquisition, screening and analysis of the customer complaints and supporting data.

2.2 Case study

2.2.1 Description of the case study unfiltered water distribution system
The water supply system in Melbourne, Australia, differs from many other cities in that, due to the quality of raw water, approximately 85 % of the potable water supplied is unfiltered (DHS/DNRE 2000). Supply catchments are forested and protected from public access, recreational use and any activities that could adversely affect water quality (South East Water 2002). The major form of ‘treatment’ in this system is natural settling during long detention periods in open dams (an average of 5 years) and chlorine disinfection. At the outlet of the major supply reservoirs, the water is treated with chlorine for disinfection, fluoride for dental health, and lime for pH correction.
A schematic of the whole of Melbourne’s system is shown in Figure 2-1. Melbourne Water Corporation, which is the water wholesaler for this system, controls the protected catchments and the majority of the water treatment plants. Three retailers, SE Water, Yarra Valley Water, and City West Water distribute the water to customers in the Melbourne metropolitan area. All four companies are State Government owned corporatised entities. The operating licence and associated customer contracts for the retail water companies define the standard of drinking water quality that the retail water companies are required to supply. More specifically, the customer contract gives consumers the right to drinking water that “is clear and free from objectionable odour and taste” (South East Water 2003). Compliance with this contractual obligation is monitored by a Government Regulator.

The three retail water companies ‘compete by comparison’ using Key Performance Indicators. One of the Key Performance Indicators used is the annual number of customer complaints for discoloured water per 1000 properties. The comparison of the three retail water companies on the basis of discoloured water complaints places ongoing pressure on the retail water companies to continually improve their service and identify the optimum way of reducing the occurrence of discoloured water, while containing expenditure.

SE Water supplies approximately 1.3 million customers with water and sewerage. Unfiltered water is supplied to SE Water from Melbourne Water Corporation through Silvan and Cardinia reservoirs. The SE Water water supply system itself comprises 81 water pumping stations, 71 reservoirs and major water tanks, 7 secondary disinfection plants, and 7880 km of water mains (SE Water 2003). The system differs from the majority of systems that have been studied in Europe and USA in that it has predominately cement lined, cast iron mains with less than 5% unlined ferrous mains.

The SE Water system is broken into 29 water quality zones for the purposes of monitoring and controlling the quality of the potable water. The 29 water quality zones are shown in Figure 2-2. A water quality zone is supplied by water that would be expected to be of similar water quality (for example, from the same source) and contains up to 100,000 people (NHMRC and ARMC 1996). The Wantirna WQZ which
Figure 2-1: The Melbourne water supply system (diagram courtesy of SE Water)
Figure 2-2: Water quality zones in SE Water’s area in Melbourne, Australia

SE Water water quality zones
27 Bunyip
28 Tynong
29 Pakenham
30 Koo Wee Rup
31 Berwick
32 Cranbourne
33 Sonerville
34 Hastings
35 Bittern
36 Balnarring
37 Flinders
39 Frankston
40 Frankston South
41 Mount Eliza
42 Mornington
44 Rosebud
45 Lang Lang
57 Knox
58 Belgrave
59 Wantirna
61 Malvern
62 St Kilda
63 Hallam
64 Dandenong
65 Chelsea
66 Mulgrave
67 Notting Hill Res.
68 Sandringham
69 Moorabbin Res.
70 Rowville
is in the north of the SE Water region, is used when more detailed investigation is required. The Wantirna WQZ is described further as required in the following chapters.

**Predicted particle sources for SE Water unfiltered water distribution system**

At the time of this study water supplied to the system controlled by SE Water in Melbourne, Australia, is predominately unfiltered so that particles attributed to treatment processes are low. As the system’s assets are predominately lined, the dominant high levels of corrosion products found in unlined systems are not present. Backflow prevention programs are in place and the system is operated under pressure so that particles associated with backflow and intrusion should also be minimal.

Therefore, based on the literature discussed in Chapter 1, the most likely sources of particles in SE Water’s system are:

- Clay, sand, silt and organic material from the source reservoir;
- Dissolved iron and manganese from the source reservoir that may precipitate out in the water distribution system due to chemical reaction with chlorine;
- Erosion products such as silica and aluminium from cement lining of mains;
- Biological growth products such as biofilm on pipe walls and micro-organisms in loose deposits;
- A minor level of corrosion products such as iron oxides from unlined fittings, and mains with breaches in the cement lining; and
- A minor level of particles from external contamination, such as sand and organic materials from main repairs;

This categorisation of the types of materials expected to occur in SE Water system is consistent with the results of chemical analysis of deposits in SE Water and other unfiltered and lined systems (Lin and Coller 1997; van der Walt *et al.* 1999; and Ekanayake *et al.* 2003).
2.3 Data used in this study

Customer complaint data, property information and mains cleaning data for the SE Water system for the period between July 1996 and July 2002 are used in the analysis unless otherwise stated.

2.3.1 Water quality customer complaint data

Since its formation in 1995, SE Water has collected data on customer complaints made against its potable water product. The information is stored in a customer complaint database. A customer who experiences “dirty” or “discoloured” water and who rings SE Water’s special toll free number is connected to the Communications Room. The Communications Room is staffed 24 hours a day, 7 days a week. The toll free number is clearly displayed on the customer’s bill and in the phone directory. In the Communications Room, the complaint is logged in the customer complaint database as a DWCC. Basic information such as the date of the complaint, the customer’s address, and the problem they are experiencing are asked of the customer and entered into the database. It should be noted that the date recorded against the complaint is the date on which the complaint is made, not the date on which the customer noticed the discoloured water. It is common practice for the communications room staff to record DWCCs that occurred within the same water quality zone and on the same day at the address of the first DWCC that occurred for that day.

Information such as an attributed cause of the complaint is added later. An attributed cause of a complaint is recorded under two scenarios: (1) when a complaint is investigated at the time of the event; and (2) during a monthly review of complaints by an engineer at SE Water.

The customer complaint database is linked to the operations database called WaterLog which details actions taken to address the complaint. This connection enables any action that results from the complaint to be linked to records within the customer complaint database. Figure 2-3 shows the process by which this data is collected.
2.3.2 Number of properties for each zone

To determine the number of occupied properties in each water quality zone and financial year, the following procedure is performed. Historical customer property addresses are extracted from the SE Water customer billing program. The properties are filtered to determine the total number of occupied properties using the criteria: (1) the quarterly record of water usage tariff is not zero; and (2) the water consumption at that property is above zero. The x,y grid coordinate for the property is used to map the location (geocode) in GeoMedia. [Geomedia is a geographical information system that is able to perform complex analysis on spatial data.] Using Geomedia, a spatial query is then run to select geocoded properties from within the water quality zone spatial boundary. A count of properties by water quality zone and financial year is then performed to produce a “property results table”.

2.3.3 Mains cleaning data

Like most of the rest of the world, the primary strategy used by SE Water to reduce the incidence of discoloured water events has been to counteract sediment accumulation through mains cleaning activities. SE Water systematically cleans the water quality zones in their entirety using unidirectional flushing or air scouring of mains from source to extremity, defined as block flushing or block cleaning. This method of cleaning is referred to as maintaining a ‘clean water front’ by Slaats (2001), as water is always drawn through freshly cleaned mains. The cleaning of these systems is typically a substantial undertaking and imposes costs on SE Water of the order of hundreds of thousands of dollars per year. In addition, smaller isolated areas may be cleaned as part of remedial action following a customer complaint or high coliform count, or as part of a mains repair. Prior to 2001 it was not part of SE Water procedures to establish a clean water front before unscheduled flushing was conducted.
The operators at SE Water conduct a flushing procedure by completely opening a designated hydrant with the aim of achieving a minimum flow rate of 10 L.s⁻¹ and to flush until the water is visibly clear. In reality the flow rate achieved by the operator depends on the system characteristics (Ryan [personal communication] 17/01/08). No requirements have been made on how many pipe volumes should be flushed from the system. Furthermore no studies have been conducted to determine if these flow rates are adequate to clean all sizes of pipes in the SE Water system.

No easily accessible detailed data is kept of the dates on which a given main in the SE Water area was cleaned. However an indication of which financial year a significant portion of a water quality zone was block cleaned was able to be determined from SE Water Water Quality Reports 1996/97, 1997/98, 1998/99, 2000, and 2001.

### 2.4 Screening of customer complaint data

Customer complaint data between July 1996 and July 2002 is used in this study because of major data reliability issues prior to this period. The concerns about the reliability of the data prior to 1995/96 financial year rise because, at that time, the Melbourne Board of Works was disaggregated to form three water retail companies and one wholesaler company. The exact dates on which individual water quality zone boundaries were redefined during this desegregation process are not known. In this process, SE Water also formed new water quality zones and new boundaries, numbers and names were allocated for operational reasons.

Despite the new boundaries being established by the end of the 1995/1996 financial year, new water quality zone names and numbers were not used consistently in the SE Water databases until 1997. To allow the data from the 1996/97 financial year to be used complaints were assigned to the appropriate water quality zone by updating water quality zone names and numbers in accordance with Table 2-1.
Table 2-1: New water quality zone numbers used by SE Water to replace redundant Melbourne Board of Works numbers as of 2005.

<table>
<thead>
<tr>
<th>Melbourne Board of Works water quality zone number</th>
<th>SE Water water quality zone number</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>62</td>
</tr>
<tr>
<td>38</td>
<td>32</td>
</tr>
<tr>
<td>43</td>
<td>44</td>
</tr>
<tr>
<td>56</td>
<td>58</td>
</tr>
<tr>
<td>60</td>
<td>61</td>
</tr>
</tbody>
</table>

Three DWCCs in the original data set are not allocated a water quality zone. Based on street address, the 3 DWCCs are manually assigned to the appropriate zone for incorporation into the analysis. These are:

- DWCC occurring on 30 May 1997 assigned to WQZ 62
- DWCC occurring on 4 November 1998 assigned to WQZ 27
- DWCC occurring on 10 November 1998 assigned to WQZ 27

The data in the SE Water database was also modified so that each category of DWCC has a reference number i.e. Brown Dirty Water Complaints = 1, Black Dirty Water Complaint = 2 etc. [The numbering system used for this process is given in Appendix 1]. This approach minimises the chance of false or very small categories arising from spelling mistakes in category names and different descriptions used for the same category in the original database. [This grouping process is discussed further in Section 2.5.2.]

2.5 Method of analysis of customer complaints

2.5.1 Method to determine proportion of water quality customer complaints

To gain an understanding of the relative importance of DWCCs over other water quality complaint types, data from July 1996 to July 2002 for the whole of SE Water system is used to calculate the proportion of each category of water quality complaints. This method is routinely used in SE Water complaint reporting.
As noted earlier, water quality complaint categories are related to customer perception. However, this relationship creates a dilemma in categorising water quality complaints as a customer may describe a number of water quality symptoms for a given water quality incident. For example, the water may be brown (discoloured water complaint) and smell musty (taste and odour complaint). To avoid duplication of a single complaint in the data base, a value judgement is taken by Communications Room staff in establishing the customer’s most important issue, usually the first symptom to which the customer refers. In this way, although all symptoms are noted in the database, the complaint is recorded only in one water quality category. In the example above, the complaint would be recorded as a discoloured water complaint as this was the first issue stated by the customer.

Based on the literature discussed previously in Section 1.4.1 brown, black and yellow water complaints are considered to be DWCCs as they are attributed to particulates. For the purposes of this study, complaints of blue water (attributed to copper corrosion, where copper pipes are only used in internal property plumbing) and white water (attributed to air or chlorine) are not considered as DWCCs because they are not associated with particles in the water distribution system.

The proportion of each type of water quality complaint can be used to gain some insight into the main sources of particles causing discoloured water. More specifically, the percentage of customer complaints in the following categories is determined:

- Discoloured water;
- White water;
- Blue water;
- Washing;
- Taste/odour;
- Suspected illness; and
- Other

This method of using the spectrum colour of a water sample to draw conclusions on causes was first published by De Rosa (1993).
2.5.2 Method to determine operational procedures that cause complaints

At the end of every month, SE Water staff assesses DWCCs to determine what events within the water distribution system can be attributed to causing the complaints. This procedure is conducted to exclude those complaints that were caused by internal property plumbing from reportable potable water complaint figures. In this study, these attributed causes are grouped into Attributed Cause Categories to assist in determining the types of operational procedures that cause discoloured water.

Inconsistent cause categories occurred as names had evolved with time. To address this inconsistency and make the available data as complete as possible, category names are combined. For example:

- ‘Main shutdown’ is combined with ‘water off’; and
- ‘Burst main’, ‘burst hydrant’, ‘burst service’ are all combined.

Other categories are grouped under similar location such as:

- ‘Melbourne Water recharge’ and ‘Melbourne Water connection’; and
- ‘Internal problem’ and ‘private extension’.

Minor operations that do not occur often or that have little impact on the system are grouped under an “other” category. Some examples of minor operations are:

- ‘Algae’– referring to the occurrence of the isolated presence of algae in the system;
- ‘Ferrule problem’ – referring to the repair of a ferrule causing a minor leaking main; and
- ‘Choked meter’ – referring to a customer meter fouling and restricting water supply or reducing water quality.

Categories are then allocated numbers (as described in Appendix 1) and DWCCs in each category counted.

The analysis in Chapter 1 concluded that particles causing discoloured water events are likely to have collected in cohesive layers at the pipe wall and eroded at higher than
usual shear stresses. To assess this hypothesis the Attributed Cause Categories are further grouped into five Cause Groups based on the location and type of cause as described below.

**Group (1): Increase in shear stress in the system**

This group of Attributed Cause Categories includes actions that may have resulted in substantial increases in applied shear stress at the pipe wall (such as high flow rates or water hammer) are classified “Increase in shear stress in system”. The Attributed Cause Categories in this group include mains bursts, hydrant bursts, flushing and air-scouring to clean mains, and service bursts (because they resulted in flushing of the main); mains and hydrant repairs, and mains shutdowns (because the procedure is concluded with the flushing of the main); change of supply direction (not source) and valve opening and closing (as these result in flow reversals, can induce water hammer, and often increase the velocities in some mains); and dead end mains (as discoloured water problems in dead end mains have been attributed to increases in velocities as discussed in Section 1.3.4).

**Group (2): Other causes in the system**

This group includes Attributed Cause Categories that may have resulted from phenomena in the water distribution system such as the presence of algae, ferrule repairs, repairs to automatic flushing devices (as these do not result in the flushing of the main) and suspected, but unconfirmed, galvanized wrought iron internal plumbing, as this may be due to a system related problem instead. Works in the area done by other companies that may have caused vibration of water mains but should not have resulted in increases in water velocity as no water was used, are also included in this grouping.

**Group (3): Causes originating outside the system**

This group of Attributed Cause Categories incorporates those operations that are not ‘within’ the water distribution system itself. This grouping is called “Outside System” and includes operations conducted on Melbourne Water Corporation assets, such as Melbourne Water Corporation main’s recharging and Melbourne Water Corporation mains connections that have been suspected to cause allochthonous events of discoloured water.
**Group (4): Internal plumbing**

This grouping includes causes attributed to internal house plumbing and private extensions such as, private mains, hot water systems, and confirmed galvanised wrought iron plumbing. The grouping is called “Internal Plumbing”.

**Group (5): No cause assigned**

This grouping includes all DWCCs that do not have a cause attributed.

From this set of groupings, the relative importance of high shear stress in creating discoloured water can be determined by calculating the percent of DWCCs per 1000 properties per annum described in Section 2.5.4.

### 2.5.3 Method to form ‘super group’ of DWCCs caused within the water distribution system

As this thesis is investigating the cause of discoloured water within an unfiltered water distribution system, it is useful to form a ‘super group’ of DWCCs that excludes those complaints which have been attributed to causes outside the water quality zone. This super group is called water distribution System related Discoloured Water Customer Complaints (S-DWCCs).

An obvious exclusion to this group is Group 3 complaints, as these occurred before the water reached the water distribution system and Group 4 complaints as these were due to internal house plumbing. Those DWCCs where no cause was determined are included in the super group, S-DWCCs, as these complaints may include causes of high shear stress causing discoloration which are not recorded in the SE Water operations database. Examples of such causes of high shear stress include:

- Naturally occurring days of high peak water demand;
- Illegal hydrant use; and
- The use of hydrants for fire fighting or fire sprinkler systems.
2.5.4 Removal of population growth bias

The population of the SE Water region grew from approximately 460,811 properties in 1996 to 527,018 properties in 2002. The number of customers in each water quality zone, and the growth in the different zones, is however variable. There is therefore a need to remove the population bias so that changes in customer complaint numbers in each water quality zone are correctly identified. To remove the bias the number of DWCC per 1000 properties (DWCC1000) for each water quality zone is calculated using Equation 2-1.

\[
DWCC1000(WQZx, Y) = \frac{DWCC(WQZx, Y)}{P(WQZx, Y)} \times 1000 \tag{2-1}
\]

Where:
- \(DWCC(WQZx, Y)\) = number of DWCCs in water quality zone \(x\) (WQZx) and financial year \(Y\) (as determined in Section 2.3.2).
- \(P(WQZx, Y)\) = number of properties in water quality zone \(x\) (WQZx) and financial year \(Y\).

The DWCC1000 for each year and water quality zone are then averaged to calculate the average number of DWCC1000 that occurred over a 1 year period for each water quality zone (DWCC1000/yr). This procedure is already used by retail water companies in Australia for the purpose of reporting customer complaints and use in asset management.

Using the super group of customer complaint data described in Section 2.5.3, the average S-DWCC per 1000 properties (S-DWCC1000) can be determined using Equation 2-2.

\[
S-DWCC1000(WQZx, Y) = \frac{S-DWCC(WQZx, Y)}{P(WQZx, Y)} \times 1000 \tag{2-2}
\]

Where:
- \(S-DWCC(WQZx, Y)\) = number of system related DWCCs in water quality zone \(x\) (WQZx).
x (QWZₙ) and financial year Y (as determined in Section 2.5.3).

\[ P(WQZₙ, Y) = \text{number of properties in water quality zone } x \text{ (WQZₙ)} \]
and financial year Y.

### 2.5.5 Selection of study zone

A study zone with a known discoloured water problem was selected for in-depth analysis. This study zone is the Wantirna WQZ. Criteria for the selection of the study zone are as follows:

- The water quality zone is supplied by Silvan Reservoir, not directly from Cardinia reservoir. The Silvan Reservoir typically has higher turbidity, which is therefore more likely to provide a higher supply rate of particulate material to the zone;
- Above company average rate of S-DWCC1000/yr. This is an indication that discoloured water is formed within the zone at a higher frequency than other zones;
- A relatively simple hydraulic system supplied by one source water, and at one point, thereby reducing the complexity of water mixing and reverse flows; and
- The high proportion of residential customers in the zone. This maximises the potential response from customers and minimises the potential for night flows that could be associated with some industry types.

This study zone is described further in Section 2.6.5.

### 2.5.6 Determination of seasonal and monthly trends of S-DWCC1000

Seasonal and monthly trends of S-DWCC1000 are determined by evaluating S-DWCC1000 for each month, season) and year for the whole of SE Water system using Equation 2-3.

\[ S\text{-DWCC1000}(WQZₙ, S, Y) = \frac{S\text{-DWCC}(WQZₙ, S, Y)}{P(WQZₙ, Y)} \times 1000 \] (2-3)
Where:

\[
S\text{-DWCC}(WQZ_x, S, Y) = \text{the number of system related DWCCs in water quality zone } x, \text{ season } S, \text{ in financial year } Y.
\]

\[
P(WQZ_x, Y) = \text{the number of properties in water quality zone } x, \text{ in financial year } Y.
\]

To determine if company interactions with customers produce an increase in DWCCs, monthly trends are also compared to times when water rate notices are issued. This comparison of S-DWCC1000 values to times of rate notices is unique to this study and is based on the assertions of Jones (2006) that customer complaints are more likely to complain when customers are made aware of the water company.

### 2.5.7 Correlation of S-DWCC with temperature and flow rate

Correlation of S-DWCC with maximum daily air temperature and peak daily flow on the day the complaint was recorded was used to determine whether these two variables can be used as a broad predictor of S-DWCC. Past complaint rates for each flow or temperature range were adjusted to determine the average daily S-DWCC in a given year to remove any bias that may occur because of changes in population figures with time. For example, Equation 2-4 below was used to calculate the adjusted average daily S-DWCC in the year 2000 for temperature.

\[
\text{Adjusted Average daily S-DWCC (t,Y) = } \frac{\sum_{t=1}^{S(t)} (S\text{-DWCC}(t,Y)) \times P(Y_{2000})}{P(Y)}
\]

(2-4)

Where:

\[S\text{-DWCC}(t,Y) = \text{the system related DWCCs occurring on days that reached a maximum daily temperature in a particular temperature range } t\text{ and financial year } Y, \text{ where } t \text{ represents temperature ranges of 0 to 5, 5 to 10, 10 to 15, 15 to 20, 20 to 25, 25 to 30, 30 to 35, 35 to 40, 40 to 45 degrees Celsius.}\]

\[P(Y) = \text{number of properties in area being examined in a financial year } Y.\]

\[P(Y_{2000}) = \text{number of properties in 2000.}\]
S(t) = number of temperature ranges.

Maximum daily temperature in Melbourne is correlated to customer complaint data for the whole of SE Water region (data from January 1997 to December 2000) as this was the period of time in which temperature data was available.

A correlation analysis between measured peak daily water flow rates and S-DWCC was also performed to provide an indication of the possible relationship between higher flow rates in the distribution system (and therefore higher shear stresses) and the formation of discoloured water. This correlation was performed by consideration of the link between the measured peak daily water flow rate at the outlet of the Wantirna Service Reservoir (which was the only inlet to the Wantirna WQZ) and the adjusted average daily S-DWCC that occurred in the Wantirna WQZ. The peak daily flow rate at the outlet of the Wantirna Service Reservoir was used as an indication of the magnitude of the peak flows occurring in the system.

For example, a higher than average peak daily flow rate at the Wantirna Service Reservoir outlet was used as an indication of higher than average peak flows occurring in the mains in the Wantirna WQZ. This was justified on the basis that the Wantirna WQZ is supplied by only one source (the Wantirna Service Reservoir) and therefore the flow rate measured at this point was an accumulation of all water demands in the zone. Peak daily flow rates from the Silvan and Cardinia reservoirs cannot be used as these supply the service reservoirs that are typically filled at night and therefore the flow peaks do not represent actual flows in mains within the water distribution system.

Undertaking this same analysis for the whole of SE Water region would require extracting daily maximum flow rates at the entrance of every water quality zone. Also, each water quality zone would need to be investigated to determine the type and location of water users. The correlation between flow rate and S-DWCC was therefore examined using data from only the Wantirna WQZ which was known to have a large residential customer base and few industrial customers.
The correlation of peak daily air temperature in Melbourne and peak daily flow rate at the Wantirna Service Reservoir outlet was used to determine if air temperature also predicted the increase of flow. A high correlation between air temperature and flow rate would allow peak flow rate days to be predicted from weather forecasts.

To determine the effect of seasonal flow patterns on discoloured water events, seasonal trends in S-DWCC1000 were evaluated in relation to seasonal average daily flow profiles. Average daily flow profiles were calculated from measured flow rates at the Wantirna Service Reservoir outlet. The seasonal average daily flow profiles were calculated by averaging the flow rate measured at 10 minute time intervals in all days within a season, for example, averaging all flow rates recorded at 23:00 hrs that occurred in summer, then all flow rates that occurred at 23:10 hrs etc.

2.5.8 Determination of trends in the location of DWCCs

To assess the importance of system features such as dead end mains in discoloured water formation, the location of DWCCs was assessed. Property addresses of DWCCs for calendar years 1996 - 2002 were assigned an x-y grid coordinate using GeoMedia as noted earlier. The x,y grid coordinate of the complaint address was used to map the location of the complaint in relation the study water quality zone. This representation was called a measels plot. The number of DWCCs that relate to dead end mains and other pipe configurations was then counted.

This technique does not allow for the exclusion of specific complaints based on known causes and therefore also incorporates complaints that are known to have been caused by discoloured water that originated outside the distribution system or where due to internal house plumbing. [As indicated in Figure 2-6, these types of additional, non system related, discoloured water complaints are few so that it is assumed that they would not unduly bias results.] It is important to note that this process is based on the Yarra Valley Water (1999) study.
2.5.9 Determination of the effectiveness of flushing to reduce system related DWCCs

To investigate the long-term effectiveness of block mains cleaning programs in reducing customer complaints, a comparison of S-DWCC1000 in each water quality zone was made between years where block flushing occurred and subsequent years. The hypothesis behind this analysis is that, if block cleaning is effective in reducing the occurrence of DWCCs, there will be evidence of a reduction in the S-DWCC1000 in the year after the zone had been cleaned.

To evaluate the effectiveness of cleaning, the ratios expressed in the equations below are determined for each financial year and water quality zone. An average ratio of all years is then calculated for each equation.

\[ P_{cr/c} = \frac{N_{cr}}{N_c} \]  \hspace{1cm} (2-5)

Where:

- \( P_{cr/c} \) = ratio of a cleaned zone having a reduction in S-DWCC1000 in the following year.
- \( N_{cr} \) = number of zones cleaned in that year that also had a reduction in customer complaints in the following year.
- \( N_c \) = number of zones cleaned in that year.

\[ P_{ci/c} = \frac{N_{ci}}{N_c} \]  \hspace{1cm} (2-6)

Where:

- \( P_{ci/c} \) = ratio of cleaned zone having an increase in S-DWCC1000 in the following year.
- \( N_{ci} \) = number of cleaned zones in that year that did not have a reduction in customer complaints in the following year.

\[ P_{ncr/nc} = \frac{N_{ncr}}{N_{nc}} \]  \hspace{1cm} (2-7)
Where:

\[ P_{ncr/nc} = \text{ratio of a zone that was not cleaned having a reduction in S-DWCC1000 in the following year.} \]

\[ N_{ncr} = \text{number of zones not cleaned in that year that had reduced customer complaints in the following year.} \]

\[ N_{nc} = \text{number of zones not cleaned in that year.} \]

\[ P_{nci/nc} = \frac{N_{nci}}{N_{nc}} \quad (2-8) \]

Where:

\[ P_{nci/nc} = \text{ratio of a zone that was not cleaned having an increase in S-DWCC1000 in the following year.} \]

\[ N_{nci} = \text{number of zones not cleaned in that year that did not have a reduction in customer complaints in the following year.} \]

In these equations, a ‘cleaned zone’ refers to a water quality zone that had been cleaned within a given financial year. A ‘reduction in complaints’ refers to a zone in which S-DWCC1000 reduced in the year following block cleaning. As described in Section 2.3.2 accurate and assessable records on exact times of block flushing were not available for a more detailed monthly or daily analysis.

A perfectly random relationship between block cleaning and S-DWCC would result in a ratio approximating 0.5 for each of the equations above. To test the hypothesis that the average ratio of each of the equations above is significantly different from 0.5, one sample non-directional t tests were performed using the Statistica test “test of means against reference constant”. A p value of 0.05 and reference constant of 0.5 were used.
2.6 Results of customer complaint analysis

2.6.1 Proportion of water quality customer complaints

As shown in Figure 2-4 the largest proportion, namely 53 %, of water quality complaints in the period July 1996 to July 2002 for the whole of the SE Water system are of discoloured water. As reported in Section 1.1, this is consistent with findings around the world.

![Figure 2-4: Distribution of water quality customer complaints in each water quality category (July 1996 to July 2002) for the whole of the SE Water region.](image)

2.6.2 Operational procedures causing DWCC

Specific causes can be attributed to approximately a quarter of DWCCs between July 1996 and July 2002 (28 % of DWCC for whole of SE Water region, 22 % of DWCCs for the Wantirna WQZ). The distribution and nature of these causes are shown in Figure 2-5. It should be noted that this analysis includes all DWCCs as discussed in Section 2.5.8.
Figure 2-5: Percent of all DWCC1000 per year (including non system related complaints) for each attributed cause category for the Wantirna WQZ and the whole of the SE Water region. *Attributed cause is not within the water distribution system.

Figure 2-5 shows that for the majority of Attributed Cause Categories, the proportion of DWCCs is similar between the whole of the SE Water region and the Wantirna WQZ. However, for the SE Water region, galvanised wrought iron internal plumbing is the single greatest contributing cause for DWCC (5%) but only a minor contributor to the Wantirna system (1%) suggesting that the use of galvanised wrought iron piping may be regional. This possibility is supported by the construction time frame of the Wantirna WQZ. Galvanised wrought iron ceased to be used in the late 1960s and most of the Wantirna WQZ was constructed post 1970. For the Wantirna WQZ, unspecified ‘works done in the area by SE Water’ caused the largest proportion of DWCCs (5% per year). In both the Wantirna WQZ and the wider SE Water region, unlined cast iron mains are not attributed by the water company to causing any DWCC, consistent with the predominance of lined and PVC mains.
2.6.3 Hydraulic events causing DWCCs

Examination of the DWCC cause groups shown in Figure 2-6 reveals that there was no cause assigned to approximately three quarters of complaints. Of those remaining, the majority may have been caused by atypical shear stress events (14 % of all complaints in the SE Water region, 15 % of all complaints in the Wantirna WQZ). [The operational procedures that may cause shear stress events are described in Section 2.5.3.]

![Figure 2-6: Average DWCC1000 per annum for each Cause Group for SE Water and the Wantirna WQZ (Data from 1996 – 2002).](image)

The analysis reported in the remainder of this chapter does not include those complaints attributed to events outside the water distribution system or internal plumbing as this investigation is focused on the causes of discoloured water within water distribution systems. Figure 2-6 shows that a small proportion of complaints for the whole of the SE Water region are due to internal property plumbing (7 %). Allochthonous events from outside the water quality zones have not been attributed to causing many of the customer complaints (3 % for the whole of the SE Water region, 0 % for the Wantirna WQZ).
2.6.4 Variance in S-DWCC1000

As shown in Table 2-2, the populations in each of the water quality zones grew at different rates. However, even when the variance in population figures is removed, customer complaint rates vary widely between water quality zones, ranging from 0.5 S-DWCC1000 to 21 S- DWCC1000 per annum, as shown in Figure 2-7. The average rate of S-DWCC1000 for the whole of SE Water is 1.9 S-DWCC1000 per annum.

Table 2-2: Population figures for water quality zones within SE Water’s region.

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<td>10,518</td>
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</tr>
</tbody>
</table>
It should be noted that WQZ 45 was not chosen as the study zone even though Figure 2-7 shows it has a vastly higher average yearly S-DWCC1000 than other zones. This decision was made because the large average yearly S-DWCC1000 figure is due to a high value of S-DWCC1000 in only the 1997/1998 financial year. The high value of S-DWCC1000 in 1997/1998 is due to a small increase in complaints and WQZ 45 having very few customers, as shown in Table 2-2. In remaining years, complaints for WQZ 45 have similar rates to those of WQZ 59 and WQZ 42.

2.6.5 Study zone

As stated in Section 2.5.5, the Wantirna WQZ (WQZ 59) is chosen as the study zone in this investigation. The Wantirna WQZ system is a rib-cage-like network with a backbone of 450 mm mains and ribs of 300 to 40 mm mains as shown in Figure 2-8. The system supplied 8890 properties in the 2001/2002 financial year. The steady growth in population is not reflected in comparable growth in the size of the distribution system. From a comparison of current figures (Ryan [personal communication] 01/02/2008) and those calculated in 1999 (Prince 1999), there has been less than a 6 km (4 %) increase in the total length of the system since 1999. Table 2-2 shows that there has been an increase in the number of houses (reflecting an increase in population) of
Wantirna of 12% between 1996 and 2002. This reflects the increasing density of housing that is occurring in Melbourne suburbs.

Figure 2-8: Schematic of the water distribution system of the Wantirna WQZ showing large pipe sizes and predominant land uses. 74% of mains are 100 to 150 mm internal diameter pipes.
The area is predominantly residential which maximises the potential response from customers, and results in a variable daily velocity profile through the system. Most of the system was constructed or has been renewed since 1977 and most pipes are, cement lined (75 %) or PVC (Prince 1999). The zone has 6 major industrial water users scattered throughout the system of residential customers which causes a minimal effect on the water demand profile that would be expected by a purely residential water quality zone (Prince 1999). As indicated in Figure 2-8, the extremity of the system supplies mainly warehouses, with low water demand.

The Wantirna Service Reservoir is supplied by the Silvan Reservoir, which historically has had the highest turbidity readings of Melbourne’s major reservoirs. Historical grab sampling gives a turbidity range of 0.7 – 2.3 NTU from July 1996 to July 2002 for water entering the distribution system from the Silvan Reservoir [The variation in turbidity as measured at the Wantirna Service Reservoir is discussed in Chapter 4]. The higher turbidity readings indicate a higher supply rate of particulate material to the zone. As noted earlier, the water is not filtered but is dosed with chlorine for disinfection, fluoride for dental health and lime for pH correction.

As shown in Figure 2-7, the Wantirna WQZ has an average of 5 S-DWCC1000 per annum, which is above the SE Water average of 1.9 S-DWCC1000. Under the assumption that each water quality zone has the same conversion rate of discoloured water events to complaints an above average S-DWCC1000 rate suggests an increased rate of discoloured water events occur in the Wantirna WQZ relative to other water quality zones. The higher level of complaints may be attributable to the Wantirna WQZ’s above company average pipe burst rate (Prince 1999). This break rate suggests that abnormal hydraulic conditions arising from pipe breakages and subsequent repair activities occur in the study zone at a higher frequency than other zones. This high pipe break rate may be due to the clay soils in the Wantirna WQZ.

Evidence of the variability in S-DWCC1000 for each water quality zone can be seen in the increase in S-DWCC1000 for WQZ 59 in financial year 2000/2001 as shown in Figure 2-9. While the trend for individual water quality zones is variable, Figure 2-9
shows there is a strong tendency for a reduction in S-DWCC1000 for the whole of the SE Water region over time. This may indicate that improved practices in preventing discoloured water events employed by SE Water are overall being successful or that customers are now accepting of the water quality supplied by SE Water.

![Figure 2-9: S-DWCC1000 for each financial year for SE Water Limited and the Wantirna WQZ from July 1996 to July 2002.](image)

### 2.6.6 Source material causing DWCCs

As shown in Figure 2-10, the discoloured water complaints reported by customers in both the whole of the SE Water region and the Wantirna WQZ have mostly been for brown water. Brown water is attributed to clay, silt and rust particles (De Rosa 1993; South East Water 1998; and Yarra Valley Water 1998) and is consistent with the hypothesis that the major cause of discoloured water is the concentration of clay and silt particles entering the unfiltered water distribution system from upstream of the service reservoir or from corrosion products.

![Figure 2-10: Percentage of S-DWCC1000 for each spectrum colour type of DWCCs in SE Water and the Wantirna WQZ.](image)
2.6.7 Awareness of the water company by the customer

Water rate notices are issued in January, April, July and October each year (Mevel 2002). Figure 2-11 shows that there is no consistent increase in the DWCCs in the months in which rates were issued or the month immediately following the issue of water rate notices. This result is contrary to work by Jones (1996) and Lawrence and Stratton (1999) who suggested that heightened awareness of a customer of a water company might in fact stimulate complaints. This result is consistent, however, with findings in the United States where heightened awareness of the water company via the issuing of water quality reports was found not to increase complaints (Johnson 2003). It may be that other localised events heightening the awareness of the water company to the public, such as customers seeing vehicles marked with the water company logos at main repairs, affect this trend. Due to the nature of the records kept the effect of this type of exposure of the water company was not able to be tested.

2.6.8 Correlation of S-DWCC1000 with flow rate and temperature

Monthly trends

The monthly trends in S-DWCC shown in Figure 2-11 demonstrate that, excluding outliers, S-DWCC have a tendency to increase from April to December, although this increase is slight. The most variable frequency of complaints received occurs in October.
Spring is also typically the period which is the most variable in temperature and rainfall, resulting in a variable demand for water and type of water use. Excluding one outlier, July (mid winter) had the least variation in customer complaints. July is in the middle of winter where typically water demand is low indicating customers are using water at the lowest rate and possibly in the least visible forms. For example, customers would observe the colour of the water less when washing clothes than when they were filling swimming pools or drinking water from the tap.

Similar conclusions can be drawn from the analysis of seasonal trends in S-DWCC1000. Figure 2-12 shows the variability in S-DWCC1000 in each season for each financial year. In the figure, S-DWCC1000 for each financial year can be observed to consistently increase from winter through spring to summer. Autumn and winter figures are similar. Figure 2-13 shows a corresponding increase in average peak daily flow rates from winter to summer at the outlet of the Wantirna Service Reservoir suggesting a relationship between peak flow rate and customer complaints.

![Seasonal trend of S-DWCC1000 for whole of the SE Water region.](image)

An alternative explanation for the high complaints in summer is that customers are using water more often in a more visible form (such as drinking more water or filling swimming pools), resulting in more discoloured water events being noticed as apposed to more discoloured water events actually occurring. Similarly higher temperatures may
have affected the appearance of the water through promoting algae growth. The potential for higher algae growth in spring may also explain why the peak daily flow rates and S-DWCC1000 numbers do not correlate in Spring and Autumn even though both seasons have similar flow rates but varying complaint rates.

Figure 2-13: Seasonal variation in the average daily flow profile at the Wantirna Service Reservoir outlet.

### Daily trends

The relationship between S-DWCC for the SE Water region and peak daily flow rate at the Wantirna Service Reservoir outlet, as shown in Figure 2-14, has a strong positive linear relationship \( r = 0.92 \) and a coefficient of determination of 0.85 for data points greater than 10 ML.d\(^{-1}\). In other words, for days where maximum daily flow rate is over 10 ML.d\(^{-1}\), 85% of the variance in S-DWCC is related to maximum daily flow rate with the remainder being due to other factors.

However, this relationship is “affected” by the large number of S-DWCC in the 0-10 ML.d\(^{-1}\) ranges. Furthermore, there are days where the flow reached 52 ML.d\(^{-1}\) but no complaints were received. Although the result for flows greater than 10 ML.d\(^{-1}\) generally supports the hypothesis that high flow rates (therefore high shear stresses) cause discoloured water, two other factors need consideration, namely; (1) the high number of customer complaints associated with low (less than 10 ML.d\(^{-1}\)) daily system demand; and (2) the lack of S-DWCC on extreme flow rate days (> 45 ML.d\(^{-1}\)).
The occurrence of complaints in periods of low maximum daily demand does not necessarily contradict the hypothesis that discoloured water events are caused by high shear stress events, as local hydraulic conditions, not represented by the overall flow rate, may play a greater role in local discoloured water formation than expected. The effect of localised hydraulics is explored further in later chapters.

The lack of complaints on high demand days may be due to the very rare nature of this occurrence as only 4 days from July 1996 to July 2002 occurred with peak daily flow rates greater than 45 ML.d\(^{-1}\).

Analysis for the correlation of temperature and S-DWCC was conducted using data from January 1997 to December 2000. Correlation between maximum daily air temperature and average daily S-DWCC for the whole of SE Water region is very strong \((r = 0.89)\), as shown in Figure 2-15, indicating that more complaints can be expected on hot days. In other words, at least statistically, 79 % of the variance in S-DWCC can be explained by maximum daily air temperature.
The relationship between maximum daily temperature and maximum daily flow rate (January 1997 to December 2000) shown in Figure 2-16 is only a moderately strong relationship $r = 0.77$. This suggests that only 59% of the variance in peak daily flow rate can be explained by maximum daily temperature. Closer examination of Figure 2-16 reveals a skewed scattering of the relationship which may indicate that much of a customer’s water use is not heavily dependent on temperature (a day of 20 degrees has a peak daily flow rate range of 15 – 30 ML.d$^{-1}$). This result indicates that, despite a high correlation between air temperature and average daily S-DWCC, and that high water demand (particularly domestic) can be reasonably assumed to occur on high temperature days, the conclusion that high temperatures result in discoloured water events and discoloured water complaints cannot be directly drawn. This is because other factors such as the type of water use, which is seasonally dependent, may be contributing to the relationship.
2.6.9 Trends in the location of DWCC

Measles plots of the location of all DWCC (including non system related customer complaints) for each calendar year provide a visual indication of the location of all DWCC in the Wantirna WQZ. (These measles plots are given in Appendix 2). There are some locations where repeated DWCCs have occurred from 1996 to 2002 indicating either areas in the system that are more prone to receiving discoloured water or customers inclined toward reporting the discoloured water events they experience. However, in general, complaints were found to be spread throughout the zone.

Table 2-3 shows that many DWCC occur in dead end mains, even though the vast majority of customers are supplied by other types of mains. Interestingly, only 3% of mains in Wantirna are dead ends (Ryan [personal communication] 01/02/2008). The disproportionate number of customer complaints occurring in dead ends is consistent with observations reported by O’Connor and O’Connor (2000) and supports the work done by Yarra Valley Water (1999) who suggest that the unique hydraulic configuration of dead ends may promote particle accumulation.

Table 2-3: Number of DWCC in the Wantirna WQZ (1996 – 2002) grouped by main configuration in which the DWCC occurred.

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2.6.10 Effectiveness of flushing in reducing DWCC

Table 2-4 shows the relationship between water quality zone cleaning and complaints in following years. The ratio of cleaned zones with a lower DWCC in the year after cleaning \((P_{cr/c})\) was 0.69. This value is significantly different from 0.5 which represents what the ratio would be if the relationship was random \((t(4) = 4.7, p < 0.05)\). This result indicates that, in the majority of water quality zones, it is likely that block flushing does result in less discoloured water complaints in the following year.

Table 2-4: Relationship between water quality zone block cleaning and reductions in complaints the following year.

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<th>(P_{ci/c})</th>
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<td>0.33</td>
<td>0.60</td>
<td>0.40</td>
</tr>
<tr>
<td>99/00 - 00/01</td>
<td>0.65</td>
<td>0.35</td>
<td>0.44</td>
<td>0.56</td>
</tr>
<tr>
<td>00/01 - 01/02</td>
<td>0.63</td>
<td>0.38</td>
<td>0.71</td>
<td>0.29</td>
</tr>
<tr>
<td>Mean</td>
<td>0.69</td>
<td>0.31</td>
<td>0.57</td>
<td>0.43</td>
</tr>
<tr>
<td>Std Deviation</td>
<td>0.09</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Std Error</td>
<td>0.04</td>
<td>0.04</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>t-value</td>
<td>4.70</td>
<td>-4.57</td>
<td>1.47</td>
<td>-1.47</td>
</tr>
<tr>
<td>p-value</td>
<td>0.009</td>
<td>0.010</td>
<td>0.215</td>
<td>0.215</td>
</tr>
</tbody>
</table>

Note:
- \(P_{cr/c}\) = ratio of cleaned zones having a reduction in S-DWCC1000 in the following year.
- \(P_{ci/c}\) = ratio of cleaned zones having an increase in S-DWCC1000 in the following year.
- \(P_{ncr/nc}\) = ratio of a zone that was not cleaned having a reduction in S-DWCC1000 in the following year.
- \(P_{nci/nc}\) = ratio of a zone that was not cleaned having an increase in S-DWCC1000 in the following year.

However, it is important to note that approximately a third of water quality zones experienced higher S-DWCC1000 in the year after the zone was cleaned \((P_{ci/c}\) shown on Table 2-4). The Wantirna WQZ was one such zone and the system related discoloured water complaints for the Wantirna WQZ are shown in Figure 2-17. These results may indicate that block cleaning is not effective in removing the material that is creating discolouration in some systems, or alternatively, material in these zones may re-accumulate in less than one year.
Figure 2-17: System related DWCCs for each financial year in the Wantirna WQZ, grouped into spectrum colour type categories (July 1996 to July 2002). The year in which the water quality zone was block cleaned is shown.

The ratio of complaints for a water quality zone in a given year when the water quality zone was not cleaned are not significantly different from that associated with random occurrences ($P_{n/cr}: t(4) = -1.47, p > 0.05$ and $P_{ncr/cr}: t(4) = 1.47, p > 0.05$ respectively). This may indicate that not cleaning a zone has no effect on complaints in the following year.

2.7 Discussion of customer complaint analysis

The most common type of customer complaint for the SE Water region is of discoloured water (made up of brown, yellow and black water complaints). This result is consistent with the experience of other water companies in Australia and around the world reported in Section 1.1. Of these discoloured water complaints, the majority are of brown and yellow water. Brown and yellow water have been reported to consist of clay, silt and rust particles (De Rosa 1993; South East Water 1998; and Yarra Valley Water 1998). The main causes of discoloured water, being clay and silt particles, is in
agreement with sampling taken in the Melbourne system by van der Walt et al. (1999), Grainger et al. (2002), and Ekanayake et al. (2003).

As the supply catchment has iron rich clay (Ekanayake et al. 2003), and few complaints were found to occur from allochthonous events directly from the water wholesaler (3% in Figure 2-6), it is concluded that the majority of discoloured water may be the result of the antecedent conditions of particles entering the system at low concentrations and accumulating in mains. It can reasonably be concluded that these particles are forming cohesive layers, as described in Section 1.3.2, as the colour about which the customer is complaining and particle analysis conducted by van der Walt et al. 1999 and Ekanayake et al. 2003 suggest that these particles include clay.

The most common cause of discoloured water leading to complaints appears to be the entrainment of the particles accumulated in the mains by high shear stress (as indicated by high flow rate), as described by the cohesion and erosion mechanism in Section 1.3.2. This tentative hypothesis is based on the attributed causes of complaints and correlations between complaints and flow rate. Figure 2-6 shows that the most common cause attributed to complaints was events that had atypical shear stress (60% of those complaints that had an attributed cause). This relationship between complaints and shear stress is shown most clearly in Figure 2-14 by the strong positive correlation between maximum daily flow rate (as an indicator of shear stress) in the Wantirna WQZ and system related DWCCs. This figure shows that 85% of the variance in system related discoloured water complaints can be explained by maximum daily flow rate. In other words, the higher the peak flow rate, the higher the number of system related discoloured water complaints that can be expected (excluding days in which the flow rate was below 10 ML.d\(^{-1}\), justified below). Higher flow rates causing a greater number of complaints can also be seen in seasonal trends, where complaint numbers were consistently higher in summer where, on average, peak daily flow rates are higher than other seasons.

However, as shown in Figure 2-14, flow rates below 10 ML.d\(^{-1}\) measured at the Wantirna Service Reservoir outlet did not support the hypothesis that higher flow rates
lead to a greater number of complaints. This phenomenon may indicate that the maximum daily flow rate for a water quality zone as a whole is too general an indicator for the formation of discoloured water and that local hydraulic conditions which actually cause discoloured water events are being masked by the overall peak daily flow rate.

Such localised hydraulic events may be those occurring in dead ends. Table 2-3 shows a disproportionate number of customer complaints occurred in dead end mains given that the majority of customers are supplied by through mains. The hydraulics in dead end mains may result in a greater period of time between high shear stress events than in through mains, leading to a greater amount of material accumulated between events and a greater concentration of particles once they are entrained (Yarra Valley Water 1999). A disproportionate number of DWCCs found to occur in dead ends is also reported for the comparable unfiltered and lined Yarra Valley Water system (Yarra Valley Water 1999). However, more investigation into the hydraulics associated with dead ends is required, as much of the hydraulics of dead end mains is based on speculation without any actual hydraulic monitoring.

The relationship between peak daily flow rate and customer complaints could also be explained by the type of water use. Complaints are not only dependent on discoloured water occurring, but on the event also being noticed by the customer. At times of high flow rate more customers are using water more often, resulting in a higher likelihood of more discoloured water events being noticed, not necessarily in a greater number of discoloured water events occurring. This conclusion is supported by Figure 2-15 which shows that more complaints can be expected on days reaching high temperatures ($r^2 = 0.79$). Under these high temperature conditions it is likely that customers use the water in more visible forms (such as drinking more water or filling swimming pools) and customers are therefore more likely to observe the discoloured water event rather than have it pass without notice. Therefore a DWCC may not be a direct indicator of actual aesthetic water quality, as a DWCC is dependent on the discoloured water event being noticed. The use of more comprehensive water quality monitoring to analyse the
relationship between flow rate and discoloured water events would remove this possible variable and is explored later in this thesis.

These conclusions are also limited by the following factors:

1) The main limitation of complaints as an indicator of discoloured water events is that it is not known how many discoloured water events are captured by complaints. The correlation between discoloured water events measured by Continuous On-line Testing (COLT) and customer complaints for the Wantirna WQZ is explored further in Chapter 4.

2) Figure 2-6 shows that approximately three quarters of complaints could not be attributed to a cause. There is therefore a high margin for error in the causes of discoloured water identified through the analysis of customer complaints. This type of study would be improved by timely investigation of customer complaints and maintaining detailed records of attributed causes. Due to the relatively low number of complaints with attributed causes, each correctly recorded complaint is of benefit. Alternatively, the causes of discoloured water could be investigated by the linking of discoloured water events measured by COLT and operational procedures recorded by the water company as described later in this thesis.

3) As noted previously, complaints are recorded against the day that a customer complains. This may not be the day that the customer received discoloured water. Therefore results from this section need to be interpreted with caution and not taken in isolation. The confidence placed on time dependent analysis such as the correlation of flow rate and complaints would be increased if SE Water extended the information obtained from the customer to include the time at which the discoloured water was first noticed by the customer.

4) As noted previously, it is common practice for communication room staff to log DWCCs that occurred within the same water quality zone and on the same day, at the same address. This limits the degree in which DWCCs can be used to assess the spatial extent of a discoloured water incident, through procedures such as measles plots used for the dead end main analysis. It is recommended that all customer complaints be logged as the actual address at which the discoloured water was noticed.
5) Customer complaints are categorised into water quality complaint types by a value judgement by SE Water staff and may be biased. This may affect the analysis of the relative proportions of types of water quality complaints.

6) Influences on a customer deciding to complain have been reported as demographics, history of the water quality supplied to the customer, and the exposure of the water company to the customer. It was found that exposure of the water company to the customer through quarterly water bills did not significantly change the number of complaints that SE Water received. The effect of demographics was not, however, investigated. The effect of demographics on complaint rates could be investigated via surveys comparing different regions, such as the studies conducted by Thurman et al. (1999) and Roseth and Rock (2003), or more accurately by comparing the correlation between discoloured water events measured with water quality monitoring and DWCCs for areas with different demographics.

Despite the inherent inaccuracies, DWCCs are the only direct measure a water company has of how the customer is reacting to the water quality being supplied and as such they are an appropriate Key Performance Indicator. If a complaint occurs it is appropriate that water companies should respond to customer complaints immediately for system operations management. If good records are kept, they are a source of information on potential causes of discoloured water.

However, based on customer complaint analysis alone it is impossible to determine either the actual number of discoloured water events that occur, or the proportion of discoloured water events that are reported by customers. Given these shortcomings it is clear that historical records of customer complaints should not be used on their own to predict the causes of discoloured water.
CHAPTER 3 : GRAB SAMPLE ANALYSIS

3.1 Introduction

As discussed in Chapter 1, measurements of aesthetic water quality taken via grab samples as part of routine water quality monitoring have historically been used to assess water quality performance of the water distribution system and, secondarily, as the basis for the application of mains cleaning programs to prevent future discoloured water events. The basis for using grab samples for these purposes is that they are an objective measure of water quality, as opposed to the subjective nature of customer complaints. However, given that discoloured water events have been described as transient and episodic in nature (Walski 1991) and have both spatial and temporal variation, it is still unclear whether grab samples taken in this manner can be used to understand or manage discoloured water events effectively.

Furthermore, customer complaints rarely occur on consecutive days, and work by De Rosa (1993) and Boxall et al. (2005) both suggest that discoloured water events may last for hours, not days. Therefore the more frequently that sampling is conducted, the more likely it is to capture discoloured water events over their short duration, and to measure the temporal variability in water quality. However, the testing for discoloured water events by grab sampling is expensive and the optimal number of grab samples needed cannot be determined as the frequency and location of discoloured water events is not known.

This chapter examines whether the existing regulatory required routine water-sampling program of SE Water, and a program of grab sampling at increased frequency developed specifically for this study, can be correlated with customer experience of discoloured water. In this investigation the measurement, through grab sampling of
turbidity, apparent colour and total iron, as a quantitative measure of discolouration is explored. The effectiveness of grab samples in capturing discoloured water events is explored further in later chapters.

3.2 Acquisition of grab sample data

Grab sampling for regulation purposes commenced in Victoria, Australia, with the introduction of the Health (Quality of Drinking Water) Regulations 1991. These regulations are based on the 1987 "Guidelines for Drinking Water Quality in Australia" developed by National Health and Medical Research Council and Agricultural (NHMRC), and Resource Management Council of Australia and New Zealand (AWRC). Frequencies and procedures applied in SE Water’s grab sampling program have evolved from being based on this 1987 "Guidelines for Drinking Water Quality in Australia" to procedures recommended by the 2004 Australian Drinking Water Guidelines (ADWG 2004). The 1996 Australian Drinking Water Guidelines (ADWG 1996) are used in this chapter as they where the regulations in place for SE Water at the time of data collection and analysis.

At the time of this study, grab samples were routinely collected from standard sampling tap sites scattered through out the Melbourne region. SE Water, and sub-contractors under SE Water direction, collected the grab samples from standard tap sites in the SE Water region. The location of these tap sites in the Wantirna WQZ study zone are shown in Figure 3-1. It can be seen in the figure that the sites provide a good spatial coverage of the zone. Samples were taken under normal flow conditions, usually between 9:00 am and 12:00 noon, using a set procedure. The water samples were then delivered to a commercial water laboratory that used standard testing procedures to test the samples in accordance to the 1996 Australian Drinking Water Guidelines.

Specifically, the laboratory uses the Standard Method 2130 B from APHA Standard Methods for the Examination of Waters and Wastewaters, using a Nephelometer to test for turbidity. Among other requirements, APHA 1998 stipulates that sample cells of clear, colourless glass or plastic be used. Samples are required to be agitated thoroughly and bubbles removed before testing. However, the sample should not be allowed to
stand for any length of time before testing. No dilution should be necessary with the turbidities generated in the potable water distribution system. The method also stipulates that the operator ensure the nephelometer is calibrated to the manufacturer’s specifications. Samples to be tested for turbidity and colour should be kept in the dark in a refrigerator until testing and the test should be conducted within 24 hours of the samples being collected. Testing for apparent colour was conducted in a similar manner, with the measurement taken before filtration in accordance with the Australian Drinking Water Guidelines 1996.

Testing for total iron is conducted using the USEPA method 200.8 and inductively couple plasma mass spectrometry (ICP-MS). Method 200.8 allows for the direct analysis of samples by pneumatic nebulization without acid digestion if the samples have been properly acid-preserved and has turbidity of > 1 NTU at the time of analysis. This procedure is referred to as "direct analysis”. Readings are compared to calibration standards to generate concentration values for the samples (US EPA 2008)

Prior to the year 2000, total coliforms were tested using a membrane filtration method based on “Report 71, Methods for the Examination of Waters and Associated Materials. After the year 2000 the method changed to Colilert

The water quality values measured by the water laboratory (turbidity, apparent colour, total iron, total coliforms and any other parameters required by regulations) were recorded in a spreadsheet and faxed and emailed to SE Water. The grab sample results were then recorded in the SE Water, Water Quality Database. The measured levels of turbidity, apparent colour, total iron and total coliforms for the Wantirna WQZ extracted from this Water Quality Database, for the period from January 1995 to December 2000, are used in the analysis in this chapter.
It should be noted that the values derived from these grab samples were routinely compared to guideline values in the ADWG (1996) to assess the performance of SE Water. Compliance with these guideline values is reported in industry benchmarking documents such as ‘WSAAfacts’ produced annually by the Water Services Association of Australia and the ‘South East Water - Water Quality Report’.
3.3 Selection of parameters

There are many different characteristics of water quality used to describe the physical appearance of water as perceived by customers. As noted in Chapter 1, humans discern discoloured water through a complex mix of refraction and diffraction (Thomas 1986). The appearance of discoloured water, as observed by customers, is rarely true colour in a strict scientific measurement sense, as it often includes particles (Boxall et al. 2001). Consequently, as described in Section 1.4.2, the most commonly agreed parameters for the assessment of the appearance of water are a combination of turbidity and true colour (Bernal et al. 1999; Gauthier et al. 1999; WHO Guidelines 1994; Clark 1994; and Tebbutt 1992). Total iron and manganese are also often included because significant levels of the particulate form of these metals can cause aesthetic problems and can provide indications of the cause of the discolouration (WHO Guidelines 1994 and ADWG 1996).

Historically SE Water measured the organoleptic parameters of turbidity, apparent colour and total iron. Turbidity is used because it is a qualitative measure of the cloudiness or muddiness of the water as influenced by the amount of fine and colloidal particulates. Apparent colour is used as it is a combination of true colour and the colour effect of particulates (ADWG 1996). Therefore these parameters give a reasonable indication of the aesthetic water quality the customer will see.

However, use of total iron can be misleading, as the measurement cannot distinguish between soluble (colourless) iron and particulate (visible) iron (Ewan and Williams 1986). Although the SE Water system has very little unlined cast iron, source water can contain clay heavy in iron (Ekanayake et al. 2003). Therefore most iron present is likely to be in particulate form, and for this case, total iron is considered a valid measurement. The ADWG (1996) recommend that turbidity and colour be tested once a month in a water quality zone and total iron tested fortnightly. However, historically SE Water only tested iron monthly, as the iron concentration was found to be stable and well below recommended values.
3.4 Method of analysis of grab samples

The analysis used in this chapter is undertaken in two parts; firstly a data screening and secondly a full interpretative study. The data screening uses routinely collected grab sample measurements taken between January 1995 and December 1998 to determine data and tap site integrity. The full interpretative study constitutes three tests to determine the effectiveness of grab sample results in detecting the customers’ experience of discoloured water.

Two sets of water quality data taken at different frequencies are used in the full interpretive study. The first set of data is turbidity, apparent colour and total iron measurements taken as part of an existing routine water-sampling program required through regulation imposed on SE Water. In accordance with ADWG (1996), one sample every month was taken at a randomly selected tap site and tested for turbidity, apparent colour and total iron. The first set of data consists of water quality data from January 1998 to December 2000. The second set of data is turbidity, apparent colour, and total iron measurements taken as part of a program of grab sampling at increased frequency developed specifically for this study. The increased sampling program took place at 11 tap sites for the period 21 July 1999 to 9 December 1999 with the water being sampled and tested weekly at each tap site. This level of grab sampling was considered to be the most frequent sampling that SE Water could economically adopt.

3.4.1 Screening of data and tap site locations

The steps to determine relevant tap sites and to ‘clean up’ the data are as follows:

Conversion of non-numerical data

Results that lie below the detectable range of measurement are recorded in the Water Quality Database as qualitative ‘values’ by the commercial water laboratory. In reality, these results are between the detectable level of the measurement technique and zero. To allow for the incorporation of these results into the analysis, the average between the detectable level and zero is used, as shown in Table 3-1. The use of these altered results was standard practice at SE Water at the time that the analysis was conducted. The remainder of the results are not modified.
Table 3-1: Conversion table of parameter results so that statistical analysis could be conducted.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Recorded Result</th>
<th>Altered Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Iron</td>
<td>&lt;0.05</td>
<td>0.025</td>
</tr>
<tr>
<td>Turbidity</td>
<td>&lt;0.5</td>
<td>0.25</td>
</tr>
</tbody>
</table>

**Operational tap sites**

Obsolete and new tap sites, and the years in which they were altered between January 1995 and December 1998, were confirmed as follows. This identification is needed due to changes in the number of tap sites in the Wantirna WQZ following the creation of SE Water in 1995 and the lack of records detailing these changes. By determining the years in which a site was not in use, the reason for the lack of sample results in that year can be accurately interpreted. For example, a tap site where no tests were performed in 1995 and 1996 is likely to be due to its creation in 1997, and not due to the lack of sampling of the site in 1995 and 1996.

Over the period investigated, the values of turbidity, apparent colour and total iron were only measured once a month in each water quality zone, using the same sample taken at a randomly chosen tap site. Since there were more than twelve tap sites in the Wantirna WQZ, this approach resulted in not every tap location being tested in a given year. Therefore using the parameters of turbidity, apparent colour and total iron may give misleading results as to which tap sites existed in a particular year. The parameter of total coliforms is therefore used instead of turbidity, apparent colour or total iron, to determine whether a tap site was operational. This is because it is required that total coliforms are tested weekly at a random tap site in a water quality zone, with the added requirement that every tap site be tested at least once. This approach results in all tap sites being tested for total coliforms in the Wantirna WQZ. A tap site is considered to be operational in a year in which the frequency of total coliform sampling is one or greater.

**3.4.2 Full interpretative study**

The 11 tap sites selected for the increased sampling program for use in the full interpretative study were chosen on the basis of the following criteria:
• The site was used as a sampling site between 1998 and 2003; and
• Spatial coverage over the Wantirna WQZ is achieved.

The tests constituting the full interpretative study are as follows:

**Test 1: Comparison with 1996 Australian Drinking Water Guidelines**

In this test it is assumed that a grab sample has detected a discoloured water event when the grab sample test result exceeds the aesthetic guideline level of the ADWG (1996). The frequency that grab sample test values under the routine monitoring program for turbidity, apparent colour and total iron exceed aesthetic guideline levels in the test period are compared with the number of DWCCs in the Wantirna WQZ in the same period. In this framework it is assumed that customers complain if values exceeded the aesthetic guidelines which are set at the point that a customer can see the aesthetic parameter in a glass of water (ADWG 1996). A result where the number of times the guidelines are exceeded is greater than the number of customer complaints indicates that grab samples taken at this frequency are a better way of measuring discoloured water events than customer complaints.

It should be noted that the ADWG (1996) aesthetic limit for the parameters used in this study are:

- Turbidity: 5 NTU
- Apparent Colour: 25 PTU
- Total Iron: 0.3 mg.L\(^{-1}\)

**Test 2: General relationship between aesthetic parameters and DWCCs**

Chapter 1 reviewed previous investigations that suggest that trends in water quality measurements may be able to predict discoloured water events. To evaluate this theory the mean, maximum and variance in the aesthetic parameters is calculated in this test. These basic statistics are used to determine the range of water quality that is being measured. The correlation between monthly average colour, turbidity, iron and S-DWCC1000 is then determined. [Monthly S-DWCC1000 figures are calculated as described in the previous chapter.] A high correlation between aesthetic parameters and
complaints would imply that water quality measured by grab samples can be used to predict discoloured water events, even if aesthetic guidelines had not been exceeded.

**Test 3: Specific relationship between aesthetic parameters and DWCCs**

The relationship between aesthetic parameters and discoloured water events is further explored in this test by a case study investigating the match in both time and location between DWCCs and grab samples. Temporal analysis is conducted by comparing the day on which complaints occurred and dates on which grab samples where taken. In this comparison it is assumed that a customer will complain on the same, or close to the, day they observed the discoloured water. A temporal match is therefore assumed to occur if the customer complaint occurred within three days of the grab sample. A grab sample result and a DWCC are deemed to be matched spatially if they both occur within the same map reference grid, or adjacent grids. The map grids used are 400 metres square. (The co-ordinates of the Melways road maps of Melbourne are used in this mapping). This matching takes into account the uncertainty in how localised discoloured water events occur, a problem identified by De Rosa (1993) who found discoloured water occurring up to 300m from the cause of an event.

### 3.5 Results

#### 3.5.1 Data screening

As noted earlier in this chapter, total coliform tests were collected weekly from a randomly selected sample tap site in the Wantirna WQZ, as recommended by the ADWG (1996). Table 3-2 shows the frequency of tests of total coliforms at each tap site in the Wantirna WQZ. The total coliform sampling indicates sites QZ59H011 and QZ59H012 were not in use after 1997 and appear to be obsolete sites arising from the rezoning of water quality zones. Due to rezoning, Tap Site QZ59H027 was not actually in the Wantirna WQZ as of 1995. These three sampling sites were therefore not included in future analysis. Tap Sites QZ59H007, QZ59H008, QZ59H014, QZ59H015, QZ59H016, QZ59H017, QZ59H018, and QZ59H021 appear to be new sites, as no samples were taken from these sites for total coliforms before 1997. QZ59H013 may also be a new tap site as it was not sampled in 1995. The choice by SE Water of tap
sites to sample for total coliform is not purely random, as it is SE Water policy for every site to be sampled at least once in a given financial year. The existence of this policy and the associated practices indicate that sites that were not sampled did not exist in the year where no results are recorded. It can also be seen in Table 3-2 that even with this policy there is considerable difference in the number of times tap sites were used, indicating some randomness in site selection.

Table 3-2: Frequency of tests done for total coliforms at each tap site for each year in the Wantirna WQZ.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>QZ59H001</td>
<td>24</td>
<td>20</td>
<td>23</td>
<td>8</td>
<td>75</td>
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<tr>
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<td>21</td>
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<td>5</td>
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<td>2</td>
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<tr>
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</tr>
<tr>
<td>Grand Total</td>
<td>209</td>
<td>179</td>
<td>85</td>
<td>88</td>
<td>561</td>
<td></td>
</tr>
</tbody>
</table>

Table 3-3 shows that, as expected, tap sampling frequency rates for turbidity, total iron, and apparent colour in the Wantirna WQZ averaged less than 1 sample per site per year in 1996 to 1998. The number of tap sites sampled per year were, however, within sampling rates recommended by ADWG (1996) for turbidity and colour (monthly sampling at random tap within a water quality zone is recommended). In contrast, total iron was tested at lower frequencies than that recommended by the ADWG (1996). Fortnightly sampling at random tap sites in a water quality zone is recommended by the
ADWG (1996) but it is SE Water policy to test for total iron on a monthly basis due to the consistent underlying iron levels, well below recommended values.

Table 3-3: Frequency of grab samples that are tested for turbidity, apparent colour and total iron in the Wantirna WQZ. (Grey cells indicate that the tap site was not in operation.)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>QZ59H001</td>
<td>12</td>
<td>4</td>
<td>3</td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>QZ59H002</td>
<td>10</td>
<td>5</td>
<td></td>
<td>1</td>
<td>21</td>
</tr>
<tr>
<td>QZ59H003</td>
<td>7</td>
<td>6</td>
<td></td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>QZ59H004</td>
<td>8</td>
<td>2</td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>QZ59H005</td>
<td>10</td>
<td>5</td>
<td></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>QZ59H006</td>
<td>9</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>QZ59H007</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>QZ59H008</td>
<td></td>
<td></td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>QZ59H009</td>
<td>3</td>
<td>2</td>
<td></td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>QZ59H010</td>
<td>11</td>
<td>3</td>
<td></td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>QZ59H011</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>QZ59H012</td>
<td>14</td>
<td>2</td>
<td></td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>QZ59H013</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>QZ59H014</td>
<td></td>
<td></td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>QZ59H015</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>QZ59H016</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>QZ59H017</td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>QZ59H018</td>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>QZ59H021</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>QZ59H027 *</td>
<td>11</td>
<td>3</td>
<td></td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>Grand Total</td>
<td>104</td>
<td>35</td>
<td>13</td>
<td>15</td>
<td>167</td>
</tr>
</tbody>
</table>

* Found to be not in the Wantirna WQZ

3.5.2 Full interpretative study

As noted earlier in this chapter, the full interpretative study of grab sample results is conducted using test results for turbidity, apparent colour, and total iron for the Wantirna WQZ between January 1998 and December 2000 for 11 tap sites. Sites QZ59H001, QZ59H002, QZ59H003, QZ59H005, QZ59H006, QZ59H007, QZ59H009, QZ59H013, QZ59H014, QZ59H015, QZ59H018 are chosen for the full interpretative study, as according to Table 3-3 they were all current sites in 1998, and give a good coverage of the Wantirna WQZ. The number of grab samples at each site that are tested for the each of these three parameters is shown in Figure 3-2. It should be noted that the
greater number of samples in 1999 is due to the increased sampling program undertaken as part of this study.

![Figure 3-2: Number of grab samples tested for turbidity, apparent colour and total iron in 1998, 1999 and 2000 for each tap site in the Wantirna WQZ.](image)

The histograms in Figure 3-3 and statistics in Table 3-4 show that, over the three year period of analysis, turbidity, apparent colour and total iron levels have approximated a normal distribution, allowing parametric statistical analysis. Turbidity grab sample values for the 1998 - 2000 period ranged from 0.3 – 4.1 NTU and total iron ranged from 0.03 to 0.2 mg.L\(^{-1}\). Turbidity and total iron values did not fluctuate to a great degree (turbidity \(\mu = 1.1\) NTU, turbidity SD = 0.4 NTU; total iron \(\mu = 0.08\) mg.L\(^{-1}\), total iron SD = 0.03 mg.L\(^{-1}\)). The maximum recorded measurements of these parameters are below aesthetic guideline levels, and hence below the level at which customers are assumed to observe discoloured water.

Apparent colour had a range from 4 PCU to 30 PCU (apparent colour \(\mu = 13\) PCU, apparent colour SD = 3 PCU). Apparent colour exceeded the aesthetic guideline of 25 PCU on one occasion (21 August 2000). Indeed, this was the only time that the aesthetic limits were exceeded during the study period. However, no DWCCs were recorded in the Wantirna WQZ on this day or, indeed anytime in August 2000.
Figure 3-3: Histograms of parameters to describe the appearance of water in the Wantirna WQZ (1998 – 2000).
Table 3-4: Descriptive statistics for parameters to describe the appearance of water in the Wantirna WQZ (1998 – 2000).

<table>
<thead>
<tr>
<th></th>
<th>Turbidity (NTU)</th>
<th>Apparent Colour (PCU)</th>
<th>Total Iron (mg.L⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aesthetic guideline</td>
<td>5</td>
<td>25</td>
<td>0.3</td>
</tr>
<tr>
<td>Mean</td>
<td>1.1</td>
<td>13</td>
<td>0.08</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>Median</td>
<td>1.0</td>
<td>13</td>
<td>0.09</td>
</tr>
<tr>
<td>Mode</td>
<td>1.0</td>
<td>12</td>
<td>0.09</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.4</td>
<td>3</td>
<td>0.03</td>
</tr>
<tr>
<td>Skewness</td>
<td>3.661</td>
<td>0.787</td>
<td>0.253</td>
</tr>
<tr>
<td>Range</td>
<td>3.9</td>
<td>26</td>
<td>0.18</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.3</td>
<td>4</td>
<td>0.03</td>
</tr>
<tr>
<td>Maximum</td>
<td>4.1</td>
<td>30</td>
<td>0.20</td>
</tr>
<tr>
<td>Count (n)</td>
<td>282</td>
<td>283</td>
<td>261</td>
</tr>
</tbody>
</table>

It can be seen from Table 3-5 that apparent colour and turbidity are strongly correlated ($r=0.91$). This result is expected, as both parameters are a general overall measurement for particulate matter in the water, with apparent colour also providing some indication of the true colour of the water. The moderately strong correlation between turbidity and total iron ($r=0.71$) may indicate that the iron is present in colloidal form, most likely clay, as the particles in the source water are rich in iron (Ekanayake et al. 2003). DWCCs do not have a strong correlation with any of the parameters and as reflected in the Pearson’s $r$-values shown in Table 3-5. This result indicates that turbidity, total iron and apparent colour do not predict customer complaints well.

Table 3-5: Correlation Pearson’s r of monthly S-DWCC1000, and monthly maximums of total Iron, turbidity and apparent colour for the Wantirna WQZ, using data from 1998 to 2000

<table>
<thead>
<tr>
<th></th>
<th>S-DWCC1000</th>
<th>Max apparent colour</th>
<th>Max total iron</th>
<th>Max turbidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-DWCC1000</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max apparent colour</td>
<td>0.383</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max total iron</td>
<td>0.439</td>
<td>0.696</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Max turbidity</td>
<td>0.229</td>
<td>0.906</td>
<td>0.708</td>
<td>1</td>
</tr>
</tbody>
</table>

Notwithstanding the fact that the maximum recorded values of turbidity and total iron were below aesthetic guideline limits, and only one value of apparent colour was above its aesthetic guideline limit, a case study analysis was conducted to match DWCCs with grab sample results in time and location. It was found that 20 complaints occurred on
days on which grab samples were taken. Only one of these pairs matched spatially. (The map reference of the grab sample site and the map reference of the DWCC were diagonally touching.). This ‘match’ is a case of a customer complaint of brown water that occurred on the 27 November 2000. The grab sample taken at this time measured a turbidity of 1.2 NTU, apparent colour of 14 PCU, and total iron of 0.14 mg.L\(^{-1}\). These values are well below the level in which a customer is expected to see discolouration in a glass of water, or even a white bath (ADWG 1996) and are therefore unlikely to represent the discoloured water that caused the complaint.

![Figure 3-4: Monthly S-DWCC1000, total iron, turbidity and apparent colour for the Wantirna WQZ, using data from 1998 to 2000.](image)

3.6 Discussion of grab sample results

The limitations in the use of grab samples to measure discoloured water events are indicated by analysis of sampling results from January 1998 to December 2000 at 11 tap sites within the Wantirna WQZ. To capture a discoloured water event with grab samples, samples would need to be taken during the time of a discoloured water event (the temporal aspect) and at a location in which the event is occurring (the spatial aspect). Analysis of grab sample results gives some insight into why routine grab
sampling does not adequately capture discoloured water events in terms of these two factors.

Grab sample data taken over a three year period at frequencies recommended by the ADWG(1996) resulted in only one sample exceeding aesthetic guideline limits, suggesting only one discoloured water event occurred. Furthermore, increasing the frequency of monitoring to over 10 times the guideline frequency for a period of 5 months did not identify any additional discoloured water events. This result is in direct contrast with the 104 DWCCs that occurred in the Wantirna WQZ over the same period shown in Figure 2-7. It is therefore reasonable to conclude that the vast majority of discoloured water events were not detected by grab sampling at frequencies recommended by the ADWG(1996), as the DWCCs suggest that at least 104 of discoloured water events occurred.

Additionally, discoloured water would appear to occur so infrequently (as shown in Figure 2-7 as being an average of 5 S-DWCC1000 in a 12 month period) that even a frequency of one sample per week at 11 locations in the Wantirna WQZ did not, and was not likely to, capture an event.

It is therefore concluded that grab samples taken at these sampling rates seriously underestimate the occurrence of discoloured water events. Hence grab sampling results, as currently implemented, may give misleading results as to the severity and frequency of discoloured water events. These conclusions are in agreement with statements made by a number of authors (Williams 2001; Black and Christman 1963; and Mevel 2002) and conclusions of the literature review in Chadderton et al. (1992). De Rosa (1993) also suggests that discoloured water events only last for minutes to hours, not days. A grab sampling program designed to capture events of this temporal trend is not economically feasible. The frequency of discoloured water events and the time over which they occur in the Wantirna WQZ is explored further in the following chapter with the use of continuous online monitoring. From this analysis the likelihood that a sampling program on a weekly basis can capture a discoloured water event is examined.
Furthermore, the only match in time and location of a DWCC and grab sample indicated that the discoloured water event noted by the customer was not captured by the grab sample, as the water quality was at average background levels. This mismatch suggests that discoloured water events are quite localised, a conclusion that is consistent with the work of De Rosa (1993). Using a water quality sampling program to investigate discoloured water events therefore requires that sampling be conducted at a coverage that is likely to capture a discoloured water event. An understanding of the coverage of a sampling program required to capture all discoloured water events can be gained by noting that, in this investigation, a DWCC occurred 700 metres from a “normal” background grab sample result, and De Rosa (1993) suggests that discoloured water events in United Kingdom systems can occur over only a 300 metre area. A grab sampling program of this coverage is not economically feasible.

It is therefore concluded that existing water quality monitoring programs that rely on grab samples taken at a nominal number of standard tap sites and at frequencies recommended by the ADWG (1996) are unlikely to characterise the physical aspects of discoloured water. Grab samples, collected at current locations and frequencies, only provide an indication of water quality under “normal” operating conditions and indeed this is what the ADWG (1996) sampling program has been designed to do. In other words it is impossible to make an assessment of the levels of turbidity, apparent colour and total iron that are reached in a discoloured water event from routinely collected grab samples.

As noted in the literature review, Ewan and Williams (1986) suggest that discoloured water events can be predicted from spatial and temporal trends in background levels of water quality parameters. These trends are used to identify long-term deterioration of water quality in the bulk flow to indicate an upcoming autochthonous discoloured water event. It would appear that trends derived from grab samples for the Wantirna WQZ cannot be used to for this purpose. The low correlation between turbidity, total iron and apparent colour results derived from grab samples with discoloured water complaint counts (shown in Figure 3-4, r < 0.45) indicates that these parameters cannot, in a practical way, be used to predict complaints. This lack of correlation between grab
samples and customer complaints may be due to the infrequent sampling at a specific location.

Furthermore, from analysis of complaints shown in Figure 2-6, many of the discoloured water events in the unfiltered system in this study appear to be associated with unexpected high shear stress and not with long-term deterioration of water quality in the bulk flow of the distribution system. [This conclusion is also supported in Chapter 4 which shows that background levels of turbidity measured by COLT do not change significantly with time or location.] It should be noted that allochthonous discoloured water events, such as those coming directly from source water, could not be predicted using grab samples taken within the water distribution system.

No DWCCs occurred within a week either side of the only time that the aesthetic guideline limit was exceeded. The only match both spatially (in same map reference area) and temporally (on the same day) between a grab sample and a customer complaint gave levels of total iron, turbidity and apparent colour at average background levels, well below the levels at which a customer would complain. One possible reason for this situation is that customers detect changes in aesthetic parameters at a lower level than recommended guideline levels.

However, it is unlikely that customers are detecting changes of aesthetic parameters at a level lower than that recommended by the ADWG (1996). This is because the one grab sample taken on the day of a complaint, and close to (but not at) the complaint location, had parameter values close to average figures for both turbidity and apparent colour, and high, but well within aesthetic guideline values of total iron. Also, the variances in the parameters measured by grab samples are very small. If it is assumed that apparent colour, turbidity and total iron sample results are representative of the common water aesthetics in the Wantirna WQZ, and customers see colour, iron and turbidity at these average levels, it would be expected that discoloured water would occur every day. However, the number of DWCCs reported to SE Water does not support this frequency of discoloured water events. Not surprisingly it can therefore be concluded that the
values of aesthetic parameters of the grab sample were not the levels at the location and time of the complaint.

Therefore industry practice, as reported by Prince (2003) and De Rosa (1993), needs to change. The use of data from grab sampling programs that are primarily designed to determine typical water quality, such as those recommended by ADWG (1996), should not be used to determine areas at risk of discoloured water events.

Since it enables very frequent monitoring, COLT at key locations is seen to be the solution to gathering data at sufficient frequency, and therefore identifying special and temporal trends, to enable management strategies for reducing discoloured water events to be developed. A program of COLT was therefore established in the Wantirna WQZ. The establishment of this COLT program and the analysis of the data obtained from this program are described in the following chapters. An explanation of the correlation between discoloured water events measured with COLT and those identified using customer complaints and grab samples identifies which measuring technique is the most effective in capturing discoloured water events.
CHAPTER 4: THE USE OF CONTINUOUS ON-LINE TESTING TO INVESTIGATE THE CHARACTERISTICS AND CAUSES OF DISCOLOURED WATER EVENTS

4.1 Introduction

Even with the limitations of using customer complaints to investigate discoloured water, the analysis of DWCCs in Section 2.6.2 suggests that in the SE Water system discoloured water is unlikely to be delivered as allochthonous events from source water or corrosion of unlined mains. Sections 2.6.3 and 2.6.8 suggest that it is more likely that discoloured water is formed during high shear stress events (as indicated by high flow rate) within the water distribution system. This position is supported by the literature discussed in Section 1.3.2 which notes that particles collected within the SE Water system are of a size, chemistry and behaviour, that suggest the antecedent accumulation of particles into cohesive layers on the internal circumference of the pipe wall. It is hypothesised that these cohesive layers are subsequently eroded when a critical shear stress of entrainment is exceeded by the applied shear stress of the flowing water.

Section 3.6 concludes that grab samples taken as frequently as once a week are not sufficient to measure the episodic and sporadic discoloured water events and that highly frequent monitoring is required. Therefore, Continuous On-Line Testing (COLT), a measuring technique that enables the automatic continuous, or very frequent, testing of the hydraulics and water quality in a main, should be considered for the investigation of discoloured water events. As noted in Section 1.4.3 such testing can be conducted either in the pipe or via a bleed from the main flow.
COLT to measure flow and turbidity was found by other researchers to be a useful method to characterise discoloured water events during short-term experiments in which events to cause discoloured water were induced by hydrant flushing (Boxall and Saul 2005; Boxall *et al.* 2001; and Schaap *et al.* 1999). The pairing of COLT of flow and turbidity is tested in this chapter to determine if it can be used, under long term monitoring arrangements, to investigate the ‘naturally’ occurring (not artificially induced) characteristics and causes of discoloured water events.

The investigations using COLT are divided into two sections: Chapter 4 describes the installation of COLT in the Wantirna WQZ, characteristics of the study area, and evaluates the effectiveness of COLT as a technique for capturing discoloured water events. The hydraulic and water quality conditions of the water quality zone under ‘normal’ conditions and during discoloured water events, as captured by COLT, are then investigated. In addition, COLT data from the identified discoloured water events are combined with other operational and system information to determine the types of procedures that cause discoloured water events. The specific hydraulic conditions recorded by COLT that form discoloured water are analysed in Chapter 5 so that the potential for the occurrence of discoloured water events at any given point in a water distribution system can be predicted.

Specifically this chapter tests the following hypotheses:

1. Underlying pipe velocities and turbidity levels in a water distribution system under ‘typical’ operational conditions can be distinguished from those experienced during discoloured water events using COLT;
2. COLT of turbidity is a more accurate indicator of when discoloured water events have occurred than customer complaints or grab samples;
3. The time, severity, and point at which a discoloured water event is created can be determined using COLT monitoring sites distributed within the water distribution system; and
4. System operations within the water distribution system that create high shear stresses cause the majority of discoloured water events.
4.2 COLT monitoring site locations

The ideal discoloured water measurement program for this study would have a COLT monitoring site on each length of pipe. Obviously, such a solution is not economically or logistically feasible. For the purpose of this study 6 COLT monitoring sites were introduced by SE Water and Melbourne Water Corporation to the Wantirna WQZ to measure discoloured water entering the Wantirna WQZ and occurring along the western transfer main within the Wantirna WQZ. The 6 monitoring sites were installed in the Wantirna WQZ in the locations shown in Figure 4-1. The choice of sites was restricted to the transfer main in order to maximise the extent of the system monitored in series, while simultaneously eliminating the complexity that too wide a range of pipe sizes and pipe materials may have on the creation of discoloured water. [This latter area is a topic worthy of further investigation but is beyond the scope of this study.]

Figure 4-1: Schematic of the Wantirna WQZ showing the location of the 6 monitoring sites (MS).
Monitoring site 1 (MS(1)) is located on the inlet to the Wantirna Service Reservoir on the Silvan-Waverley main line by Melbourne Water Corporation. MS(1) was commissioned on the 12th February 2001. Monitoring site 2 (MS(2)) is located on the outlet of the Wantirna Service Reservoir on the 900mm internal diameter main leading to the Wantirna WQZ. This monitoring site was installed by Melbourne Water Corporation and was commissioned on the 17th September 2001. The other monitoring sites are spaced along the west 450 mm transfer main within the Wantirna WQZ. The location of MS(3), MS(5) and MS(6) are existing sites that were used in a previous study to investigate pressure variances within the Wantirna WQZ. MS(3) and MS(5) were commissioned on the 12th February 2001. MS(4) was commissioned on the 17th July 2001. MS(6) was commissioned on the 18th June 2001. [Details of the location of each monitoring sites are provided in Appendix 3.] [A schematic of the water distribution system of the Wantirna WQZ showing pipes of large size is shown in Figure 2-8.]

The locations of MS(1) and MS(2) are used to determine whether allochthonous discoloured water events have travelled through the Wantirna Service Reservoir and originate directly from source water or the service reservoir. The locations of MS(3) through MS(6) allow the movement of discoloured water events over long distances to be characterised, and increase the range of operational events to which each monitoring site may be exposed. This approach also reduces the affects that may occur due to variation in pipe sizes and pipe material on discoloured water formation. In addition, by keeping pipe sizes above 400 mm diameter, it is likely that the dynamic component of shear stress is small and the applied shear stress can be approximated by the steady state shear stress (van den Boomen and van Mazijk 2002).

MS(1) and MS(2) are Melbourne Water Corporation owned and operated. SE Water own and operate MS(3) through to MS(6). MS(1), MS(2) and MS(4) are linked via telemetry which allows for instant monitoring of the sites by the water authority office. MS(3), MS(5) and MS(6) on the other hand, are monitored using data loggers with the data being downloaded from the sites every 2 weeks by a contracted company, C-Tech.
(Figure 4-2 shows C-Tech downloading data from MS(6)). C-Tech provides this data to SE Water where it is transferred to a COLT database.

Figure 4-2: Cabinet housing COLT equipment at MS(6) for turbidity and flow rate and the contractors from C-Tech downloading data from the data logger.

4.3 Turbidity monitoring equipment

4.3.1 Setup of turbidity meters

Each monitoring site has a flow meter (to enable the calculation of velocity and steady state shear stress) and a turbidimeter (to measure nephelometric turbidity as an indication of discoloured water). All monitoring sites use the same type of turbidity monitoring equipment (HACH 1720D Low Range Process Turbidimeter) thereby eliminating the variation that can occur between different models of turbidimeters, a problem identified by Slaats (2002) and Gippel (1988).

‘Monitoring’ is performed through water fed continuously to the turbidity meter via a ‘spear’ that collects water from the centre of the transfer main. A valve is used to
maintain the flow to the turbidity meter within design requirements. Before being measured, the water travels through an internal bubble trap to remove air bubbles. Air bubbles can give false turbidity readings as the surface of the bubble refracts light in a manner similar to that of a particle. The water then enters the sample chamber. Measurement is made by directing a beam of monochromatic light (870 nm LED) from the sensor head assembly down into the sample. Light scattered at 90 degrees by suspended particles in the sample is detected by a submerged photocell. The amount of light scattered is linearly proportional to the amount of turbidity in the sample. The meter measures turbidity every 30 seconds as a standard protocol. The values obtained over the data logging time intervals are averaged to give a single logged value.

Design requirements for flow into the turbidimeter are 250 to 750 mL/minute to maintain an effective bubble trap (Hach Company 1998). The initial pipe configuration illustrated in Figure 4-3 used between 12 February 2001 and 2 May 2001 to regulate flow and pressure proved ineffective because the needle valve periodically blocked due to the build-up of particulate material. An alternative control set-up which has a greater pipe size and used a ball valve, as shown in Figure 4-4, was therefore implemented. This arrangement prevented the valve from blocking while still maintaining inflows within the desired range.

The 1720D turbidimeter measures turbidity in the range 0 to 40 NTU with an accuracy of ± 2 % of the reading or ± 0.020 NTU, whichever is greater. For this study the turbidimeters are set to a range 0 to 10 NTU resulting in a maximum error of 0.2 NTU (equal to 2 % of 10 NTU). This range was chosen because it provides sufficient accuracy to identify the low turbidity readings at the beginning of a turbidity event while still monitoring the level at which the literature discussed in Section 1.4.2 predicts customers to begin to complain, namely 5 NTU. The turbidity increment used to log data is equal to the maximum error for all turbidimeters except for the meter at MS(4). Due to problems with the configuration in relation to SE Water telemetry that were never resolved, MS(4) had a turbidity increment of 2 NTU, but appeared to still to have the same error margin as the other monitoring sites.
Figure 4-3: Initial pipe and valve design for 450 mm ID transfer main to 1720D Low Range Process Turbidimeter that resulted in valve blockages and variances in flow.
Figure 4-4: Final pipe and valve design for 450 mm ID transfer main to 1720D Low Range Process Turbidimeter that did not have valve blockages and minimised variances in flow rate.
4.3.2 Maintenance of turbidimeters

The turbidimeters required careful maintenance as the sample chamber of the turbidimeter was found to: (1) promote particle collection due to low velocity conditions in the chamber; (2) promote algae growth and the hatching of Helminths (parasitic worms) because of heat and light from the globe; and (3) attract ants in search of water. These problems were controlled by periodic cleaning.

Cleaning of the turbidimeter was performed by taking the turbidimeter offline, removing the plug at the bottom of the turbidimeter and flushing the meter thoroughly with water. When algae were present, a bottlebrush was also used to remove attached material. Visual inspection of the meters determined that obvious fouling was controlled when MS(1) and MS(2) were cleaned every 4 weeks and MS(3) through MS(6) were cleaned every two weeks. This schedule of cleaning is in agreement with cleaning frequencies recommended by Burlingame et al. (1998). This schedule also fitted into the cycles of when data was downloaded from MS(3), MS(5) and MS(6). In addition, turbidity results recorded at these meters were checked fortnightly and anomalies investigated. Verification of calibration at 0 NTU and 20 NTU using a solid medium standard Hach Ice-Pic Calibration-Verification Module was conducted after the meters were cleaned.

Random comparisons of the on-line turbidimeter measurements and a handheld turbidimeter (a Hach 2100P) were used to achieve further verification of meter results for MS(3) through MS(6). In order to limit the number of times the turbidimeters were disturbed, verification of calibration checks were conducted when the monitoring sites were being visited for other reasons. However, these comparisons were not

![Figure 4-5: Samples were collected from on-line turbidimeter to compare results with a portable handheld turbidimeter on site.](image)
undertaken for MS(1) and MS(2) because of site access restrictions.

The verification procedure using the HACH 2100P is as follows:-

1. Calibration of the hand held meter is verified before each visit using the standard solid verification cells provided with the meter, in accordance with the manufacturer’s instructions;
2. The turbidity reading on the display of the on-line turbidimeter is recorded;
3. The sample cell for the hand held meter is rinsed twice in the outlet water;
4. A sample is collected from the outlet tube of the on-line turbidimeter as shown in Figure 4-5 and the surface of the sample cell is cleaned in accordance with the manufacturer’s instructions;
5. The hand held meter turbidity result is then recorded;
6. Steps 2 to 5 are repeated three times;
7. If corresponding turbidity results have a difference greater than 0.5 NTU, an extra recording is taken; and
8. If two or more pairs of results have a difference greater than 0.5 NTU, then the calibration of the on-line turbidimeter is considered suspect and re-calibration is undertaken using the Ice-Pic.

[The test results from this process are provided in Appendix 4.]

The on-line turbidimeter that is used in this study meets all performance criteria specified by USEPA Method 180.1 (Hach Company 1998). These specifications require the instrument’s response peak to be between 400 – 600 nm, resulting in an apparent colour of reading greater than 20 – 30 HCU increasing the turbidity reading (Hach Company 1998). As shown in the previous chapter, grab sample results of apparent colour during this study average 13 PCU, a value which should not generally result in interference. However water quality testing of grab samples indicate that apparent colour has reached 30 HCU so it is assumed that, during discoloured water events, apparent colour may increase the turbidity reading.

Even if apparent colour did exceed 20 HCU and turbidity readings were increased, this was not considered as a major limitation because the Australian Drinking Water
Guidelines (1996) state that, when colour exceeds 25 HCU, a customer will actually begin to see the colour in a glass of water. Therefore the turbidimeter result would be affected by true colour at a level at which would be considered a discoloured water event. This situation was considered appropriate for the study, as the condition would result in the turbidimeter taking into account the additional affect of true colour in the occurrence of a discoloured water event.

4.4 Flow meters

4.4.1 Set up of flow meters

Two types of flow meters are used in this study. No flow meter is situated at MS(1). An existing orifice plate monitoring device is used to measure flow rate at MS(2). The meter is located on the 900mm main feeding the Wantirna WQZ. The accuracy of this meter is unknown. However it was still used due to the expense and difficulty of replacement. GLI International propeller flow meters were installed at MS (3) through MS (6) specifically for this study. The GLI International meters were chosen for their accuracy at low flows (0.06 m.s\(^{-1}\) to 9 m.s\(^{-1}\) at ± 1 %), low installation costs, and ease of removal so that the meter could be reused once the project is completed. Flow rate measurements were recorded at MS(3) through MS(6) at the same time increments as for turbidity data.

4.4.2 Verification of flow meters

Verification of the calibration of the flow meters was undertaken by generating a hydraulic disturbance of a known flow rate at a known time. The disturbance was created between 2:00 hours and 5:00 hours, when water consumption is at a minimum to allow the induced flow rate to be easily identified. The induced flow rate was recorded using a portable McCrometer flow meter (0 to 40 L.s\(^{-1}\)) which is connected to the hydrant used to create the induced disturbance. The flow rate recorded at the hydrant is compared to the flow rate recorded at the on-line flow meters.
The disturbance used to calibrate the flow meter was generated at two locations, a hydrant in the reticulation system downstream of MS(6) (Site A), and a hydrant in the reticulation fed from off-takes mains between MS(5) and MS(6) (Site B).

The procedure that was used in the verification of the flow meters is as follows:

1. Attach the portable flow meter to the hydrant at Site A;
2. Record time at which that hydrant is turned on (start time);
3. Measure flow from the hydrant at Site A with the hydrant valve fully open;
4. Remove the portable flow meter and continue to run the hydrant with the hydrant valve fully open;
5. Attach the portable flow meter to the hydrant at Site B and open hydrant valve;
6. Record time at which the hydrant at Site B is opened (start time);
7. While hydrant at Site A continues to run, measure flow at hydrant at Site B with the hydrant valve fully open. Leave the hydrant running for 25 minutes;
8. Reduce the flow from the hydrant at Site B to half and record the flow rate (half flush start time);
9. Record time at which the hydrant at Site B is reduced to half (half flush start time);
10. Record flow rate from the hydrant at Site B and remove flow meter while allowing the hydrant to continue to run;
11. While the hydrant at Site B continues to run, close the hydrant valve at Site A;
12. Record time at which the hydrant valve at Site A is closed (finish time);
13. Attach the portable flow meter to the hydrant at Site A;
14. Open the hydrant valve at Site A to half and record the flow rate and start time;
15. Continue to let the hydrant at Site A run for 25 minutes;
16. Close the valve at Site A and record the time (finish time); and
17. Close the hydrant valve at Site B and record the time (finish time).

The flow rates that are recorded at the two sites are compared to the flow rates recorded by the on-line flow meters at the monitoring sites. The on-line flow meters are considered to be calibrated correctly if the time and magnitude of the flow rates are
equal (taking into account any water demand that may have occurred in the system at the time). Results from the flow meter verification can be found in Appendix 5.

![Figure 4-6: Location of Sites A and B used to verify flow rates measured at the monitoring sites.](image)

4.5 Raw data manipulation to remove data errors

The raw COLT data has a date-time field and a result field. Both these fields required manipulation, as described in the following sections.

4.5.1 Date and time corrections

Correction to time increments

Data from MS(1) and MS(2) is also used by Melbourne Water Corporation and is collected at 10 minute intervals, according to the water company’s telemetry procedure. MS(3), MS(5) and MS(6) are logged to an on-site data logger in 10 minute time increments. As discoloured water events in other systems have been found to occur over minutes to hours, not days (Williams 2001; Black and Christman 1963; and Mevel 2002) it is reasonable to hypothesise that discoloured water events in the Wantirna
WQZ will also occur over this time frame (this is confirmed later in this chapter). A 10 minute increment will therefore provide sufficient accuracy to determine when turbidity begins to increase and allow up to two weeks of data to be stored in the data-logger before downloading is required. However, MS (4) is pre-programmed to collect data at 6 minute intervals, in line with other telemetry sites under SE Water’s control. To allow for comparison between MS(4) and other monitoring sites, data from MS(4) is converted to 10 minute time increments by linear interpolation.

**Correction for daylight savings times (DST)**

Data collected by telemetry is automatically corrected for daylight savings time. Clocks at monitoring sites where the data is logged to on-site data loggers did not adjust automatically for daylight savings time. To allow for comparison with the telemetry sites, system operations information and customer complaints, all times are matched to MS(3) which is always in daylight savings time. Daylight savings time adjustments during the data collection period are as follows:

- **25 March 2001** lose 1 hour at 3:00 AM (becomes 2:00 AM) (DST ends)
- **28 October 2001** gain 1 hour at 2:00 AM (becomes 3:00 AM) (DST starts)
- **31 March 2002** lose 1 hour at 3:00 AM (becomes 2:00 AM) (DST ends)

**4.5.2 Removal of error readings**

The following corrections are made to data records:

- Due to flow meter limitations, low flow rates are sometimes recorded as negative readings. As the meter cannot record reverse flows these are altered to zero readings;
- A “–99” reading indicated a fault has occurred in the flow or turbidity meter, such as errors associated with high ambient temperature. These readings are excluded from further analysis; and
- Zero turbidity readings are set as false readings and are excluded from the analysis as 0 NTU is an unrealistic turbidity reading in an unfiltered system (as indicated by the routine grab sample analysis described in the previous chapter) and is more likely to be due to faults with the turbidimeter (such as blown globes).
4.6 Method to calculate spike turbidity and pipe velocity

On-line turbidity readings are influenced by drift just prior to cleaning and calibration. Although the increase in turbidity is within the error margin of the turbidimeter, the regular occurrence of the increased background levels and subsequent drop after cleaning suggested fouling of the turbidity meter over the time between cleaning of the meter. “Background” turbidity is therefore affected by both underlying turbidity levels in the water system and turbidity due to fouling of the turbidimeter.

To enable COLT data to be used as a continuous data set and to aid in the ease of identification of discoloured water events, the background turbidity was removed from turbidity readings in the form of a background datum as described in Equation 4-1.

\[
BD(n)_i = Q_2(n)_i + e_{ntu} 
\]

(4-1)

Where:

- \( BD(n)_i \) = background datum at time \( i \) and site \( n \).
- \( Q_2(n)_i \) = median (2\textsuperscript{nd} quartile) of the valid turbidity readings at site \( n \) within the two week cleaning cycle in which time \( i \) occurs.
- \( e_{ntu} \) = maximum error of the turbidity meter (0.2 NTU).

A cleaning cycle is defined at the period of time between meter calibration and cleaning, described in Section 4.3.2 as being two weeks for most meters. The median average of turbidity data for each two week cleaning cycle is used to calculate the background datum of turbidity, while also assisting in the monitoring of any change in background levels. A median based average for background levels is less affected than a mean by outliers of maximum turbidity readings as a result of discoloured water events.

The turbidity remaining after removal of the background turbidity comprises turbidity over and above background turbidity readings and is defined as Spike Turbidity (SNTU) as described by Equation 4-2. Spike turbidity data is calculated for all sites and all valid data.
\begin{equation}
SNTU(n)_i = NTU(n)_i - BD(n)_i
\end{equation}

Where:
- \( SNTU(n)_i \) = spike turbidity at time \( i \) and site \( n \).
- \( NTU(n)_i \) = turbidity reading at time \( i \) and site \( n \).

### 4.6.1 Calculating velocity

Average water velocity is calculated from COLT of flow rate. The average water velocity at a monitoring site, \( n \), at time, \( i \), \( V(n)_i \), is calculated using Equation 4-3.

\begin{equation}
V(n)_i = Q(n)_i / A(n)
\end{equation}

Where:
- \( Q(n)_i \) = flow rate recorded at monitoring site \( n \) at time \( i \).
- \( A(n) \) = pipe area at monitoring site \( n \).

It should be noted that velocity, as opposed to flow rate, is used in these calculations to allow for the comparison between mains of different sizes. For example, the main at MS(2) is 600 mm in diameter and the mains at MS(3) through MS(6) are 450 mm in diameter.

Velocity is also used as the hydraulic parameter as an indicator of shear stress, rather than shear stress directly, to aid in comparisons to operational procedures and customer demands. [The role of shear stress in creating discoloured water events is described more fully in Chapter 5.]

### 4.7 Method of analysis of typical conditions

When typical conditions are defined, atypical conditions that are assumed to characterise discoloured water events are easily identifiable. To characterise the typical conditions of spike turbidity and velocity of the Wantirna WQZ, the following methods are used.
4.7.1 Overall conditions

Basic statistics of maximum, minimum, mean, median, and standard deviation of turbidity and velocity at MS(1) through to MS(6) are calculated to gain an understanding of the range of spike turbidity and velocity values experienced by the Wantirna WQZ.

4.7.2 Calculation of an average daily profile

To characterise the typical daily pattern of spike turbidity and velocity, an average daily profile of spike turbidity and velocity at each monitoring site is determined. An average daily profile of velocity is calculated for overall conditions and seasonal conditions for each monitoring site. For example, an average daily profile of velocity at MS(3) for summer is calculated using all data collected in the summer period at MS(3). The mean is calculated for each 10 minute time interval and plotted to produce the diurnal curve. Under this process water velocity readings that occur at 1 December 2001 0:00, 2 December 2001 0:00, 3 December 2001 0:00, to 28 February 2002 0:00 are averaged to determine the value of velocity at 0:00 hours for the average daily profile for summer. This process is then repeated to calculate the values for 0:10, 0:20, 0:30 … 23:50 hours.

The maximum and minimum velocity for each time interval is calculated for each monitoring site and time period investigated to reveal the range of velocity experienced. These results are displayed as maximum and minimum value bars on the average daily profiles.

The same process is used to calculate average daily profiles for spike turbidity. It is important to note that the on-line turbidimeters are set to record a maximum turbidity of 10 NTU. Therefore, the maximum value of spike turbidity is limited to 10 NTU minus the background datum determined by Equation 4-2.

4.7.3 Average weekly profile

The average weekly profile is used to assess the variation in velocity and spike turbidity profiles between weekdays and weekends in each season. This profile is used to determine if typical conditions vary for different days of the week. Correlation with
known trends in residential and commercial water consumption with the average weekly profile aids in the understanding of the weekly variation in typical conditions.

An average weekly profile for each season is constructed using the same method as average daily profile described in the previous section, except that readings at each time increment on a weekday are averaged. For example, all data at 12:00 on Mondays are averaged, then all data at 12:10 Mondays etc. Average weekly profiles were only conducted for MS(3). MS(3) is chosen over the other sites because MS(3) is near the top of the system and therefore the velocity profile is the more generalised representation of water consumption. MS(2) is not used due to data collection issues described later in this chapter. The average weekly turbidity and velocity profile at other monitoring sites, and hence the spatial variability of velocity and spike turbidity can be determined from comparisons between monitoring sites using the average daily profiles.

4.8 Method of analysis of discoloured water events

Discoloured water events in this COLT analysis are defined as events that are a major turbidity event (identified using the method described in Section 4.8.1 below) and that can be verified as having occurred within the main being monitored (as identified using the method described later in Section 4.8.2). For example, a major turbidity event where the high turbidity is due to instrument malfunction is not considered a discoloured water event.

An analysis of discoloured water events is then used to: (1) determine which system operational procedures cause discoloured water events and hence which procedures are at the highest risk of causing discoloured water events; (2) the minimum time between discoloured water events to allow for the accumulation of sufficient material within the main to allow a discoloured water event to occur; and (3) compare the capture rate of discoloured water events using COLT to that of customer complaints and grab samples.

4.8.1 Identification of major turbidity events
The complaint threshold is defined as the point at which a customer will detect turbidity and therefore have a likelihood of complaining. As discussed in Section 1.4.2, for
aesthetic considerations, the literature recommends that turbidity in drinking water be kept below 5 NTU because this is the level at which most customers will detect turbidity. The spike turbidity complaint threshold ($\text{SNTU}_{\text{cth}}$) is defined as the complaint threshold of turbidity (5 NTU) minus the background datum as described in Equation 4-4.

$$
\text{SNTU}_{\text{cth}} = 5 - Q_2(\text{BD})
$$

Where:

$$
Q_2(\text{BD}) = \text{the median (2nd quartile) background datum of all valid data defined in Equation 4-1}
$$

A major turbidity event is defined in Equation 4-5 and occurs when spike turbidity, as measured by COLT, exceeds $\text{SNTU}_{\text{cth}}$ minus 1 NTU. Major turbidity events are set at this level to ensure that all events likely to be discoloured water events are included in the analysis and to limit the number of events excluded because the turbidity peak had reduced before it reached the monitoring site.

Thus a major turbidity event is assumed to occur when:

$$
\text{SNTU}_{\text{max}} > \text{SNTU}_{\text{cth}} - 1.
$$

Where:

$$
\text{SNTU}_{\text{max}} = \text{maximum daily spike turbidity recorded at a monitoring site.}
$$

### 4.8.2 Information sources used to verify discoloured water events

A number of information sources are used to determine if a major turbidity event is a discoloured water event and the cause of the event. The information sources are shown in Figure 4-7 and discussed below.

(1) **COLT database**

This database contains COLT data under the following categories: date-time, velocity ($v$) and spike turbidity (SNTU).
(2) Street to MS table

The “Street to MS Table” identifies the upstream and downstream monitoring sites of each street in the Wantirna WQZ. The table therefore enables the linking of the location of customer complaints and recorded operational procedures to monitoring sites for the purpose of comparison of data on major turbidity events.

The table is developed using the hydraulic model, Stoner SynerGEE (described later in Section 4.8.3). Using this hydraulic model, steady state analysis is performed to produce plots of the velocity magnitude and direction in each main at 03:00 hours (the hour in the day of lowest demand) and 20:00 hours (the hour in the day of peak demand). From these plots it is determined which mains were serviced from water that had first flowed through a specific monitoring site under the two extreme conditions of the day. Pipe
locations in the hydraulic model are then compared to pipe locations in SE Water Geographical Information System to determine which streets are effectively monitored by each monitoring site.

(3) Customer complaint database
The customer complaint database was described in Chapter 2.

(4) Operations database
WaterLog is a SE Water database that records all system operation procedures such as burst main or mains flushing that occur in the SE Water service area. Information such as the type of procedure, time, location and whether the water was turned off are recorded in this database.

(5) Country Fire Authority advice
The Lilydale Country Fire Authority (CFA) services the Wantirna WQZ region. The CFA provided information on whether a fire was attended on days on which discoloured water events are recorded by COLT. Information in this database includes the streets affected, times and reason for attendance.

(6) Monitoring site visitation and event log
The monitoring site visitation and event log records the times and reason for attendance at each monitoring site by SE Water, or their subcontractors, to register any potential disturbances or recalibration of the turbidimeter. Problems encountered at the site, such as ant infestations, are also noted.

(7) Melbourne Water Corporation operations advice
Information on operational procedures conducted on Melbourne Water Corporation assets upstream of the Wantirna WQZ, including the Wantirna Service Reservoir, Silvan-Waverley Main Line, and Silvan Reservoir were supplied by Melbourne Water Corporation upon request.

(8) Operators’ and contractors’ journals and expert opinion
Where no operational procedure is recorded in WaterLog or where information in WaterLog is incomplete, information is sourced from SE Water system operators and
contractors. Information is obtained from private work journals, memory, and expert opinion on procedures conducted at an event and to determine causative factors for trends observed in COLT data.

### 4.8.3 SynerGEE hydraulic model

**Hydraulic modelling**

The SynerGEE hydraulic model, like most hydraulic models, conducts an extended time simulation (also called variable state simulation or quasi steady state simulation) by calculating a series of steady state balances to simulate the dynamic behaviour of the system over time. The time interval of these steady state balances is called the time step or increment. For example, using a time step of 1 hour and 24 steady state balances, the hourly changes in velocity and pressure over one day can be simulated. This is the most common type of extended simulation. However it does not model transient shock wave effects (water hammer) or the effects of dual phase flow.

The model uses Kichhoff’s first law ("the flow into or out of a node in a network must sum to zero in order for mass to be conserved" (Stoner Associates 1998). The Hazen-Williams equation which includes a friction factor (C) that is assumed to vary with age of the main to take into account the effects of pipe deterioration is used to model head losses. C factors were obtained from SE Water. [A more detailed account of the mathematics of the SynerGEE model can be found in Stoner Associates (1998).]

The extended time simulation is “driven” by the water demand where the water demand is modelled by base demand profiles assigned to nodes. Base demand profiles are dimensionless temporal patterns used to model the relative demand for a particular type of user over the duration of the modelled period, say 24 hours. Base demand profiles are often developed from short term monitoring of flow rate. The profile can either be a generalised pattern that is produced by a number of users of that type that is then scaled, or a specific profile from monitoring of the water use of a specific user.
The base demand profile is proportioned by a base demand factor at each node, usually proportional to the number of representative users at the node. For example, 4 residential houses, 2 commercial properties and 6 high-density units may represent the demand at a particular node. It may be known that these three types of users all have different demand patterns and thus 3 dimensionless base demand profiles are needed. To calculate the total demand at the node, the resident demand profile is multiplied by a factor of 4, the commercial demand pattern profile is multiplied by a factor of 2, and the high-density demand profile is multiplied by a factor of 6.

To calibrate the hydraulic model to a specific day on which measurements were taken with COLT, a global demand multiplier is used to scale all base demand factors so that the flows predicted by the model reflected flows measured in the real system at all monitoring sites.

**Modelled scenario**

SynerGEE is used to provide a model of the Wantirna WQZ to simulate conditions on 31 January 2000. This date is chosen for the modelling because it represents a day characterised by high residential demand conditions and does not include any atypical demands such as bursts. All physical characteristics for the Wantirna WQZ are extracted from the Geographic Information System at SE Water to build the model.

In the Wantirna WQZ four general water demand patterns for four categories of users and five specific patterns for five large water users are developed. The four general categories are residential houses, high-density houses, commercial users, and industrial users. Property user types and x,y grid coordinates are extracted from the SE Water billing program. The x,y grid coordinates are used to assign a user to the closest node within a predefined supply block as part of the information extraction program. The total number of users assigned to each node is counted and a table of number of users for each type for each node as produced and imported into SynerGEE.

The water demand pattern for residential houses is developed from flow measurements on the modelled day (31 January 2000) at the outlet of the Wantirna WQZ (MS(2)). The peak flow rate divided by the diurnal flow rate pattern for that day produces a
dimensionless flow pattern that was used as the water demand pattern. The hydraulic modellers at SE Water know by experience that the commercial, industrial and high-density housing residential demand profiles have a similar pattern to winter flows. Thus flow measurements on 14th July 1999 (a day in winter) at the outlet of the Wantirna WQZ (MS(2)) is used to develop the water demand pattern for these users. To develop the water demand patterns for each of the five large users, flow rate monitoring at each large user over a two week period was conducted. The results of this monitoring is then moderated and validated through consultation with employees of the large users. In the consultation process staff of the large users are asked to detail water use patterns by season, week, holidays and shifts to ensure that the flow rate monitored was typical of the large users’ water demand.

To verify that the model is simulating the hydraulics of the system accurately, the simulated flow and/or pressure data is compared to measured data at certain points. The demand factors are adjusted until the simulated data matches the measured data, within a certain tolerance. On the 31 January 2000, there were pressure data loggers installed at MS(3), MS(5) and MS(6). The global demand factor is adjusted until the pressure data predicted by the model matches the pressure data measured by these pressure data loggers in the field.

Filling of the two tanks that make up the Wantirna Service Reservoir is not modelled in the analysis and they are assumed to drain. This is a realistic assumption because the tanks are filled over a few hours at night and take several days to empty.

4.8.4 Determination if major turbidity events are discoloured water events

A major turbidity event, as defined in Section 4.8.1, is said to be a discoloured water event if it is the result of high turbidity in the main being monitored (and not a result of turbidity meter error). To determine if the major turbidity events identified are discoloured water events, the following criteria are used. An answer supporting the case that the major turbidity event was a discoloured water event is assigned a tick and an
answer suggesting that the event was due to meter error is assigned a cross. More weight is given to the first two criteria in excluding major turbidity events.

1. Is there any recorded disturbance or malfunction of monitoring equipment on the day the major turbidity event occurred?
   O Yes the monitoring equipment was cleaned, calibrated or otherwise interfered with.
   P No, it was continuously operating well and not disturbed.
   The monitoring site visitation and event log for SE Water and Melbourne Water Corporation monitoring sites are used to determine if equipment at the monitoring site was disturbed on the day the major turbidity event occurred. An exact day match is required if malfunction, interference, cleaning or calibrated is considered to have occurred.

2. Did the major turbidity event occur at more than one monitoring site?
   P Yes the major turbidity event occurred at more than one site.
   O No it only occurred at one site.
   A diurnal profile of velocity and spike turbidity is extracted from COLT data for each monitoring site on the day of the event and compared to determine if velocity and turbidity increases are recorded at more than one site. An exact day match is required if an event is to be considered to have occurred at more than one monitoring site.

3. Did an operational procedure or incident occur at the same time as the increase in turbidity?
   P Yes an operational procedure or incident occurred at the same time. The procedure or incident is noted.
   O No there was no operational procedure or incident recorded at the same time as the major turbidity event.
   WaterLog, CFA Advice, operators and contractors journals, interviews with SE Water staff, and Melbourne Water Corporation advice are used to determine if a procedure or incident occurred at the time and location of the turbidity event.
Much of this information is recorded against a street address. The ‘street to MS table’ is used to determine which monitoring site supplies the water to the street on which the operation occurred. An exact day and time match is needed to establish that an action led to a discoloured water event. The cause categories defined in Section 2.5.2 are used when possible.

4. Did a DWCC result?

P Yes
O No.

A customer complaint is said to have resulted from a discoloured water event when it occurs at the same location and time. A customer complaint is assumed to occur at the same time as a turbidity event if the complaint occurs in the following three days. A three-day period is used, as the date field in the customer complaint data is the day a customer complains, not necessarily the day they observed the discoloured water. A customer complaint is similarly assumed to be at the same location as a discoloured water event if it occurs on a street that is supplied by a pipe that comes off the transfer main between two monitoring sites that experience turbidity at a level to be classified as a discoloured water event. Customer complaints are recorded against a street address. The ‘street to MS’ table is used to determine which monitoring site supplies the water to the street on which the customer complaint occurred.

4.9 Determination of the cause of discoloured water events

Discoloured water events identified in the previous section are grouped into system hydraulics and operational procedure causation groups to determine the cause of discoloured water events.

Hydraulic cause

To determine if the discoloured water events were created by high velocity (as an indicator of high shear stress), diurnal profiles of velocity and spike turbidity are created for each discoloured water event. If a discoloured water event occurs at the same time as an increase in velocity, (particularly if the velocity exceeded the peak daily velocity
identified using the seasonal average daily profiles for a specific site), then it is assumed that the discoloured water event is a result of the velocity increase.

System hydraulic categories considered are:

1. Discoloured water event created within the water distribution system and related to a atypical high velocity event;
2. Discoloured water event created within the water distribution system and not related to a high velocity event; and
3. Discoloured water event entered the water quality zone through the Wantirna Service Reservoir.

A result where the majority of discoloured water events are velocity related and created within the water distribution system supports the position that high shear stresses within the water distribution system are the dominant cause of discoloured water events.

**Operational procedure**

On the basis of the results of Criteria 3 in Section 4.8.4 causes are attributed to discoloured water events. Attributed cause categories are:

1. Cause unknown, not flow related;
2. Flushing;
3. From upstream of the service reservoir;
4. Mains repair (valve closure);
5. Burst main or hydrant;
6. Normal demand;
7. Change in supply, not flow related;
8. Hydrant used (not by SE Water);
9. Cause unknown, flow related;
10. Hydrant repair;
11. Fire sprinkler system used; and
12. Turbidimeter failure or error **.

** Not strictly a cause of discoloured water events but included as a category for completeness.
The most frequent third of the attributed cause categories are identified as having the “highest frequency”, the middle third as having “medium frequency”, and the least frequent third as having the “lowest frequency”.

Discoloured water events are grouped under the following operational procedure categories:
1. Fire fighting;
2. Normal demand;
3. Source water;
4. SE Water operational procedure; and
5. Formed in the water distribution system but the cause unidentified.

### 4.10 Determination of the effectiveness of COLT and customer complaints

Two investigations are conducted to determine how well COLT identification of discoloured water events correlates with occurrences of DWCCs.

**Investigation 1**

This investigation determines if there is a DWCC for each discoloured water event identified using COLT. To conduct this investigation the proportion of discoloured water events identified using COLT that occur within 3 days of and prior to a DWCC is first determined. These events are then investigated further to determine if any similarities can be identified. Characteristics that are considered in this analysis of similarities include:
1. Time of discoloured water event and DWCC;
2. Location of event relative to the complaint using the MS to street table; and
3. Attributed cause of the event as determined in Section 4.9.

**Investigation 2**

This investigation is the converse of investigation 1 in that it determines if COLT captures all discoloured water events identified by DWCCs. This investigation uses
DWCCs that occurred over the period of time that COLT is conducted and within the area that is effectively monitored by the COLT monitoring sites.

The maximum recorded spike turbidity at each monitoring site in the three days preceding each DWCC is determined. The two monitoring sites between which the complaint occurs are then identified. By comparing these two pieces of information with the SNTU_{cth} (Equation 4-4) and typical underlying conditions determined in Section 4.7, the proposal that the turbidity measured in the transfer main can predict DWCCs can be tested.

4.10.1 Determination of the time needed for particle accumulation between major discoloured water events
As noted previously, it is assumed that discoloured water events require the antecedent conditions of particles collecting in the water mains for a discoloured water event to occur (see Section 1.3.2). The number of days between discoloured water events that were created within the water distribution system, as identified by COLT, is used to gain understanding on how much time is needed for the accumulation of material sufficient to allow a discoloured water event to occur.

4.11 Results of background conditions
As noted earlier, COLT of the Wantirna WQZ occurred between 12 February 2001 and 4 July 2002. Thirty five fortnightly cleaning cycles occurred during this sampling period. [Graphs of typical raw data collected by COLT at each monitoring site can be found in Appendix 7.] The count of cleaning cycles, shown in Table 4-1, is less than the total number of cleaning cycles possible between 12 February 2001 and 4 July 2002 indicating that none of the turbidimeters operated for the whole of the sampling period. [The monitoring site visitation log provided in Appendix 6 gives a summary of when and why sites were off-line.]
Table 4-1: Basic statistics for background datum of turbidity readings (NTU) at MS(1) through MS(6).

<table>
<thead>
<tr>
<th></th>
<th>MS(1)</th>
<th>MS(2)</th>
<th>MS(3)</th>
<th>MS(4)</th>
<th>MS(5)</th>
<th>MS(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum</strong></td>
<td>1.6</td>
<td>1.5</td>
<td>1.5</td>
<td>1.9</td>
<td>1.7</td>
<td>3.1</td>
</tr>
<tr>
<td><strong>Minimum</strong></td>
<td>1.08</td>
<td>1.06</td>
<td>0.92</td>
<td>1.26</td>
<td>1.13</td>
<td>1.17</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td>1.32</td>
<td>1.36</td>
<td>1.20</td>
<td>1.47</td>
<td>1.39</td>
<td>1.45</td>
</tr>
<tr>
<td><strong>Median</strong></td>
<td>1.3</td>
<td>1.4</td>
<td>1.2</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Variance</strong></td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
<td>0.02</td>
<td>0.13</td>
</tr>
<tr>
<td><strong>Standard Deviation</strong></td>
<td>0.13</td>
<td>0.14</td>
<td>0.16</td>
<td>0.16</td>
<td>0.14</td>
<td>0.36</td>
</tr>
<tr>
<td><strong>Count of cleaning cycles</strong></td>
<td>29</td>
<td>12</td>
<td>31</td>
<td>25</td>
<td>31</td>
<td>25</td>
</tr>
</tbody>
</table>

4.11.1 Variation in background datum of turbidity

A table of the background datum of turbidity calculated for each two-week sample period can be found in Appendix 6. Figure 4-8, which is derived from this data, shows that the median level of background datum is relatively stable across monitoring sites, ranging from 1.2 and 1.4 NTU. However, although the variability in the background datum at each monitoring site is similar at MS(1) through MS(5), it is larger at MS(6). The monitoring site visitation log indicates that more incidences of algae growth within the on-line turbidimeter were detected at MS(6) than any other site and this may explain the larger variability for this monitoring site.

![Figure 4-8: Median, minimum and maximum levels of background datum turbidity at MS(1) through MS(6).](image-url)
4.11.2 Spike turbidity complaint threshold

The median of background datum across all trials (Q BD) is 1.4 NTU and therefore the spike turbidity complaint threshold (SNTU cth), as calculated by Equation 4-4, is 2.6 NTU.

4.11.3 Average conditions at each site over whole sampling period

As expected, and as shown in Table 4-2, on average the spike turbidity is effectively 0. It can also be seen in Table 4-2 that the standard deviation of spike turbidity is between 0.1 – 0.3 NTU, with the largest standard deviation and variance experienced at MS(6), the monitoring site furthest from the service reservoir. Under the assumption of a normal distribution for spike turbidity, this result indicates that 99.7 % of the time (3 standard deviations from the mean) spike turbidity would range from 0 to 0.9 NTU, well under the spike turbidity complaint threshold. Interestingly, Table 4-2 shows that the maximum spike turbidity exceeds the SNTU cth at all sites and increases with distance from the Wantirna Service Reservoir.

Table 4-2: Basic statistics of spike turbidity (NTU) at MS(1) through MS(6)

<table>
<thead>
<tr>
<th></th>
<th>MS(1)</th>
<th>MS(2)</th>
<th>MS(3)</th>
<th>MS(4)</th>
<th>MS(5)</th>
<th>MS(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong></td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Maximum</strong></td>
<td>4.8</td>
<td>8.4</td>
<td>8.4</td>
<td>8.7</td>
<td>8.8</td>
<td>8.8</td>
</tr>
<tr>
<td><strong>Minimum</strong></td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Variance</strong></td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Standard Deviation</strong></td>
<td>52259</td>
<td>20552</td>
<td>51948</td>
<td>41703</td>
<td>54662</td>
<td>41587</td>
</tr>
<tr>
<td><strong>Count of COLT readings</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As expected, average water velocity reduces with distance from the Wantirna Service Reservoir, as shown in Table 4-3. This table also shows that the standard deviation of the water velocity also reduces with distance from the Wantirna Service Reservoir, indicating less variability in velocity in the extremities of the system. This lower level of variability is consistent with lower numbers of customers supplied by the uniformly sized transfer main with distance from the Wantirna Service Reservoir. The lower number of mainly residential customers also results in a smaller potential variability in velocity. In addition, the majority of customers serviced by the pipe network
downstream of MS(6) are warehouses with very little consumption and very little potential for variability. It is also interesting to note that the velocity at MS(6) is less than the measurement error of the flow meter for the majority of the time. This would affect the accuracy of the velocity measured during non peak times and also contribute to the lower standard deviation at this location.

<table>
<thead>
<tr>
<th></th>
<th>MS(2)</th>
<th>MS(3)</th>
<th>MS(4)</th>
<th>MS(5)</th>
<th>MS(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong></td>
<td>0.39</td>
<td>0.34</td>
<td>0.29</td>
<td>0.15</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>Maximum</strong></td>
<td>2.14</td>
<td>1.77</td>
<td>1.26</td>
<td>1.20</td>
<td>0.62</td>
</tr>
<tr>
<td><strong>Minimum</strong></td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td><strong>Variance</strong></td>
<td>0.11</td>
<td>0.04</td>
<td>0.03</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td><strong>Standard Deviation</strong></td>
<td>0.33</td>
<td>0.20</td>
<td>0.16</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td><strong>Count of COLT readings</strong></td>
<td>20552</td>
<td>51948</td>
<td>41712</td>
<td>54662</td>
<td>42027</td>
</tr>
</tbody>
</table>

4.11.4 Average daily conditions at each monitoring site over the whole sampling period

Average daily conditions at each monitoring site over the complete sampling period are shown in Figure 4-9. Predictably, there is a morning and evening peak in water demand. The morning demand begins at approximately 5:30 hours and peaks at 8:00 hours, corresponding to the time most people are likely to be getting ready for work or school. The evening peak begins at 16:00 hours and peaks at 19:00 hours corresponding to the likely peak activity time for cooking, bathing children, watering gardens etc. This pattern is observed at all monitoring sites, except MS(6), within the water distribution system. The different conditions at MS(6) arise because the majority of properties below MS(6) are warehouses with very little water use and hence negligible peaks in water velocity. It should also be noted that MS(2) is situated on a larger sized main than the other monitoring sites and there is very little additional water demand between MS(2) and MS(3), resulting in lower velocities at night at MS(2) than at other sites.
Velocities at the monitoring sites situated closest to the Wantirna Service Reservoir (MS(2), MS(3) and MS(4)) remain at levels that cause turbulent flow, even over night (minimum of 0.1 m.s\(^{-1}\), giving a Reynolds Number of 39,474). It is therefore unlikely that particles are accumulating in the transfer main at MS(2) through MS(4) by the sedimentation process described in Section 1.3.1. Overnight velocities at MS(5) and MS(6), however, are constantly below the detection limit of the flow meter (minimum velocity of 0.06 m.s\(^{-1}\), Reynolds number of 23,684) and therefore it is not known whether these sites achieve laminar conditions. It is therefore also unknown whether the sedimentation process is occurring between MS(4) and MS(6).

As shown in Figure 4-10, the average daily profile of spike turbidity at all monitoring sites does not fluctuate much above 0 NTU and never approaches SNTU\(_{\text{cth}}\). This further indicates that, on an average day, turbidity levels would not be seen by a customer.

When the maximum and minimum spike turbidity values are considered on the average daily profiles, a peak in maximum spike turbidity for MS(3), MS(4) and MS(5) occurs at the same time as the morning and evening peak in velocity. For example, the relationship between the maximum spike turbidity and maximum velocity for MS(3), as shown by the bars around the average line graph in Figure 4-11, reveals that there are peaks in spike turbidity that coincide with the morning and evening peaks in velocity.
Figure 4-10: Average daily profile of spike turbidity at MS(1), MS(2), MS(3), MS(4), MS(5) and MS(6).

Figure 4-11: Average daily profile of spike turbidity (SNTU(3)) and velocity (V(3)) for MS(3) showing maximum and minimum values.
However, at all monitoring sites, a number of peaks in maximum spike turbidity appear to be unrelated to velocity events, for example, at MS(3) as shown by the peak in spike turbidity at 13:00 hours in Figure 4-11 (trends at MS(4) and MS(5) are very similar and not shown here) and at MS(6) as shown in Figure 4-12 at 10:00, 13:00 and 16:00 hours. Spike turbidity at MS(6) is more variable than other sites. In fact, turbidity at MS(6) often reaches the maximum range set for the turbidimeter. The jump in maximum SNTU recordings pre-midnight and post-midnight in Figure 4-12 is due to an event for which the turbidity meter did not record data before midnight for that specific event and therefore the large turbidity recorded for that event is not contained in the pre-midnight data. To determine if the variability of maximum and minimum values is due to seasonal variation or indeed represents discoloured water events, the seasonal average daily profile for each site is calculated.

![Graph showing spike turbidity (SNTU) and velocity (V) for MS(6)](image)

**Figure 4-12**: Average daily profile of spike turbidity (SNTU(6)) and velocity (V(6)) for MS(6) showing maximum and minimum values.
4.11.5 Average seasonal conditions

Seasonal average daily conditions
At MS(2), MS(3), MS(4) and MS(5) the highest velocities occur in summer and autumn as shown in Figures 4-13 (a) through (e). These figures demonstrate what appears to be a marked summer/autumn profile and a winter/spring profile. Figure 4-13(e) shows that velocities for average daily conditions at MS(6) are constantly below the detectable level for the flow meter. Figures 4-14 (a) through (e) show that spike turbidity on an average day is very low. However, variability can be seen to increase with distance from the Wantirna Service Reservoir.

Figure 4-13 (a): Seasonal variation in velocity at MS(2). (Data for autumn and winter not available.)

Figure 4-13 (b): Seasonal variation in velocity at MS(3).
Figure 4-13 (c): Seasonal variation in velocity at MS(4).

Figure 4-13 (d): Seasonal variation in velocity at MS(5).

Figure 4-13 (e): Seasonal variation in velocity at MS(6).

Figure 4-14 (a): Seasonal average daily profile in spike turbidity at MS(2).
Figure 4-14 (b): Seasonal average daily profile in spike turbidity at MS(3).

Figure 4-14 (c): Seasonal average daily profile in spike turbidity at MS(4).

Figure 4-14 (d): Seasonal average daily profile in spike turbidity at MS(5).

Figure 4-14 (e): Seasonal average daily profile in spike turbidity at MS(6).
Seasonal average weekly conditions

Figure 4-15 shows that morning peaks in water velocity at MS(3) occur at similar times on weekdays in all seasons. Predictably, morning peaks on Saturday and Sunday appeared later in the day than the weekdays. The biggest morning peak in velocity occurs on Saturday with this morning peak velocity for a given day decreasing through the rest of the week from Sunday to Friday. These observations are consistent with known trends in residential water consumption with more washing and gardening done on weekends and the high proportion of residential water users in the Wantirna WQZ. Figure 4-15 also shows that evening peaks and over night flows are higher in summer/autumn than winter/spring. This is most likely to be due to the increased water consumption due to garden sprinkler systems. Temporal patterns in water velocity are similar at MS(2), MS(4) and MS(5), with the magnitude of the variation obvious from the average daily profiles, and are excluded for simplicity. Patterns in water velocity at MS(6) do not vary from the average daily profile shown earlier.

![Figure 4-15: Seasonal variation in average weekly profile at MS(3).](image)

Peaks in average spike turbidity tend to occur in conjunction with morning and afternoon velocity peaks as shown in Figures 4-16 through 4-19. The regular small turbidity events that occur most mornings, as shown on the average weekly profiles, may suggest the accumulation of material over night with a subsequent re-suspension
or release of all or some of this material when velocity increases each morning. The newly accumulated material may have a lower critical shear stress and therefore lower associated velocity, at which material is resuspended than the existing sediment reservoir because it has had less time to consolidate (a mechanism found by Grainger et al. (2002) and discussed further in the literature review). This effect is more prominent in spring, which may indicate a seasonal influence on particle characteristics or behaviour.

Figure 4-16: Summer average weekly profile for MS(3).

Figure 4-17: Autumn average weekly profile for MS(3).
4.12 Major turbidity events

Forty-eight major turbidity events occurred between 12 Feb 2001 and 4 June 2002 at MS(2), MS(3), MS(4), MS(5) and MS(6). These events are shown in Table 4-4. [Diurnal profiles of all the major turbidity events are given in Appendix 8]. The 48 major turbidity events can be broadly grouped into five categories. Category 1 is a discoloured water event created by a sudden large increase in water velocity. Category 2 is a discoloured water event likely to be caused by high velocities derived from high system demand patterns. Category 3 is a discoloured water event caused by a sustained high velocity. Category 4 is a major turbidity event due to failure of the turbidimeter. Category 5 is a major turbidity event created within the water distribution system but not due to high velocity. Each of these categories is explained in more detail in the following sections using an example major turbidity event related to that category.
Table 4-4: Summary table of determination of discoloured water events (DWE). (The nature of the criteria contained in C1 through C4 is provided in Section 4.8.4)

<table>
<thead>
<tr>
<th>Date</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>DWE</th>
<th>ATTRIBUTED CAUSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Mar-01</td>
<td>P</td>
<td>O</td>
<td>O</td>
<td>P</td>
<td>P</td>
<td>Cause unknown, not flow related</td>
</tr>
<tr>
<td>28-Mar-01</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>O</td>
<td>P</td>
<td>Cause unknown, not flow related</td>
</tr>
<tr>
<td>11-Apr-01</td>
<td>P</td>
<td>O</td>
<td>O</td>
<td>P</td>
<td>P</td>
<td>Cause unknown, not flow related</td>
</tr>
<tr>
<td>23-Jul-01</td>
<td>P</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>P</td>
<td>Cause unknown, not flow related</td>
</tr>
<tr>
<td>28-Feb-02</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>O</td>
<td>P</td>
<td>Cause unknown, not flow related</td>
</tr>
<tr>
<td>28-Jun-01</td>
<td>P</td>
<td>O</td>
<td>P</td>
<td>O</td>
<td>P</td>
<td>Flushing</td>
</tr>
<tr>
<td>18-Jul-01</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>P</td>
<td>Flushing</td>
</tr>
<tr>
<td>3-Oct-01</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>P</td>
<td>Flushing</td>
</tr>
<tr>
<td>21-Dec-01</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>P</td>
<td>Flushing</td>
</tr>
<tr>
<td>4-Apr-02</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>P</td>
<td>Flushing</td>
</tr>
<tr>
<td>7-Sep-01</td>
<td>P</td>
<td>P</td>
<td>not clear</td>
<td>not clear</td>
<td>P</td>
<td>Upstream of service reservoir</td>
</tr>
<tr>
<td>7-Sep-01</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>P</td>
<td>Upstream of service reservoir</td>
</tr>
<tr>
<td>16-Oct-01</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>O</td>
<td>P</td>
<td>Upstream of service reservoir</td>
</tr>
<tr>
<td>29-Oct-01</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>O</td>
<td>P</td>
<td>Upstream of service reservoir</td>
</tr>
<tr>
<td>26-Jan-02</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>O</td>
<td>P</td>
<td>Upstream of service reservoir</td>
</tr>
<tr>
<td>22-Jul-01</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>Hydrant repair (valve closure)</td>
</tr>
<tr>
<td>4-Apr-02</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>P</td>
<td>Hydrant repair (valve closure)</td>
</tr>
<tr>
<td>20-Nov-01</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>P</td>
<td>Mains repair (valve closure)</td>
</tr>
<tr>
<td>5-Jan-02</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>P</td>
<td>P</td>
<td>Mains repair (valve closure)</td>
</tr>
<tr>
<td>23-Aug-01</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>Burst hydrant</td>
</tr>
<tr>
<td>24-Apr-01</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>Burst main</td>
</tr>
<tr>
<td>7-Mar-02</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>O</td>
<td>P</td>
<td>Burst main</td>
</tr>
<tr>
<td>15-Nov-01</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>O</td>
<td>P</td>
<td>High system demand</td>
</tr>
<tr>
<td>10-Jan-02</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>O</td>
<td>P</td>
<td>High system demand</td>
</tr>
<tr>
<td>20-Nov-01</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>P</td>
<td>Change in supply</td>
</tr>
<tr>
<td>24-Nov-01</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>P</td>
<td>Change in supply</td>
</tr>
<tr>
<td>25-Jul-01</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>P</td>
<td>Hydrant used</td>
</tr>
<tr>
<td>2-Oct-01</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>O</td>
<td>P</td>
<td>Hydrant used</td>
</tr>
<tr>
<td>4-Jul-01</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>P</td>
<td>Cause unknown, flow related</td>
</tr>
<tr>
<td>20-Jul-01</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>O</td>
<td>P</td>
<td>Cause unknown, flow related</td>
</tr>
<tr>
<td>7-Apr-02</td>
<td>P</td>
<td>P</td>
<td>O</td>
<td>O</td>
<td>P</td>
<td>Fire sprinkler system malfunction</td>
</tr>
<tr>
<td>26-Feb-01</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>Turbidimeter failure or error</td>
</tr>
<tr>
<td>14-Mar-01</td>
<td>O</td>
<td>O</td>
<td>P</td>
<td>O</td>
<td>O</td>
<td>Turbidimeter failure or error</td>
</tr>
<tr>
<td>3-Apr-01</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>P</td>
<td>O</td>
<td>Turbidimeter failure or error</td>
</tr>
<tr>
<td>3-Aug-01</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>Turbidimeter failure or error</td>
</tr>
<tr>
<td>21-Sep-01</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>Turbidimeter failure or error</td>
</tr>
<tr>
<td>24-Sep-01</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>P</td>
<td>O</td>
<td>Turbidimeter failure or error</td>
</tr>
<tr>
<td>26-Sep-01</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>Turbidimeter failure or error</td>
</tr>
<tr>
<td>27-Sep-01</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>Turbidimeter failure or error</td>
</tr>
<tr>
<td>3-Dec-01</td>
<td>O</td>
<td>P</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>Turbidimeter failure or error</td>
</tr>
<tr>
<td>8-Dec-01</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>Turbidimeter failure or error</td>
</tr>
<tr>
<td>30-Jan-02</td>
<td>O</td>
<td>O</td>
<td>P</td>
<td>O</td>
<td>O</td>
<td>Turbidimeter failure or error</td>
</tr>
<tr>
<td>25-Feb-02</td>
<td>O</td>
<td>P</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>Turbidimeter failure or error</td>
</tr>
<tr>
<td>8-Apr-02</td>
<td>O</td>
<td>P</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>Turbidimeter failure or error</td>
</tr>
<tr>
<td>12-Apr-02</td>
<td>P</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>Turbidimeter failure or error</td>
</tr>
<tr>
<td>22-Apr-02</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>Turbidimeter failure or error</td>
</tr>
</tbody>
</table>
It can be seen that 15 of the major turbidity events are caused by instrument failure or error (Category 4), leaving 33 events that can be classed as true discoloured water events.

4.12.1 Category 1: Hydrant burst (23 August 2001)

Spike turbidity exceeded the spike turbidity complaint threshold at MS(5) on 23 August 2001 as shown in Figure 4-20. A major turbidity event is therefore deemed to have occurred on this day. [There was no data available from MS(2) at this time due to an error in meter location described in Appendix 6.] At 21:12 hours †† on the 23rd August 2001 SE Water received a call from a customer that a car had struck a hydrant in Berriabri Street, Scoresby. Berriabri Street is supplied by an off-take between MS(5) and MS(6). A crew arrived at the burst hydrant at 21:52 hours and turned off the water at 22:11 hours.

This event is reflected in the COLT data where the water velocity at MS(3), MS(4), and MS(5) increased at 21:00 hours (likely time of hydrant burst) and reduced at 22:20 hours (near the time that water is said to have been turned off). It should be noted that, due to the nature and location of this event, no increase in velocity can be seen at MS(6) because this is downstream of the demand point created by the hydrant burst.

The hydrant was repaired and the water turned on again at 23:10 hours. After a hydrant repair, it is standard procedure to flush the associated main. This procedure is reflected in the COLT data where an increase in velocity occurs at 23:10 hours. The operations database also records that the crew left the site at 23:52 hours, which coincides with a drop in velocity associated with the end of the flushing procedure.

Figure 4-20 shows that the velocity of 0.68 m.s\(^{-1}\) reached at MS(5) coincides with a turbidity peak of 8.76 NTU. An even higher velocity was reached at MS(3) and MS(4)

†† Note that operations database information were corrected from day light savings times as discussed in Section 4.5.1.
but this did not result in a major turbidity event (MS(4) velocity = 0.77 m.s\(^{-1}\), turbidity = 2.05 NTU; MS(3) velocity = 0.88 m.s\(^{-1}\), turbidity = 0.52 NTU).

No turbidity peak occurs at MS(1), indicating that the escalated turbidity did not enter through the Wantirna Service Reservoir. Figure 4-20 shows that the secondary, lesser velocity peak generated by the flushing procedure results in a small increase in turbidity at MS(5) but not at MS(1), MS(3) or MS(4). It can be seen from a comparison of the spike turbidity profiles at each monitoring site along the transfer line shown in Figure 4-20 that the major turbidity event takes 7 hours to travel from MS(5) through to MS(6) due to the very low velocities over this period. During the movement of the major turbidity event from MS(5) through to MS(6) the profile of the peak changes, with the peak dispersing by widening and decreasing in magnitude.

A DWCC was also recorded on the 23\(^{rd}\) August 2001 at 23:31 hours in Helpmann Street, Wantirna South placing the DWCC at the time of the major turbidity event. Helpmann Street is supplied by an off-take between MS(4) and MS(5). The customer received brown water and could not clear it by running his back garden tap. It was reported that his neighbour had also received discoloured water. It is therefore concluded that the hydrant burst caused the discoloured water event on 23 August 2001.
Figure 4-20: Category 1: major turbidity event, on 23 August 2001. COLT results of spike turbidity (SNTU) and water velocity (V) recorded at MS(1), MS(3), MS(4), MS(5) and MS(6). [The red shape on the left of the figure represents a burst hydrant on off-take between MS(5) and MS(6) attributed to causing the event.]
4.12.2 Category 2: Events attributed to high system demand (10 January 2002)

A high system demand and a correspondingly high turbidity reading were recorded on 10 January 2002. Figure 4-21 shows that the greatest turbidity for this event was recorded at MS(5) and coincided with the evening diurnal velocity peak. The maximum observed velocity at MS(5) associated with the peak was 0.55 m.s\(^{-1}\) with a maximum turbidity of 2.27 NTU. Even though the velocities reached at MS(3) and MS(4) were higher than MS(5), the turbidities measured at MS(3) and MS(4) were lower than at MS(5) (1.12 m.s\(^{-1}\) and 2.18 NTU; 1.11 m.s\(^{-1}\) and 1.35 NTU respectively). This major turbidity event did not travel through the Wantirna Service Reservoir either because, as shown in Figure 4-22, no increase in turbidity was recorded at MS(1) or MS(2).

It can be seen from Figure 4-22 that a more dispersed and lower turbidity peak was observed at MS(6) some two hours later than at MS(5). This delay reflects the travel time of the peak from MS(5) to MS(6) as the water velocity at these two sites at this time is low. WaterLog recorded no operational procedures or incidents at the time or location of the major turbidity event. No DWCCs were recorded in the customer complaint database for this day or the three days after the event.

As shown in Figure 4-22, the evening peak in velocity reached at MS(3) on the 10 January 2002 is higher than in any of the previous 6 days. (Similar patterns are observable for MS(5) and MS(4) but excluded for simplicity). In fact, the peak velocity of 1.12 m.s\(^{-1}\), reached on 10 January 2002 at MS(3), is higher than the average peak velocity for summer at MS(3) shown in Figure 4-16. It is concluded that the discoloured water event recorded on 10 January 2002 is associated with higher than usual system demand.
Figure 4-21: Category 2: discoloured water event on 10 January 2002. COLT results of spike turbidity (SNTU) and water velocity (V) recorded at MS(1) through MS(6).
Figure 4-22: Category 2: Spike turbidity (SNTU) and water velocity (V) for MS(2) and MS(3) for the week before discoloured water event occurring on 10 January 2002. The dotted lines show the value of evening peak in velocity on 10 January 2002 at MS(2) and MS(3).
4.12.3 Category 3: Event attributed to high velocity where cause is not explicitly known (25 July 2001)

Figure 4-23 shows that on the 25 July 2001 a major turbidity event occurred at MS(6) where spike turbidity reached 5.10 NTU. No escalation in spike turbidity is recorded entering the Wantirna Service Reservoir at MS(1) or at MS(3), suggesting that the turbidity spike did not enter through the Wantirna Service Reservoir from source water. The major turbidity event at MS(6) coincides with an escalation in velocity at MS(6), from near 0 m.s\(^{-1}\) to 0.2 m.s\(^{-1}\), which is sustained between 16:10 hours to 19:20 hours.

The different profiles in spike turbidity shown in Figure 4-23 at MS(5) and MS(6), together with the instantaneous nature of the major turbidity event at MS(6), suggest that material between MS(5) and MS(6) is mobilised and combined with the material recorded as turbidity at MS(5). It can be seen from the spike turbidity graph at MS(6) in Figure 4-23 that spike turbidity increases from 0 NTU to 5.10 NTU when the water velocity increased from 0 to 0.15 m.s\(^{-1}\).

A peak in turbidity of 0.93 NTU is recorded at MS(5) when the water velocity reached a maximum at 0.44 m.s\(^{-1}\). No turbidity event is recorded at MS(3) and MS(4). That no turbidity event is recorded at MS(3) and MS(4) is expected as the velocities reached during the event at MS(3) and MS(4) are not greater than the velocities reached at the time of morning peak in system demand. This is consistent with the literature discussed in Section 1.3.2 that proposed that that particles (represented here by turbidity) should not be generated unless the critical shear stress is exceeded (represented here by a velocity) and that the critical shear stress is determined by past peaks in shear stress (as represented by the morning peak in velocity here).

The spike turbidity profiles at MS(5) and MS(6) shown in Figure 4-20 and Figure 4-23 respectively are typical of discoloured water events that are attributed to sudden high velocity events. These events are characterised by increases in spike turbidity when velocity exceeds a critical value. In all cases spike turbidity decreased with an extended tail and took a number of hours to return to near original values.
Figure 4-23: Category 3: discoloured water event on 25 July 2001. COLT results of spike turbidity (SNTU) and water velocity (V) recorded at MS(1) through to MS(6). The red shape shows the likely location of the illegal hydrant use associated with causing the event.
It can be seen from Figure 4-23 that the water velocity at the point when spike turbidity began to be generated (critical velocity of entrainment) is greater at MS(5) than at MS(6). This variability in the critical velocity of entrainment can also be seen between discoloured water events at the same location. For example, the critical velocity of entrainment at MS(5) is different for the discoloured water event described in Category 1, Category 2 and Category 3 (shown in Figures 4-20, 4-21, 4-23 respectively). Boxall et al. (2001) hypothesises that this variability is due to past hydraulic conditioning of the cohesive layer which in turn affects the critical shear stress (indicated by variability in water velocity in these cases). This lends support to the hypothesis that the critical velocities of entrainment (and its related critical shear stresses) are variable within a water system. [An analysis to estimate the critical shear stresses is conducted in the following chapter.]

The box shaped velocity pattern shown in Figure 4-23 is not consistent with typical system water demand shown by the average daily profiles for all monitoring sites in Figure 4-13. However, no operational procedures or incidents are recorded for this time or location. Operations staff at SE Water concluded that in their expert opinion the profile is that of hydrant use. Based on these results it is concluded that the discoloured water event at MS(6) on 25 July 2001 is associated with illegal hydrant use.

4.12.4 Category 4: Events attributed to turbidimeter failure or error (8 August 2001)

A peak in spike turbidity of 5.42 NTU occurred at MS(3) on 3 August 2001. The event, which is shown in Figure 4-24, is the result of a single high spike turbidity reading at 14:20 hours. As can be seen in Figure 4-24, no high velocity event coincided with the turbidity event and no increase in turbidity occurred at MS(1), MS(4), or MS(5). MS(2) and MS(6) did not have data available for this analysis (see Appendix 6 for a summary of reasons). No operational procedures or incidents occurred and the Country Fire Authority (the fire fighting service for the region) did not attend any events in the area. No DWCCs were recorded within the three days after the major discoloured water event.
Figure 4-24: Category 4: discoloured water event on 3 August 2001. COLT results of spike turbidity (SNTU) and water velocity (V) recorded at monitoring sites MS(1), MS(3), MS(4), and MS(5).
Examination of the monitoring site visitation log (detailed in Appendix 6) shows that MS(3), MS(4), MS(5) and MS(6) were visited on the day of the turbidity event for data retrieval, cleaning and calibration of the turbidity meters. Algae was found to be growing in the MS(3) turbidimeter and the inflow to the turbidimeter had stopped due to a blocked inlet valve. The meter was cleaned and the valve cleared and reset.

However there was no way of cleaning the transmission piping from the main to the meter. The increase in velocity in the inlet pipe when the blocked inlet valve was opened is likely to have mobilised algae from the inlet pipe and resulted in the major turbidity event recorded at MS(3). The exact time that the meter was cleaned was not recorded so that an exact time match between the two events could not be conducted.

Based on these results it is concluded that the major turbidity event recorded at MS(3) on 3 August 2001 is due to the cleaning of the turbidity meter and the event is not a discoloured water event. Data associated with this event is therefore excluded from further analysis.

The majority of major turbidity events that are attributed to turbidity meter interference, failure or error occurred on days on which the turbidimeters were cleaned and calibration verified. Spike turbidity tended to increase to the maximum levels measured by the turbidity meter in one time increment (10 minutes), taking one to two increments (10 to 20 minutes) to reduce to near background turbidity readings. The spike turbidity profile at MS(3) in Figure 4-24 is typical of the shape of turbidity events attributed to being “turbidimeter failure or error”.

### 4.12.5 Case 5: Events not attributed to velocity increase

Major turbidity events that are discoloured water events but not associated with increases in water velocity fall into the following categories: (1) events likely to have entered through the Wantirna Service Reservoir; (2) events with an unknown cause; and (3) events suspected to be caused by water hammer.
Events entering through the Wantirna Service Reservoir tend to be recorded at more than one monitoring site. These turbidity events have a temporal pattern consistent with travel time down the transfer main and tend to attenuate with time and distance down the system. For example, Figure 4-25 shows a discoloured water event attributed to an allochthonous discoloured water event entering from through the Wantirna Service Reservoir.

Figure 4-25: Category 5: discoloured water event on the 24 November 2001. COLT results of spike turbidity (SNTU) and water velocity (V) recorded at monitoring sites MS(2) through MS(6).
Discoloured water events with unknown causes typically have peaks in spike turbidity recorded at more than one monitoring site and have no common profile. An example of such conditions is the event 28 of February 2002 shown in Figure 4-26.

Figure 4-26: Category 5: discoloured water event on 28 February 2002. COLT results of spike turbidity (SNTU) and water velocity (V) recorded at monitoring sites MS(3) through MS(6).
Discoloured water events suspected of being caused by water hammer occur at times when it is known valves were being closed. An example of this situation is the discoloured water event on 4 April 2002, shown in Figure 4-27. During this event, turbidity recorded at MS(6) was attributed to flushing following a hydrant repair but the turbidity events at MS(3), MS(4) and MS(5) were attributed to water hammer in the main when the water was turned off to repair a hydrant.

Figure 4-27: Category 5: discoloured water event on 4 April 2002. COLT results of spike turbidity (SNTU) and water velocity (V) recorded at monitoring sites MS(1) through MS(6).
4.13 Causes of discoloured water events

Table 4-5 shows the major turbidity events categorised by attributed causes for the Wantirna WQZ. It can be seen from this table that 15 major turbidity events are due to false readings of the turbidimeter during meter cleaning, verification of calibration, blocked valves, ant infestation and algae growth (defined as ‘turbidimeter failure or error’), and were therefore not considered to be discoloured water events. Examination of Table 4-4 shows that this category of major turbidity event is more common at the start of the study and is rectified for the later period of the study by ant nest extermination and replacement of valves on the inlet of the turbidity meters as described previously in Section 4.3.1.

The remainder of the major turbidity events are considered to be discoloured water events. The dominant cause of discoloured water events shown in Table 4-5 are events attributed to mains flushing (5), events entering through the Wantirna Service Reservoir (5), and events formed in the water distribution system but with no obvious cause and not related to hydraulic conditions (5).

Table 4-5: Major turbidity events by attributed cause for the Wantirna WQZ.

<table>
<thead>
<tr>
<th>Attributed Cause</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbidimeter failure or error</td>
<td>15</td>
</tr>
<tr>
<td>Cause unknown, not flow related</td>
<td>5</td>
</tr>
<tr>
<td>Flushing</td>
<td>5</td>
</tr>
<tr>
<td>Upstream of service reservoir</td>
<td>5</td>
</tr>
<tr>
<td>Mains or hydrant repair (valve closure)</td>
<td>4</td>
</tr>
<tr>
<td>Burst main or hydrant</td>
<td>3</td>
</tr>
<tr>
<td>High system demand</td>
<td>3</td>
</tr>
<tr>
<td>Change in supply, not flow related</td>
<td>3</td>
</tr>
<tr>
<td>Hydrant used (not by SE Water)</td>
<td>2</td>
</tr>
<tr>
<td>Cause unknown, flow related</td>
<td>2</td>
</tr>
<tr>
<td>Fire sprinkler system malfunction</td>
<td>1</td>
</tr>
</tbody>
</table>

From the results in Table 4-5 the frequency, by category of attributable cause, of creating discoloured water events within the water distribution system, is assigned according to the criteria described in Section 4-9 as follows:
Highest frequency:

- Mains cleaning using flushing (5/33 discoloured water events)
- Allochthonous turbidity event that travelled through the service reservoir (5/33 discoloured water events)
- Water hammer due to valve closure during mains repair (4/33 discoloured water events).

Medium frequency:

- Burst main or hydrant causing high flows (3/33 discoloured water events)
- High system wide demand (3/33 discoloured water events)
- Water supplied from alternative source resulting in reverse flows (3/33 discoloured water events)

Lowest frequency:

- Hydrant use, either for fire fighting or illegally (2/33 discoloured water events)
- Fire sprinkler system (1/33 discoloured water events)

Figure 4-28 shows the number of discoloured water events, re-grouped by system operation category. It can be seen in this figure that the largest proportion of the discoloured water events are created within the water distribution system and attributable to SE Water operational procedures (13/33, 39%). 6 of the 33 discoloured water events (18%) appeared to be created within the distribution system but it was not possible to identify any cause.

Figure 4-29 shows that most discoloured water events occur under circumstances that create water velocities higher than average background levels (20/33, 61%). It can be seen in the figure that 15% of the discoloured water events recorded by COLT were not created in the water distribution system and entered as allochthonous material through the Wantirna Service Reservoir (5/33).
Some events did not appear to be a result of either high water velocity or from upstream of the service reservoir (8/33, 24 %). It is possible that 4 of these events were created by dynamic shear forces caused by instantaneous pressure variance such as water hammer as they occurred at times of valve closures.
4.14 Comparison of discoloured water events measured by COLT and DWCCs

Only 5 out of 33 discoloured water events had DWCCs within three days of the event. There was no predominant cause that led to these 5 complaints. A description of each of these events is below.

1. The discoloured water event that occurred on 1 March 2001 reached a maximum spike turbidity at MS(4) of 4.9 NTU, which is above the spike turbidity complaint threshold. The event could not be associated with an operational, system or hydraulic cause. However, 2 DWCCs were registered within three days of this event. The first complaint occurred on 2 March 2001 where a customer in a dead end main supplied by off-takes between MS(4) and MS(5) complained of brown water. The second complaint occurred on the 4 March 2001 where a customer in the reticulation system supplied from off-takes between MS(5) and MS(6) complained of receiving brown water.

2. The discoloured water event that occurred on 11 April 2001 reached a maximum spike turbidity of 6.9 NTU at MS(4), which again is above the spike turbidity complaint threshold. The cause of the event is not known and appears not to be related to a high velocity. One brown water DWCC was registered on the same day as the turbidity event in the section of the reticulation system supplied from off takes between MS(5) and MS(6).

3. The discoloured water event that occurred on 24 April 2001 reached a maximum spike turbidity of 2.38 NTU at MS(3). This turbidity event was associated with a burst main. One brown water customer complaint was registered on the same day as the turbidity event in the section of reticulation system supplied from off takes between MS(4) and MS(5).

4. The discoloured water event that occurred on 28 August 2001 was attributed to a burst hydrant. The maximum spike turbidity was recorded at MS(5) at a value of 8.79 NTU which is above the complaint threshold. A DWCC of brown water was registered on the same day in the section of the reticulation system supplied from off takes between MS(4) and MS(5).
5. The discoloured water event that occurred between 7 September and 12 September 2001 is attributed to works on Melbourne Water Corporation assets upstream of the Wantirna Service Reservoir. The event resulted in measurements at the upper limit of the turbidimeter (10 NTU) for an extended period at all monitoring sites that were operational. This upper limit of the turbidimeter is well above the complaint threshold of 5 NTU. The event resulted in 37 white water complaints between MS(2) and MS(6) (not strictly counted as DWCCs) and 1 brown water complaint between MS(5) and MS(6).

Results of the reverse analysis show a similar lack of correlation between customer complaints and discoloured water events measured by COLT in the transfer main. It can be seen from Table 4-6 that the spike turbidity measured by COLT in the transfer main in the Wantirna WQZ is not always above the spike turbidity complaint threshold when a complaint occurs. In fact, the table shows that only 50% of complaints can be explained by discoloured water events recorded in the transfer main using COLT. The implications of these results is discussed further in Section 4.16.

### 4.15 Time needed for particle accumulation between discoloured water events

Section 1.3.2 noted that, in order to create a discoloured water event within the water distribution system, particles must first accumulate in the main. Table 4-7 shows that there is no pattern in the number of days between discoloured water events that were attributed to being formed within the water distribution system and the severity of that event. Some events accumulate sufficient material within 1 day to cause a discoloured water event. An alternate explanation is that not all material was removed in the previous event. However, as shown in Figure 4-30, the frequency of events appears to be random and is likely to be more related to how often a high shear stress event occurs and how high that shear stress event is rather than whether enough fresh material has accumulated. This result supports literature that describes the occurrence of discoloured water events as sporadic and episodic (Walski 1991). The relationship between shear stress and spike turbidity is explored further in the next chapter.
Table 4-6: Discoloured water complaints and white water complaints in the reticulation system that supplied by the Wantirna WQZ between 12 February 2001 and 4 June 2002 showing maximum recorded spike turbidity in the monitored transfer main in preceding three days.

<table>
<thead>
<tr>
<th>Date of DWCC</th>
<th>Freq of DWCC</th>
<th>Type of DWCC</th>
<th>Maximum spike turbidity recorded in the preceding 3 days</th>
<th>Suspected cause of discoloured water event from customer complaint database</th>
<th>Suspected cause of discoloured water event from COLT analysis</th>
<th>Discoloured water event registered on COLT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>MS(1)</td>
<td>MS(2)</td>
<td>MS(3)</td>
<td>MS(4)</td>
</tr>
<tr>
<td>2-Mar-01</td>
<td>1</td>
<td>DW/Brown</td>
<td>0.2</td>
<td>0.3</td>
<td>0.2</td>
<td>4.9</td>
</tr>
<tr>
<td>4-Mar-01</td>
<td>1</td>
<td>DW/Brown</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td>4.9</td>
</tr>
<tr>
<td>7-Mar-01</td>
<td>1</td>
<td>DW/Brown</td>
<td>0.6</td>
<td>0.2</td>
<td>0.3</td>
<td>0</td>
</tr>
<tr>
<td>9-Mar-01</td>
<td>1</td>
<td>DW/Brown</td>
<td>0.4</td>
<td>0.2</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>20-Mar-01</td>
<td>1</td>
<td>DW/Black</td>
<td>0.8</td>
<td>0</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>5-Apr-01</td>
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<td>DW/Brown</td>
<td>0.3</td>
<td>0.1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>11-Apr-01</td>
<td>1</td>
<td>DW/Brown</td>
<td>0.1</td>
<td>6.9</td>
<td>1.6</td>
<td>0</td>
</tr>
<tr>
<td>24-Apr-01</td>
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<td>DW/Brown</td>
<td>0.4</td>
<td>2.4</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>26-Jun-01</td>
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<td>DW/Brown</td>
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<td></td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>17-Aug-01</td>
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<td>DW/Brown</td>
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<td>0.1</td>
<td>0</td>
<td>0</td>
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<tr>
<td>23-Aug-01</td>
<td>1</td>
<td>DW/Brown</td>
<td>0.3</td>
<td>0.5</td>
<td>2.1</td>
<td>8.8</td>
</tr>
<tr>
<td>7-Sep-01</td>
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<td>DW/White</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10</td>
</tr>
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<td>8-Sep-01</td>
<td>36</td>
<td>DW/White</td>
<td>0</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>9-Sep-01</td>
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<td>DW/White</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>20-Sep-01</td>
<td>1</td>
<td>DW/Brown</td>
<td>0</td>
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<td>0.1</td>
</tr>
<tr>
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<td>DW/Brown</td>
<td>0.1</td>
<td>3.2</td>
<td>1.4</td>
<td>1.8</td>
</tr>
<tr>
<td>8-Nov-01</td>
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<td>DW/Brown</td>
<td>0.3</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4-Jan-02</td>
<td>1</td>
<td>DW/Brown</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>30-Jan-02</td>
<td>1</td>
<td>DW/Brown</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>8.6</td>
</tr>
<tr>
<td>22-Feb-02</td>
<td>1</td>
<td>DW/Brown</td>
<td>0.2</td>
<td>0.4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>18-Mar-02</td>
<td>1</td>
<td>DW/Brown</td>
<td>0.3</td>
<td>0.1</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>22-May-02</td>
<td>1</td>
<td>DW/Brown</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Note: Green = monitoring sites between which the customer complaint occurred.
Table 4-7: Days between discoloured water events generated within the water distribution system

<table>
<thead>
<tr>
<th>Date</th>
<th>Attributed Cause</th>
<th>Days</th>
<th>Maximum Spike Turbidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>23-Jul-01</td>
<td>Cause unknown, not flow related</td>
<td>1</td>
<td>3.4</td>
</tr>
<tr>
<td>3-Oct-01</td>
<td>Flushing</td>
<td>1</td>
<td>6.2</td>
</tr>
<tr>
<td>20-Jul-01</td>
<td>Cause unknown, flow related</td>
<td>2</td>
<td>3.2</td>
</tr>
<tr>
<td>22-Jul-01</td>
<td>Hydrant repair</td>
<td>2</td>
<td>9.5</td>
</tr>
<tr>
<td>25-Jul-01</td>
<td>Cause unknown, flow related</td>
<td>2</td>
<td>4.6</td>
</tr>
<tr>
<td>7-Apr-02</td>
<td>Fire sprinkler system malfunction</td>
<td>3</td>
<td>4.3</td>
</tr>
<tr>
<td>24-Nov-01</td>
<td>Change in supply, not flow related</td>
<td>4</td>
<td>2.7</td>
</tr>
<tr>
<td>20-Nov-01</td>
<td>Mains repair, not flow related</td>
<td>5</td>
<td>7.2</td>
</tr>
<tr>
<td>10-Jan-02</td>
<td>High system demand</td>
<td>5</td>
<td>3.3</td>
</tr>
<tr>
<td>4-Jul-01</td>
<td>Cause unknown, flow related</td>
<td>6</td>
<td>2.8</td>
</tr>
<tr>
<td>7-Mar-02</td>
<td>Burst main</td>
<td>7</td>
<td>8.8</td>
</tr>
<tr>
<td>28-Feb-02</td>
<td>Cause unknown, not flow related</td>
<td>9</td>
<td>8.7</td>
</tr>
<tr>
<td>24-Apr-01</td>
<td>Burst main</td>
<td>13</td>
<td>3.4</td>
</tr>
<tr>
<td>11-Apr-01</td>
<td>Cause unknown, not flow related</td>
<td>14</td>
<td>6.9</td>
</tr>
<tr>
<td>18-Jul-01</td>
<td>Flushing</td>
<td>14</td>
<td>3.3</td>
</tr>
<tr>
<td>5-Jan-02</td>
<td>Mains repair, not flow related</td>
<td>15</td>
<td>4.7</td>
</tr>
<tr>
<td>28-Mar-01</td>
<td>Cause unknown, not flow related</td>
<td>27</td>
<td>8.4</td>
</tr>
<tr>
<td>21-Dec-01</td>
<td>Flushing</td>
<td>27</td>
<td>8.7</td>
</tr>
<tr>
<td>4-Apr-02</td>
<td>Flushing</td>
<td>28</td>
<td>8.9</td>
</tr>
<tr>
<td>23-Aug-01</td>
<td>Burst hydrant</td>
<td>29</td>
<td>8.8</td>
</tr>
<tr>
<td>2-Oct-01</td>
<td>Authorised hydrant use</td>
<td>40</td>
<td>8.6</td>
</tr>
<tr>
<td>19-Feb-02</td>
<td>High system demand</td>
<td>40</td>
<td>2.7</td>
</tr>
<tr>
<td>15-Nov-01</td>
<td>High system demand</td>
<td>43</td>
<td>3.2</td>
</tr>
<tr>
<td>28-Jun-01</td>
<td>Flushing</td>
<td>65</td>
<td>2.7</td>
</tr>
<tr>
<td>1-Mar-01</td>
<td>Cause unknown, not flow related</td>
<td>&gt;16</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 4-30: Histogram of the number of days between discoloured water events attributed to being caused in the water distribution system.
4.16 Discussion

4.16.1 COLT and customer complaints

Over the time period of the COLT, more discoloured water events were measured in the Wantirna WQZ transfer main using COLT (33 events) than were reported by customers (22 events). However, both measuring techniques identified some discoloured water events that the other measuring technique did not. It is important to note that 13 of these customer complaints appear to be due to localised discoloured water, as COLT of the transfer main did not indicate a discoloured water event in the preceding three days. This result suggests that customers are likely to have seen some events created in the reticulation system that did not occur in the transfer main. Such a conclusion indicates the potential limitation of the selection of the locations of the COLT sites. As it is not cost effective to install on-line monitoring on every pipe, optimal selection of monitoring site locations to identify discoloured water events clearly requires further investigation.

In contrast in Section 4.11 it is shown that, of the 33 discoloured water events that were recorded by COLT in the Wantirna WQZ transfer main, only 5 were reported by customers. This difference in results between the two measuring techniques may be because customers: (1) do not report all discoloured water events they observe; (2) have not received the discoloured water because the customer was not using water at the time of the event; or (3) did not receive discoloured water because the event dispersed during transport from the COLT monitoring site.

It is likely that the majority of the discoloured water events created in the transfer main did indeed reach customer areas. This likelihood exists because temporal patterns of turbidity from COLT in the transfer main of the Wantirna WQZ shown in Section 4.11 indicate that discoloured water can be transported for hours without significant dissipation other than a decrease in the peak level of turbidity and an expansion of the temporal distribution of the turbidity event. This transportation over a long time frame was also observed by Grainger et al. (2002) who found that, under laboratory conditions, the peak of discoloured water events were maintained over hours in a 100
mm diameter test rig under steady state flow conditions. However, to be certain of the transport of particles from the main transfer main to customer areas in the reticulation system in real water distribution systems, additional in situ monitoring of smaller sized reticulation mains, or laboratory experiments to determine re-deposit rates under the variable hydraulic conditions and pipe sizes experienced in a true reticulation system is recommended.

The suggestion that customers may not be complaining when they have observed discoloured water or because they did not see the event when it occurred, is consistent with the observations of other studies discussed in the literature review. These studies note that the response of customers is a complex issue, related to many factors besides the actual occurrence of discoloured water. Assuming at least 1 customer observed each of the 33 discoloured water events recorded by COLT sites, 5 reported complaints would result in a 15 % conversion rate of observed events over the time period monitored. This proportion of reported to actual events is consistent with previous studies discussed in the literature review that indicated between 7 and 30 % of customers will complain about the discoloured water events they observe.

COLT however, was better than customer complaints at identifying the operational procedures causing discoloured water events. Table 4-6 shows that 42 out of 48 discoloured water events identified using COLT could be linked to a cause. In contrast Section 2.6.2 shows that only 22 % of DWCCs in the Wantirna WQZ could be attributed to a cause.

It is therefore concluded, not unexpectedly, that COLT of turbidity is more accurate than customer complaints in identifying when and why discoloured water events have occurred in the main being monitored. However, even with their limitations, customer complaints have their place in discoloured water event management. Customer complaints have a more economical spatial coverage of a water distribution system than COLT. However, in order for customer complaints to be correctly and effectively utilised in discoloured water event management, the rate of conversion from discoloured water events to reported complaints needs to be understood. Although it is known from
previous studies that the complaint conversion rate is variable with location, no studies could be found that looked at the variation at a location over time. As discoloured water events and complaints occur so infrequently it was not considered appropriate to conduct this investigation with the data from this study. It is recommended that further investigation be conducted to determine the temporal consistency of the complaint conversion rate and that this is done using a comparison between discoloured water events identified using COLT and customer complaints.

4.16.2 COLT and grab samples

This study found that COLT is more effective than grab sampling methods in identifying discoloured water events. The effectiveness of COLT over grab sampling is demonstrated by a comparison of Chapter 3 and Chapter 4 results. Only one discoloured water event was detected in a three year period using a routine sampling recommended by the Australian Drinking Water Guidelines (1996) for water quality monitoring. In contrast 33 discoloured water events were identified by 6 COLT locations over a 16 month period.

The reason that COLT is more able to identify discoloured water events than grab sampling is evident from the diurnal profiles of discoloured water events taken by COLT. These diurnal profiles identify that most discoloured water events extend over only a few hours. Therefore turbidity COLT time series data obtained from a sampling rate of 1 per 10 minutes allowed underlying turbidity readings of approximately 1.4 NTU to be distinguished from atypical turbidity readings that constituted discoloured water events. Conversely grab sampling at 1 tap site per month in a water quality zone has a very high chance of not sampling a discoloured water event. Increasing grab sampling frequencies to increase the chance of capturing a discoloured water event is likely to be economically and practically infeasible. COLT allows the duration and magnitude of the sporadic and transient discoloured water events to be determined, while being economically and logistically feasible.

As such the adoption of any alternative grab sample programs for the identification of discoloured water events should be carefully investigated based on the increased
understanding of discoloured water formation and transport gained from COLT in this study before implementation. For example, the program of random sampling in time and location proposed by Liebeschuetz and Hulsmann (1990) would appear inappropriate for the investigation and management of discoloured water events. The inappropriateness of the Liebeschuetz and Hulsmann (1990) approach arises from COLT of turbidity showing that their base assumption that the short-term variability in turbidity readings is less than the variability in location is false, at least for the unfiltered and lined water distribution system investigated in this study. This may also be true for other supply systems. It is therefore recommended that grab sampling not be used for the investigation and management of discoloured water events.

4.16.3 Underlying conditions for the formation of discoloured water

Understanding the underlying conditions of a system is important to identification of atypical discoloured water events and also gives insight into the antecedent conditions needed to create discoloured water events. Underlying conditions were characterised two ways: (1) background datums of each two week block of turbidity data associated with cleaning cycles to remove the ‘day to day’ underlying turbidity levels in the water system and errors associated with the fouling of the turbidity meter; and (2) average daily profiles and average weekly profiles of water velocity and spike turbidity to characterise typical conditions.

The proportion of the background datum associated with underlying turbidity levels in the transfer main appear to be reliably stable, as shown by the mean and standard deviations of background datum levels in Table 4-1. However, despite the regular cleaning of on-line turbidimeters, there was a small but regular increase in turbidity due to fouling of the turbidimeters. This prevented COLT measurements of turbidity from being used directly.

The fouling of the COLT turbidity meters occurred from algae growth and particle accumulation within the turbidimeter. This fouling created a slight, but nonetheless greater, range in background readings of turbidity at MS(6) than any other monitoring site. The increased range of, and therefore variability in, background readings at MS(6)
may be associated with a reduction in chlorine residual as this site is the greatest distance from the Wantirna Service Reservoir resulting in an increase growth of algae in this section of the system.

The background datum levels were also higher in spring at all sites. The reason for the minor, but nevertheless consistently higher levels in spring, is unclear without particle analysis. However, in spring, algae growth occurred in the turbidimeters to the point where it could be seen by the naked eye, and algae counts are known to be higher in spring in the source water, Silvan Reservoir. The issue of algae growth and particle accumulation is unique to long-term use of continuous on-line turbidimeters, and therefore had not been a reported problem for the short term use of COLT for discoloured water research reported in other studies. Further investigation of the differences in particle properties in spring and at the extremities of the system would be advantageous but is beyond the scope of this study.

Notwithstanding these difficulties with the turbidity data, the background turbidity datum was removed from the COLT turbidity data to produce the parameter ‘spike turbidity’. Spike turbidity is therefore a measure of the turbidity over and above the underlying turbidity levels in the water system. This process also removed any errors associated with turbidimeter fouling. This approach allowed turbidity associated with unusual events to be easily identified and the turbidity dataset to be used as a continuous stream of data. The development and use of the spike turbidity measure is believed to be a new contribution from this study.

The small standard deviation of the background turbidity datum, together with the consistently low and unvarying nature of spike turbidity in the average daily profiles, illustrate that during typical system hydraulic conditions no indications are given of the potential of a discoloured water event to occur in the transfer main. Spike turbidity in both the average daily profile and the average weekly profile were negligible, indicating that under average conditions turbidity would never reach the point at which a customer could see turbidity with the naked eye. However, as expected, during discoloured water events turbidity escalated.
In addition, during most of the discoloured water events spike turbidity did not occur at MS(1) or MS(2) indicating that material which contributed to the turbidity event did not come directly through the service reservoir form source water and was already present in the transfer main. These observations suggest that material causing discoloured water events were held on the internal pipe wall and subsequently mobilised to form the discoloured water event.

The work of Walski et al. (2001) indicates that the shape of the average daily profile for velocity shown in Figure 4-9 is typical for a water quality zone that is highly residential. The velocity profile indicates a variable seasonal demand. Maximum velocity peaks (as indicators of high shear stress) typically occur on a daily basis in the mornings, on a weekly basis on Saturdays, and on a seasonal basis in summer. Based on the studies considered in the literature review which suggest that discoloured water in an unfiltered water distribution system is caused by the erosion of cohesive layers at the internal main wall during high shear stress events, the timing of these peaks suggest that these periods are at higher risk of experiencing turbidity events. Indeed small increases in turbidity, below the error margin of the turbidity meter, were consistently noted in raw turbidity data at morning peaks in velocity. As the morning peak in water velocity (as an indicator of shear stress) were often close to the magnitude of the evening peak in water velocity, this observation suggests that material being disturbed at the morning peak in velocity in the transfer main was not present to be disturbed at the evening peak in water velocity. It is likely that the longer period of low flows over night allows for a greater accumulation of material than the time between the morning and evening peaks in water velocity.

4.16.4 Causes of discoloured water events

COLT of turbidity in this study confirmed the episodic and transient nature of discoloured water events suggested by studies discussed in the literature review. The COLT of turbidity in this study allowed for the observation of both the episodic nature of discoloured water events, shown by the varying time between discoloured water events in Table 4-7, and the transient nature of the discoloured water events shown by
the transport of these events along the transfer main in the discoloured water event profiles.

By removing underlying turbidity levels from the COLT turbidity data, the peak turbidity reached during a discoloured water event, as well as the time over which the event occurred were easily identified. The discoloured water event profiles revealed that discoloured water events typically lasted a few hours at a particular location, with movement of water transporting the event. Consistent with theoretical models of dispersion, the duration of the turbidity event tended to increase and the peak diminish with transport along the transfer main. An example of a transported discoloured water event is shown in Figure 4-20. It should also be noted that the underlying daily hydraulic conditions were variable (as seen by the differences in seasonal average daily profiles and between days in the average weekly profile).

From a correlation between COLT and the operational database, it was found that 85% of discoloured water events were created within the water distribution system itself. As shown in Figure 4-30, 61% of discoloured water events were associated with water velocities in the transfer main being higher than background velocity conditions identified using the average daily profiles. A smaller group was attributed to water hammer (12% of all events). Both the high velocity and water hammer events are likely to result in high shear stress, a condition which supports the conclusions of the literature review, that discoloured water is formed when a critical shear stress is exceeded. The estimation of the hydraulic conditions at which a discoloured water event is created is explored in the following chapter.

No previous studies that established the frequency of operational procedures in causing discoloured water based on an objective measurement of discoloured water were identified. In contrast, in this study, an objective method where discoloured water events identified by COLT of turbidity and flow rate were correlated with system operations for the Wantirna WQZ was used to identify the frequency by which certain operational procedures caused discoloured water. The only studies found with
comparable ranking of problematic operational procedures involved the assigning of risk by a survey of water industry expert opinion (Chambers 2000).

In general terms, risk is defined as the severity of an event multiplied by the likelihood. Risk cannot be calculated for the operational procedure categories defined in this study. Assuming that the occurrence of a discoloured water event implies that the severity of the procedure is high, risk can be defined as the probability that an operational procedure causes discoloured water. Such an analysis would show how problematic that procedure is, reflecting the number of times the procedure is carried out and the number of times it causes a problem. However, for many of the operational procedure categories in this study, the total number of operational procedures that have occurred in the system cannot be determined, for example, the number of fire sprinkler systems that have been used. As such, the risk of many of the operational procedure categories cannot be determined.

Using the COLT method the operational procedures that had the highest frequency of causing discoloured water in the transfer main of the Wantirna WQZ over the time period monitored were mains cleaning using flushing and mains repairs (which potentially includes an aspect of water hammer due to valve closure). In fact, it was determined that the largest proportion (39 %) of discoloured water events with an identifiable cause was created by water company operations.

A natural extension of determining which operational procedures cause discoloured water events in the transfer main in the Wantirna WQZ over the period monitored is to extrapolate that these procedures also cause discoloured water events in other parts of the system. This hypothesis would be supported by the same operational procedures identified as causing discoloured water events in the transfer main using COLT, also being identified as causing discoloured water customer complaints in the reticulation system. However, measurements taken by COLT over a different period or in a different water quality zone may indicate a different ranking in the frequency of operational procedures. Therefore, direct extrapolation of the frequency of operational procedures that cause discoloured water events to other areas should be done with extreme caution.
The caution needed when extrapolating the frequency of operational procedures that cause discoloured water events to other areas is evident when results are compared with the conclusions of problematic procedures indicated by other studies. Results from this investigation are generally consistent with the risk categories from the survey reported by Chambers (2000). However, some differences nevertheless were evident. For example, hydrant operations were assigned to being a medium risk by Chambers, but occurred at a high frequency for the Wantirna WQZ (flushing uses hydrants, 5/33 occurrences, plus hydrants used for fire fighting or illegally, 2/33 occurrences). Assigning hydrant operations as high risk, however, is supported by van der Hoven and Vreeburg (1992).

In addition, some of the items listed by Chambers (2000) as causing discoloured water events, for example, step tests for leakage control, pump switching, poor service reservoir maintenance, did not occur in the Wantirna WQZ. These differences can be attributed to the differences in system management and design. For example procedures for detecting leakage were not conducted, and there are no pumps, in the Wantirna WQZ.

Notwithstanding these limitations, there is the potential for the number of discoloured water events that occur in the water distribution system to be lowered by altering the way in which procedures that cause a higher frequency of discoloured water events are conducted. For example, the following procedures could be investigated:

1. Flushing of mains has been noted in this and other studies as an important contributor to the formation of discoloured water. For example, work reported by Kiwa Water Research (Slaats 2002) highlights the problems with flushing isolated areas without ensuring that upstream water mains are free from material or that this material will not be suspended at the shear stress generated. This approach is typically referred to as insuring a “clean water front”. This consideration is particularly important within a transfer main, as flushing of the transfer main could potentially lead to discoloured water reaching a large number of customers. It is policy at SE Water to use the clean water front
technique for routine block mains cleaning, as described in Chapter 2. However, it has been SE Water procedure that isolated mains be flushed to remedy water quality issues without ensuring that a clean water front is used. It is therefore unlikely that all mains flushing recorded in the operations log were conducted using an adequate clean water front. Therefore one potential option would be to review the SE Water isolated flushing procedures to determine if best practice for the minimisation of discoloured water events is being used. (This issue is discussed further in the following chapters); and

2. Valve closure was considered to be a highest risk operational procedure in this study. Determining if best practice in closing valves is being used by onsite maintenance crews may result in a reduction of discoloured water events that occur as a result of water hammer.

Improved understanding of the way in which operational procedures could be conducted to reduce the incidences (and perhaps severity) of discoloured water events, and the effect of such procedures on upstream mains, would be aided by knowing the hydrodynamic limits of discoloured water formation. For example, the minimum critical shear stress at which discoloured water begins to be formed. An investigation of critical shear stress limits is conducted in the following chapter.

Of those events that were not caused by water company operations, many were due to events outside the control of the retail water company, namely: high customer water demand (9 %), discoloured water events entering the water distribution system from upstream of the service reservoir which is controlled by the wholesaler water company (15 %), fire fighting (9 %), bursts (9 %) and unknown causes (18 %).

In this investigation, 15 % of discoloured water events were caused by discoloured water entering the distribution system as distinct events through the Wantirna Service Reservoir. These allochthonous incidents were mostly from works on transport mains between the dosing plant and the Wantirna Service Reservoir, and as such would not be unique to unfiltered supplies and emphasises the role of transfer mains leading to water quality zones in discoloured water formation. These figures indicate that an additional
15% of discoloured water events recorded in the transfer main could be prevented by improved management upstream of the service reservoir to prevent distinct discoloured water events entering the water quality zone. Such enhanced management could take the form of improved procedures conducted on the supply mains, or alarming the Wantirna Service Reservoir intake turbidimeter so that inlet water is shut off if a major event, likely to cause discoloured water, occurs upstream of the service reservoir.

Such a system would require the retail water company such as SE Water to have real-time access to key sites monitoring water entering the distribution system. At the present time these sites are only accessed by the wholesaler, Melbourne Water Corporation. Alternatively, the organisation owning the sites (which in this case was the water wholesaler, Melbourne Water Corporation) could alert the retailer of the event. Neither of these alternatives currently occurs. It is interesting to note that the graphs of the individual discoloured water events entering the Wantirna WQZ through the service reservoir show that most events dissipated rapidly with transport down the transfer main. This observation suggests that supply of discoloured water from upstream of the service reservoir is not a high risk to the whole of this water quality zone. However, the events do provide a source of particles into the water distribution system.

The 18% of discoloured water events that were created within the water distribution system and had no identifiable cause could have been caused by an unknown source of water hammer, vibration of the main by heavy machinery, or a yet unidentified cause.

4.16.5 Limitations

In this investigation, COLT of turbidity was sampled from the centre of mains of 450 mm or greater diameter. Grayman et al. (2000) and Schaap (2002) report that stratification of turbidity can occur in large pipes (> 400 mm) in the United Kingdom and in the Netherlands under some situations. In these cases, the top of the pipe has lower turbidity than the bottom of the pipe. However, van der Walt et al. (1999) and Grainger (2003) found that sedimentation velocities using particles from the SE Water system were very slow, even under laminar conditions. Hence, once particles are in suspension they take a few hours to stratify. Furthermore, Walski et al. (2001) indicate
that an assumption of homogeneous mixing (no stratification) is valid during turbulent flow conditions.

The flow in the majority of the transfer main of the Wantirna WQZ remains at levels that cause turbulent flow, even overnight. Therefore, it is likely that homogeneous mixing occurs in the transfer main in the Wantirna WQZ during discoloured water events and stratification does not need to be taken into account. Further empirical investigation of the effect of stratification on large mains using particles that occur in the unfiltered SE Water system is likely to validate this assumption.

The site selection for COLT used in this study did not allow for the measurement of discoloured water that was created in the smaller pipes supplied from the transfer main. The monitoring program reported in this study therefore gave information on discolouration creation and transport in the large cast iron cement lined transfer main. The significance of this limitation is evident in the 50% of DWCCs in the Wantirna WQZ that occurred when no discoloured water event was measured by the COLT monitoring sites on the transfer main. Further research is required to verify that the findings are also applicable to smaller pipes and other material types. This gap could be addressed by an additional monitoring program that includes use of COLT on a range of pipe sizes and materials. A monitoring program based on findings on how discoloured water is actually formed is discussed later.

The issue of maintenance of COLT sites is important, for the reason that on-line turbidity meters are designed for monitoring water within treatment plants, rather than remote locations. For example, 15 of the 48 major turbidity events recorded by COLT were attributed to ant infestation, sample cell fouling, disturbance of equipment by visitors to the site, or blown globes, and not due to turbidity in the transfer main. In this study the major turbidity events due to these causes were identified by the use of a visitation log and comparison to operational and customer complaint information. The monitoring site visitation log proved particularly useful in identifying major turbidity events that had occurred due to errors in the turbidimeter, rather than turbidity in the transfer main. These events could have contaminated the results if their invalidity had
not been identified. It is recommended that in future studies, field turbidimeters be checked regularly and a site visitation log kept.

When using existing technology, it is recommended that an initial program of weekly inspections be undertaken to determine the maintenance intervals required. For the investigation reported in this study, maintenance was conducted every two weeks, which is in agreement with Burlingame et al. (1998). Given the level of fouling of the turbidimeter observed in this investigation it would have been advantageous to have conducted maintenance weekly. However, maintenance this frequently would not have been economically feasible.

The development of more reliable turbidity meters for remote use, even if accuracy below 1 NTU were sacrificed, would be of benefit to measuring discolouration in unfiltered water distribution systems for the purpose of discoloured water research. Such turbidity meters would need to be insensitive to air temperature fluctuations that typically occur in the location in which they are being used (0 to 45 degrees Celsius in Melbourne, Australia) and self-cleaning. A notification method for readings consistently below or above typical background readings would aid in the rapid identification of equipment malfunctions such as blown globes or ant infestation.

The verification of the location of monitoring sites is also important. In this investigation, it was discovered from the results of a discoloured water event that MS(1) was not installed on the correct main. Because discoloured water events occurred rarely at this site, inaccurate data was produced for the majority of the monitoring period before the problem was identified. At the time of discovery the monitoring site was moved to the correct main and all invalid data excluded from analysis. As a result, the ability to confirm when a discoloured water event came through the Wantirna Service Reservoir was compromised for the majority of the monitoring period. An alternative method of verifying monitoring site locations would have allowed the identification of the faulty location. It is therefore recommended that future research to develop a method for verifying COLT site location be undertaken.
Despite these limitations in the use of COLT to measure discoloured water events, the turbidity and flow rates obtained from this monitoring system were used successfully to identify both the characteristics of discoloured water events and the operational procedures causing discoloured water. It is therefore concluded that COLT measures discoloured water events more accurately than customer complaints or grab samples and thereby leads to a more complete understanding of the causes of discoloured water. The following chapter uses COLT of flow rate and turbidity to estimate the hydraulic point at which discoloured water is formed, namely, the critical shear stress of entrainment.
CHAPTER 5: ANALYSIS OF HYDRAULIC CONDITIONS
TRIGGERING DISCOLOURED WATER

5.1 Introduction

The extent to which the conceptual model of entrainment of cohesive layers formed on the inner circumference of pipes describes discoloured water formation within the unfiltered Wantirna WQZ is investigated in this chapter. The conceptualised process involves particles entering the distribution system at low concentrations, collecting at the internal pipe wall via van der Waals forces, and forming cohesive layers. These cohesive layers are then eroded when a critical shear stress of entrainment is reached, creating discoloured water. This conceptual model is shown in Figure 5-1 [and described in Section 1.3.2].

Figure 5-1: Conceptual model of particle movement forming discoloured water in an unfiltered water distribution system.
Although the exact mechanism of how particles accumulate on the internal pipe walls in an unfiltered water distribution system is not explicitly investigated in this work, it is assumed to occur during turbulent flow due to van der Waals forces as described by Sethi (1996). The basis of the assumption that this process, and results of this study that support it, as it applies to the formation of discoloured water in the Wantirna WQZ is discussed further later in Section 5.9.5.

COLT values of flow rate (used to calculate shear stress) and turbidity (as an indicator of particles present in the bulk water flow creating discoloured water) described in the previous chapter, are used for this portion of the study. Using these values the hydraulic conditions within the main that form discoloured water are investigated to determine the potential for discoloured water events to be predicted at any point in a water quality zone.

COLT and the customer complaint analysis described in previous chapters indicate that the majority of discoloured water events are triggered by high flow rates or high water velocity events (as an indicator of high shear stress). Studies discussed in Section 1.3.2 also suggest that erosion of material in the cohesive layer is likely to begin when the applied shear stress ($\tau_0$) at the cohesive layer and water interface exceeds a critical shear stress ($\tau_c$), as described by Equation 1-1, duplicated as Equation 5-1 below.

$$\tau_{xs} = \tau_0 - \tau_c$$

\begin{align*}
\tau_{xs} > 0, & \text{ erosion will occur.} \\
\tau_{xs} \leq 0, & \text{ no erosion will occur.}
\end{align*}

It is therefore believed that the cohesive layers in the Wantirna WQZ will follow the standard hypothesis of cohesive layers discussed in Section 1.3.2 wherein particles held in the cohesive layer will only erode when the excess shear stress ($\tau_{xs}$) is greater than zero and material has accumulated at the pipe wall.

The discoloured water events described in the previous chapter suggest that the critical shear stress varies both spatially and temporally within the pipe network, as the relationship between maximum turbidities generated and the associated water velocity
was variable. For example, in Category 3, Section 4.12.3, the water velocity at the point when spike turbidity began to be generated was greater at MS(5) than at MS(6). The variability of critical shear stress with location and time is explored further in this chapter.

Boxall et al. (2001) hypothesise that this variability is due to past hydraulic conditioning of the cohesive layer which in turn affects the critical shear stress. To illustrate, Figure 5-2(a) shows a cohesive layer at a pipe wall with an initial layer strength equal to the initial critical shear stress $\tau_{C1}$. The cohesive layer is eroded by an applied shear stress equal to $\tau_0$ which is greater than the initial critical shear stress $\tau_{C1}$ by an amount equal to the excess shear stress of $\tau_{xs}$. This erosion process continues until equilibrium has occurred between the applied shear stress and the strength of the cohesive layer, resulting in the critical shear stress increasing from $\tau_{C1}$ to $\tau_{C2}$, as shown in Figure 5-2(b). Therefore, predicting when a cohesive layer begins to be entrained creating a discoloured water event, lies in the ability to estimate the critical shear stress for a particular section of pipe within the water distribution system at any given time.

Two aspects of the erosion process are investigated in this chapter, namely:-

1. The shear stress conditions which result in discoloured water events;
   Specifically:-
a) The critical shear stress is variable in location and time and can be estimated by the peak shear stress experienced over a preceding period of time; and
b) The predicted critical shear stress can be used to determine the likelihood of a discoloured water event from an operational procedure; and

2. Confirmation of whether exceeding the critical shear stress is the main cause of discoloured water.

5.2 Data set used

The COLT dataset described in Chapter 4 is used in this chapter. It should be noted that this dataset does not include readings associated with white water events, turbidity meter interference and meter errors. All turbidity readings in the dataset are reported as spike turbidity and all hydraulic data in the dataset are reported as water velocity. As the portion of this study investigates discoloured water formation within the water distribution system, and not directly from source water, only monitoring sites within the water distribution system are used. Specifically, data collected at monitoring site 3 (MS(3)), monitoring site 5 (MS(5)), and monitoring site 6 (MS(6)) within Wantirna WQZ are used. Data from monitoring site 4 (MS(4)) is not included due to difficulties with the turbidity increment at this site [described in Section 4.3].

The following section describes the methods used to analyse the dataset so that the above hypothesis can be tested. In particular, the following analyses are performed: -

1. Steady state shear stress, as applied to the pipe wall, is calculated from water velocity; and
2. Two estimates of the critical shear stress are calculated.

Two methods are used to test the estimates of the critical shear stress: -

1. The ANITU Method which uses selected discoloured water events; and
2. The SNTU Method which uses all COLT data over the period monitored.

The methods used to determine \( \tau_0, \tau_c \) estimates and \( \tau_{xs} \) are as follows.
5.3 Determining shear stress at the cohesive layer and water interface

Shear stress contains two components, a dynamic component caused by the acceleration of the water and a steady state component based on the steady state velocity of the water. Work done by Kiwa Water Research validates the use of a steady state shear stress in the 450 mm diameter transfer main monitored by COLT. Their work suggests that the dynamic component of shear stress is small compared to the steady state component for large mains (van den Boomen and van Mazijk 2002). Therefore all shear stresses calculated in this study are steady state shear stresses determined from the COLT flow rate data and an estimate of the pipe roughness. Steady state shear stress is given by Equation 5-2 (Crowe et al. 2001 and Walski et al. 2001).

\[
\tau_0 = \frac{f}{8} \rho V^2 \tag{5-2}
\]

Where:

\( V \) = average velocity of the water.
\( \tau_0 \) = shear stress at pipe wall.
\( \rho \) = density of water at 15 degrees Celsius, 999 kg.m\(^{-3}\).
\( f \) = Colebrook – White resistance coefficient.

The Colebrook – White resistance coefficient can be estimated from the Swamee and Jain equation (Crowe et al. 2001):

\[
f = \frac{0.25}{(\log_{10}(\frac{k_s}{3.7D} + \frac{5.74}{Re^{0.5}}))^2} \tag{5-3}
\]

Where:

\( k_s \) = equivalent sand-grain roughness = 0.0003 m (cement lined main in good condition Crowe et al. 2001).
\[ D = \text{the internal diameter of the pipe} = 0.47 \text{ m at MS(3) to MS(6)}. \]
\[ Re = \text{Reynolds number} = \frac{V D}{v}. \]
\[ v = \text{kinematic velocity} = 1.14 \times 10^{-6} \text{ m}^2 \text{s}^{-1} \text{ (Crowe et al. 2001)}. \]

### 5.4 Determining average excess shear stress between two monitoring sites

The excess shear stress at each monitoring site is calculated by Equation 5-1, using the estimate of \( \tau_c \) discussed in Section 5.5. \( \tau_{xs}(A-B)_i \) is then defined as the average excess shear stress between MS(A) and MS(B) at time \( i \) and calculated using Equation 5-4.

\[
\tau_{xs}(A-B)_i = \frac{\tau_{xs}(A)_i + \tau_{xs}(B)_i}{2} \quad (5-4)
\]

### 5.5 Estimates of the critical shear stress to be tested

The critical shear stress of entrainment (\( \tau_c \)) is defined in Section 1.3.2 as the shear stress required to begin to significantly entrain material from the cohesive layer. Hence \( \tau_c \) approximates the shear strength of the cohesive layer at the water and cohesive layer interface.

As illustrated in Figure 5-2, \( \tau_c \) is likely to vary both spatially and temporally within the water distribution system due to the cohesive layers at the pipe wall eroding until they are in equilibrium with the applied shear stresses. Similarly, the applied shear stress is variable with time and location. This process results in \( \tau_c \) being some function of: (1) the maximum applied shear stresses (\( \tau_{0,\text{max}} \)) that occurred at the time of the previous turbidity event (Boxall et al. 2001); (2) the regeneration rate of material collecting into the cohesive layer (\( R_r \)) which may reduce the critical shear stress (Boxall et al. 2001);

---

\(^{12}\) Based on studies reported in Ackers et al. (2001) it is assumed that the cohesive layer in the transfer main is only a few microns thick. This assumption allows the location of the cohesive layer and water interface to be approximated by the location of the pipe wall, as the thickness of the cohesive layer is negligible compared to the pipe diameter.
and (3) the consolidation rate which strengthens the layer ($R_c$) (Grainger *et al.* 2001), as shown in Equation 5-5.

$$\tau_c = \Phi(\tau_{0,\text{max}}, R_r, R_c)$$

(5-5)

The average daily profiles of velocity for each season reported in Chapter 4 suggest that maximum daily applied shear varies with season, such that:

$$\tau_{0,\text{max, summer}} > \tau_{0,\text{max, autumn}} > \tau_{0,\text{max, spring / winter}}$$

Where:

$$\tau_{0,\text{max, y}} = \text{maximum daily applied shear stress of the average conditions in season y.}$$

The pipe sizes between MS(3), MS(5) and MS(6) are equal, and the average daily profiles of velocity reported in Chapter 4 suggest that maximum daily applied shear varies at each location, such that;

$$\tau_{0,\text{max}(3)} > \tau_{0,\text{max}(5)} > \tau_{0,\text{max}(6)}$$

Where:

$$\tau_{0,\text{max}(x)} = \text{the maximum daily applied shear stress at monitoring site x.}$$

As illustrated by Equation 5-5, the magnitude of $\tau_c$ is not solely due to the applied shear stress, but also $R_r$ and $R_c$. $R_r$ reduces the shear strength of the layer and $R_c$ increases the strength of the layer. Particle sampling in the studies described in the literature review found that particles in Melbourne, Australia, are of similar material throughout the system and therefore have similar consolidation rates. The uniform nature of the material in the Wantirna WQZ provides the base for assuming that $R_r$ and $R_c$ are constant for a specific location within the water distribution system. If this is the case, $\tau_{0,\text{max}}$ over a specific period of time provides a close estimate of $\tau_c$. Hence, because $\tau_{0,\text{max}}$ varies with season and location, $\tau_c$ will vary with time and location, such that:

$$\tau_{c, \text{summer}} > \tau_{c, \text{autumn}} > \tau_{c, \text{spring / winter}}$$

$$\tau_{c(3)} > \tau_{c(5)} > \tau_{c(6)}$$
To test this hypothesis, two empirically derived estimates of $\tau_c$ from $\tau_{0,max}$ over two time periods were evaluated, namely, one day and one week.

### 5.5.1 The Daily Peak Estimate

If Equation 5-6 is true and $\tau_c$ is equal to the peak shear stress in the preceding 24 hours (Daily Peak Estimate) then two scenarios are occurring:-

1. No significant amount of material collects in a 24 hour period (i.e. $R_r$ is small); or
2. If significant material is collecting ($R_r$ is significant), then an increase in the strength of the layer due to consolidation is occurring ($R_c$ is significant) within a 24 hour period.

$$\tau_c = \tau_{0,\text{max}(-1d)}$$ (5-6)

### 5.5.2 The Weekly Peak Estimate

If Equation 5-7 is true, $\tau_c$ is equal to the peak shear stress in the preceding 7 days (Weekly Peak Estimate) rather than the Daily Peak Estimate. The adoption of the Weekly Peak Estimate would indicate the strength decrease of the surface of the cohesive layer due new material collecting on the layer ($R_r$) is greater over one day than the strength increase due to consolidation ($R_c$) over one day. Also, the adoption of the Weekly Peak Estimate would indicate that over a period of 7 days the strength increase due to consolidation becomes greater than the loss of strength due to new material collecting.

$$\tau_c = \tau_{0,\text{max}(-7d)}$$ (5-7)
5.6 Determining the best estimate of the critical shear stress

5.6.1 ANTU Method (method using selected discoloured water events)

Figure 5-3 illustrates SNTU(B)\(_i\), defined as the spike turbidity measured at MS(B) at a certain time \(i\), is dependent on the net gain or net loss of turbidity in the bulk water phase during travel from an upstream location. SNTU(B)\(_i\) is therefore due to:

- SNTU(A)\(_y\), defined as the spike turbidity already in the bulk water phase (NTU\(_{in}\)), as measured at the upstream monitoring site MS(A) at time \(y\);
- NTU\(_\text{gain}\), defined as the addition of turbidity into the bulk water phase between MS(A) and MS(B), for example, from the erosion of the particles from the cohesive layer at the pipe wall; and
- NTU\(_\text{loss}\), defined as the loss of turbidity from the bulk water phase between MS(A) and MS(B), for example, due to recollection of particles back into the cohesive layer during transport over the section of pipe between MS(A) and MS(B).

This mechanism can be described by the following equation:

\[
\text{SNTU(B)}_i = \text{SNTU(A)}_y - (\text{NTU}_\text{loss})_z + (\text{NTU}_\text{gain})_z
\]  \hspace{1cm} (5-8)

Where:

- SNTU(B)\(_i\) = spike turbidity recorded at MS(B) at time \(i\).
- SNTU(A)\(_y\) = spike turbidity recorded at MS(A) at time \(y\).
(NTU \_loss)_z = \text{loss of turbidity during time } z \text{ in the pipe between MS(A) and MS(B)}. \\
(NTU \_gain)_z = \text{gain of turbidity during time } z \text{ in the pipe between MS(A) and MS(B)}. \\
z = \text{time taken for SNTU(A)}_y \text{ to be transported along the length of main to MS(B), where } i = y+z. \\

The net gain of turbidity in the bulk water phase between MS(A) and MS(B) as measured at MS(B), is defined as the Autochthonous Turbidity (ANTU). The process that leads to autochthonous turbidity is the collection of particles into cohesive layers under antecedent conditions and subsequent erosion of particles from these layers back into the bulk flow. A positive ANTU indicates turbidity has been generated between monitoring sites. Hence:

\[
\text{ANTU(A-B)}_i = (\text{NTU \_gain}_z - \text{NTU \_loss}_z)
\]

Where:

\text{ANTU(A-B)}_i = \text{the autochthonous turbidity generated between MS(A) and MS(B) as measured at MS(B) at time } i.

To determine \text{ANTU(A-B)}_i, the time taken for the turbidity associated with a reading of SNTU(A)_y to be transported to MS(B), z, under ideal conditions (assuming no loss or gain of turbidity) must be taken into account. In this study the spike turbidity transposed from MS(A) to MS(B) is defined as SNTU(TA)_i. Therefore, as illustrated in Figure 5-4 and defined in Equation 5-11, \text{ANTU(A-B)}_i is the difference in magnitude between SNTU(B)_i and SNTU(TA)_i.

Spike turbidity at MS(A) at time y, defined as SNTU(A)y, is transported along the length of main to MS(B), taking a period of time z so that it arrives at MS(B) at y+z=i as shown in Equation 5-10.
Figure 5-4: Diurnal pattern of SNTU(A) and SNTU(B) measured at MS(A) and MS(B). Modelled transported turbidity spike SNTU(TA) and calculated ANTU(A-B) is shown.

\[ SNTU(TA)_i = SNTU(A)_{y+z} \]  

(5-10)

Where:

- \( SNTU(TA)_i \) = proportion of spike turbidity at MS(B) at time \( i \) predicted to be from spike turbidity measured at MS(A).
- \( SNTU(A)_{y+z} \) = measured spike turbidity at MS(A) at time \( y \) plus the travel time between MS(A) and MS(B), \( z \), where \( y+z = i \).

Thus ANTU(A-B)_i is given by the following equation:

\[ ANTU(A-B)_i = SNTU(B)_i - SNTU(TA)_i \]  

(5-11)
To calculate SNTU(TA)$_i$, the travel time $z$ is calculated using the average velocity of the water (adventive transport). Adventive transport is based on the assumption that longitudinal dispersion of the discoloured water event in the main is negligible. This assumption is applicable if the turbidity in the bulk flow is completely mixed such as during turbulent flow (Walski et al. 2001). Turbulent flow occurs in the Wantirna WQZ transfer main in almost all cases, even during low flows at night (see Section 4.11.4). Not accounting for dispersion is therefore appropriate given that it is the difference between the two measured spike turbidities that is of interest, rather than the exact loss or gain of material.

The average velocity in the transfer main being monitored in the Wantirna WQZ is longitudinally and temporally variable. Longitudinal variability arises from branch mains (off-takes) along the length of the transfer main shown in Figure 5-5 which results in less flow in the same sized pipe with distance from the Wantirna Service Reservoir.

Temporal variability in average velocity arises from the daily pattern of water demand, shown by the velocity profiles recorded at each monitoring site in Figure 4-9. The presence of these two factors means that calculating $z$ between MS(A) and MS(B) is complex. SNTU(TA)$_i$ is therefore determined using EPANET as explained in the following section.

**Determining SNTU(TA) using EPANET**

The free-ware hydraulic computer model EPANET 2.0 is used to determine SNTU(TA) by modelling the propagation of SNTU(A) to MS(B) as a non-reactive chemical and with the travel time being calculated on the basis of the quasi-steady state velocity as it varies with time and location along the pipe length.

Using EPANET 2.0 to determine SNTU(TA) requires three steps:

1. Building a skeletonised hydraulic model of the monitored pipe network;
2. Calibrating this hydraulic model for each event; and
3. Modelling the propagation of the turbidity trace for each event at each of the downstream monitoring sites.
Figure 5-5: EPANET skeletonised network of the Wantirna WQZ showing internal pipe diameters, off-take alphabetical label and monitoring sites (● = node; -- = pipe; ○ = monitoring site).
For this study, ANTU is calculated for 15 discoloured water events that were attributed by the analysis in Chapter 4 to atypical flow conditions in the Wantirna WQZ. In each case ANTU(A-B) between firstly MS(3) and MS(5), and secondly MS(5) and MS(6), are determined. As noted previously, MS(4) is not used due to difficulties with the turbidity increment at this site as described in Section 4.3.

From Equation 5-11 the autochthonous turbidity between MS(3) (upstream site) and MS(5) (downstream site) at time i, $\text{ANTU}(3-5)_i$, is determined by:

$$\text{ANTU}(3-5)_i = \text{SNTU}(5)_i - \text{SNTU(T3)}_i$$  \hspace{1cm} (5-12)

Where:

- $\text{ANTU}(3-5)_i$ = autochthonous turbidity generated between MS(3) and MS(5) at time i.
- $\text{SNTU}(5)_i$ = spike turbidity at MS(5) at time i.
- $\text{SNTU(T3)}_i$ = predicted spike turbidity from MS(3) as it arrives at MS(5) at time i.

Similarly, from Equation 5-11, $\text{ANTU}(5-6)_i$ is determined by:

$$\text{ANTU}(5-6)_i = \text{SNTU(6)}_i - \text{SNTU(T5)}_i$$  \hspace{1cm} (5-13)

Therefore, for each event there are two SNTU(TA)’s to be calculated, namely, SNTU(T3) and SNTU(T5).

**Building the skeletonised model**

Node information (identification numbers, elevation, and x-y coordinates) and pipe information (identification numbers, length, diameter, and friction coefficients) of the Wantirna WQZ were exported from the SynerGEE Model described in Section 4.8.3 and configured to EPANET format.
The service tanks supplying the Wantirna WQZ are modelled as a reservoir with a constant head of 135 metres. In reality, the Wantirna Service Reservoir has a varying head. The affect of this assumption is minimal as the predicted velocities from the EPANET model and the measured velocity from COLT at MS(3) and MS(5) result in a Mean Error Squared value, as defined in Equation 5-14, of less than one.

As noted earlier, in determining SNTU(TA), the transport of SNTU(A) to MS(B) is modelled as a non-reactive chemical trace with the travel time being dependent on the quasi-steady state velocity variation along the pipe length. To determine the propagation of a trace of the turbidity event between two monitoring sites, only the changes in velocity along the length of the pipe between the two monitoring sites needs to be modelled. This enables the skeletonised model of the Wantirna WQZ containing the transfer main and immediate off-takes, shown in Figure 5-5, to be used.

As described in Section 4.8.3, the full sized SynerGEE Model requires 9 demand patterns to simulate typical demand, and consultation with 6 industry water users as the extremities of the system are modelled. However, the effect of the industry users is minimal in relation to the large number of residential water customers at the transfer main level. As a result the demand patterns merge and become a generalised daily demand pattern for typical (non-event) demand. This situation allows the skeletonised EPANET model to apply only one dimensionless base demand profile at all off-takes from the transfer main (labelled A to V on Figure 5-5). The need to develop only one dimensionless base demand profile to describe non-event demand for each discoloured water event modelled enables faster development time. Skeletonisation also removes the expense in determining what, if any, commercial/industrial water use was occurring in the system on the day and time of the discoloured water event. [The theory of skeletonisation of water systems can be found in Walski et al. (2001).]

It should be noted that although, in the EPANET model, the base demand profile is modelled as the same dimensionless pattern at each off-take, the relative quantity of demand is varied between off-takes using a base demand factor.
In order to calculate the base demand factors at each off-take in the EPANET model, a base demand profile is developed from the SynerGEE Model flow rate at the node representing MS(3) over a 24 hour period. MS(3) data is used, as this site is in the top section of the transfer main and thus represents the most generalised demand pattern for the transfer main. To calculate the base demand profile, the flow rate for each one hour time increment is divided by the average flow rate over the 24 hour period. The EPANET model base demand factors are then determined for each off-take by minimising the mean error squared (MES) between the flow rate at each off-take node predicted by the SynerGEE Model and the flow rate predicted by the skeletonised EPANET Model as shown in Equation 5-14. A MES result of less than 1 is considered adequate.

\[
\text{MES} = \left( \frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \right)
\]

Where:
- \( n \) = count of time steps;
- \( y_i \) = flow rate predicted by EPANET model at time step i; and
- \( \hat{y}_i \) = flow rate predicted by SynerGEE model at time step i.

One set of base demand factors is used. A global demand factor that varies with each event that scales all the base demand factors uniformly is used to account for seasonal variation. Comparison of results using this approach with on-line flow data recorded at the monitoring sites during events validated this assumption.

**Calibrating the hydraulic model for each event**

Two demand patterns are needed to enable the EPANET model to predict the hydraulic conditions associated with a particular discoloured water event. One demand pattern models the “day to day” typical customer demand (base demand profile) and the other models the atypical demand associated with the event (event demand profile). The hydraulic model that just uses the base demand profile is called the “base model”. The hydraulic model that uses both the base demand profile and the event demand profile is called the “event model”.

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The base demand profile is derived from a dimensionless pattern based on the average daily profile of velocity at MS(3) for the season in which the event occurred. The base demand profile is allocated to all off-take nodes and apportioned according to the appropriate off-take demand factor. The model is then calibrated to the base demand component of the measured velocity recorded at each monitoring site using a global demand multiplier. This hydraulic model is the base model.

An event demand profile is allocated to each appropriate off-take to simulate the particular event. The off-take to which the event demand profile is allocated is determined from the operations information described in Section 4.8. For example, a hydrant opening reported to have occurred in the reticulation supplied by off-take V would be modelled by applying an event demand profile at off-take V. The event demand profile is derived from the difference between the measured velocity at the COLT monitoring site upstream of the event location and the predicted velocity at the same monitoring site using the base model. The event demand factor is then used to apportion the event demand profile to calibrate the event model to the measured velocity at each monitoring site. This hydraulic model is the event model.

The hydraulic time step in the modelling is set at 10 minutes to match COLT flow collection rates at the monitoring sites for ease of comparison and for demand pattern development.

**Turbidity Modelling**

To determine SNTU(TA) the propagation of a chemical trace, SNTU(A), between MS(A) to MS(B) is calculated using the event model. For example, to determine SNTU(T3) the propagation of a chemical trace SNTU(3) between MS(3) to MS(5) is calculated.

The event model is set up in the following way. To model a non-reactive chemical trace, both bulk flow reactions and pipe flow reactions are set to zero. The node representing MS(A) is set as a ‘setpoint booster source’, which assigns the chemical trace leaving the node to an allocated water quality time pattern irrespective of the flow. This approach is valid as the pattern of SNTU(A) during the event is used as the water quality time
pattern and SNTU(A) already takes into account the velocity pattern. Initial water quality at the upstream node is set to 0 mg.L\(^{-1}\) and the source quality factor is set to one so that the water quality time pattern is not altered.

Water quality in EPANET is recorded in mg.L\(^{-1}\) while turbidity data is recorded in NTUs. As no reactions are being modelled in this process, no conversion from NTU to mg.L\(^{-1}\) is needed. The output water quality time pattern at MS(B) predicted by the EPANET event model is taken as SNTU(TA) and similarly assumed to be in NTU. ANTU(A-B) is then calculated from Equation 5-11.

The ‘water quality’ modelling time step is set to 10 seconds to overcome limitations imposed by the Lagrangian time-based modelling approach in EPANET. The water quality modelling time step must be less than the predicted time taken for a discrete parcel of water to travel along an individual pipe link (Rossman 2000). If the time step is too large, a gain in turbidity is predicted along a length of pipe when no such gain should occur. [See Rossman (2000) for a mathematical discussion of this limitation.]

**Generated and slug autochthonous turbidity**

The literature discussed in Section 1.3.2 suggests that turbidity in the unfiltered SE Water system is generated when particles, which collect into a cohesive layer on the internal circumference of the pipe wall, are eroded. This erosion occurs when the excess shear stress (\(\tau_{xs}\)) is greater than zero. The cohesive layer ceases to be eroded when the layer is exhausted or when \(\tau_{xs}\) is less than zero. It is important to note that it is likely that the hydraulic conditions needed to maintain particles in suspension is less than the hydraulic conditions needed to erode the cohesive layer (Raudkivi 1990).

The modelling of this mechanism may result in ANTU(A-B), being due to the combination of turbidity generated immediately at the time against which it is recorded, and a component of the turbidity originating from closer to MS(A) which has taken time \(z\) to reach MS(B). Therefore turbidity generated immediately near MS(B), and which has a very small or no travel time, is called generated autochthonous turbidity. Turbidity that is generated between MS(A) and MS(B) and is then transported from the point of generation to MS(B), is called slug autochthonous turbidity. While turbidity is being
generated (from the erosion of the cohesive layer at the pipe wall when the applied shear stress exceeds the critical shear stress) these components cannot be separated so that autochthonous turbidity is a function of both these components. When erosion between MS(A) and MS(B) stops (when the critical shear stress is greater than the applied shear stress), turbidity from between MS(A) and MS(B) may still be arriving at MS(B), so that slug autochthonous turbidity may still be recorded. This mechanism is subject to:

$$\text{ANTU}(A-B)_i = \text{both generated and slug autochthonous turbidity} \quad (5-15)$$

only when $$\tau_{xs,i} > 0$$

$$\text{ANTU}(A-B)_i = \text{slug autochthonous turbidity at any value of } \tau_{xs,i}$$

Practically, it can be reasonably assumed that when generated autochthonous turbidity is being added to slug autochthonous turbidity the measured turbidity is increasing with time, such that:

$$\text{ANTU}(A-B)_i = \text{sum of generated and slug autochthonous turbidity} \quad (5-16)$$

when $$d\text{ANTU}(A-B)/dt > 0$$

**Estimating the critical shear stress**

As noted at the beginning of this section, the objective of this analysis is to determine the best estimate of $$\tau_c$$. Both estimates of $$\tau_c$$ described in Section 5-5 are tested in the following manner. A data set that includes only discoloured water events that were previously concluded to be caused by atypical high flow conditions, as shown in Table 4-4, is used. For each estimate of $$\tau_c$$ the relationships between $$\text{ANTU}(A-B)_i$$ [when $$d\text{ANTU}(A-B)/dt > 0$$] and $$\tau_{xs}(A-B)_i$$ are compared to the conditions of Equation 5-15. The best estimate of $$\tau_c$$ is that estimate that results in the greatest number of values of $$\text{ANTU}(A-B)_i$$ being greater than zero occurring when the excess shear stress is also greater than zero.
5.6.2 SNTU Method (method using all valid COLT data)

To determine the best estimate of $\tau_c$ using this method, all validated data from Chapter 4 is used. Values of maximum daily spike turbidity ($\text{SNTU}_{\text{max}}$) and maximum daily excess shear stress ($\tau_{\text{xs,max}}$) are correlated for MS(3), MS(5) and MS(6) using each of the estimates of $\tau_c$ described in Section 5.5. $\tau_{\text{xs,max}}$ is defined as the difference between the maximum daily shear stress, ($\tau_{0,\text{max}}$) and the $\tau_c$ estimate. A result where the majority of discoloured water events occur (defined as when $\text{SNTU}_{\text{max}}$ exceeds the spike turbidity complaint threshold described in Section 4.11.2) when $\tau_{\text{xs,max}}$ is greater than zero would suggest the best estimate of $\tau_c$ is being used.

It must be noted that $\text{SNTU}_{\text{max}}$ is a product of both autochthonous turbidity generated within the water quality zone and allochthonous turbidity that entered the water quality zone through the Wantirna Service Reservoir. Particles from both sources will be carried along the transfer main by the bulk water flow. $\text{SNTU}_{\text{max}}$ may therefore be affected by turbidity events travelling down the system and not necessarily created at the monitoring site being analysed. This limitation means that, strictly speaking, the magnitude of $\text{SNTU}_{\text{max}}$ is not solely dependent on $\tau_{\text{xs,max}}$. An investigation into individual values of $\text{SNTU}_{\text{max}}$ that are over the complaint threshold when $\tau_{\text{xs,max}}$ is below zero are conducted to confirm or deny the validity of the method and the estimate of the $\tau_c$.

5.7 Results from analysis using ANTU method

5.7.1 Discoloured water events used for analysis

Fifteen discoloured water events attributed to atypical high velocity conditions from the analysis described in Chapter 4 were considered for use in this method. However, as shown in Table 5-1, not all these events are suitable for analysis. Events were not included in the analysis when the location of the hydraulic disturbance was not known and therefore the precise off-take on which to model the event could not be determined.
Table 5-1: Suitability of discoloured water events attributed to being caused by atypical high flow conditions to investigate the relationship between excess shear stress and autochthonous turbidity.

<table>
<thead>
<tr>
<th>Event No.</th>
<th>Date</th>
<th>Attributed Cause</th>
<th>Data included in study</th>
<th>Reasons for exclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>MS(3) – MS(5)</td>
<td>MS(5) – MS(6)</td>
</tr>
<tr>
<td>1</td>
<td>24 Apr 01</td>
<td>Burst main</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>28 Jun 01</td>
<td>Flushing</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>4 Jul 01</td>
<td>Cause unknown, flow related</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>18 Jul 01</td>
<td>Flushing</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>20 Jul 01</td>
<td>Cause unknown, flow related</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>22 Jul 01</td>
<td>Hydrant repair</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>7</td>
<td>25 Jul 01</td>
<td>Cause unknown, flow related</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>8</td>
<td>23 Aug 01</td>
<td>Burst hydrant</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>9</td>
<td>2 Oct 01</td>
<td>Authorised hydrant use</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>10</td>
<td>3 Oct 01</td>
<td>Flushing</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>11</td>
<td>15 Nov 01</td>
<td>Normal demand</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>12</td>
<td>21 Dec 01</td>
<td>Flushing</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>13</td>
<td>19 Feb 02</td>
<td>Normal demand</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>14</td>
<td>7 Mar 02</td>
<td>Burst main</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>15</td>
<td>7 Apr 02</td>
<td>Fire sprinkler system malfunction</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Events 6, 9 and 10 produced ANTU between MS(5) and MS(6) but not between MS(3) and MS(5) and were therefore not included in the analysis between MS(3) and MS(5). Events 8 and 11 did not produce ANTU between MS(5) and MS(6) and therefore were not included in the analysis between MS(5) and MS(6). Events 2 and 3 did not have sufficient data to conduct the analysis between MS(3) and MS(5). Events 1 and 12 did not have sufficient data to conduct the analysis between either pair of monitoring sites. Although Event 13 is attributed to being created by steady state shear stress between MS(3) and MS(5), the event was not attributed to steady state shear stress between MS(5) and MS(6) (as shown in Appendix 8). Therefore all these events were excluded from analysis for the particular relevant proportion of the network, i.e. MS(3) through MS(5) or MS(5) through MS(6).
5.7.2 EPANET hydraulic model

The majority of flow patterns at nodes A to V generated by the skeletonised EPANET Model shown in Figure 5-5, using a base demand profile calculated from the Stoner model shown in Figure 5-6 and the base demand factors shown in Table 5-2, are a good fit to the flow patterns from the full scale SynerGEE Model described in Section 4.8.3.

![Dimensionless base demand profile](image)

**Figure 5-6: Dimensionless base demand profile calculated from SynerGEE Model.**

However, it can be seen from the MES results in Table 5-2 that modelled flows at the off-take D and V do not achieve a good hydraulic fit. However, the base demand factor for off-take D is accepted as adequate based on visual inspection of the fit between the flow rate at the node representing off-take D in the SynerGEE Model and the predicted fit using the base demand profile shown in Figure 5-7 as the peak flow rate of the two patterns has a difference of only 3.2 L.s\(^{-1}\).

The inadequate hydraulic fit at off-take V occurs because the base demand factor was chosen on the basis of the COLT flow rate data at MS(6) and not the flow rate predicted by the SynerGEE model. The flow rate data at MS(6) was used because, during typical conditions, flow rates measured at MS(6) are below the detectable level of the flow meter (as described in Chapter 4) whereas flows estimated by the SynerGEE Model are above the detectable level of the flow meter. Therefore, the SynerGEE Model overestimates the demand at off-take V. An off-take demand factor of 8 for off-take V was found to give a predicted flow rate in the EPANET model just under the detectable level of the COLT flow meter and is assumed to give a more accurate fit to the real
situation under typical conditions. Use of this higher off-take demand factor at off-take V is supported by the hydraulic fit to COLT flow rate data at MS(3), MS(5) and MS(6) during atypical flow rate events, for example Figures 5-8 through 5-10. The base demand factors shown in Table 5-2 are adopted for the remainder of the modelling.

Table 5-2: Base demand factors adopted for each off-take in the EPANET Model.

<table>
<thead>
<tr>
<th>Off-take</th>
<th>Base demand factors</th>
<th>Mean error squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>34.5</td>
<td>0.05</td>
</tr>
<tr>
<td>B</td>
<td>10</td>
<td>0.22</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>D*</td>
<td>64.9</td>
<td>4.44</td>
</tr>
<tr>
<td>E</td>
<td>9.5</td>
<td>0.01</td>
</tr>
<tr>
<td>F</td>
<td>1.3</td>
<td>0.01</td>
</tr>
<tr>
<td>G</td>
<td>23.5</td>
<td>0.85</td>
</tr>
<tr>
<td>H</td>
<td>0.3</td>
<td>0.07</td>
</tr>
<tr>
<td>I</td>
<td>0.1</td>
<td>0.00</td>
</tr>
<tr>
<td>J</td>
<td>10.8</td>
<td>0.02</td>
</tr>
<tr>
<td>K</td>
<td>4.7</td>
<td>0.01</td>
</tr>
<tr>
<td>L</td>
<td>6.2</td>
<td>0.02</td>
</tr>
<tr>
<td>M</td>
<td>5.1</td>
<td>0.05</td>
</tr>
<tr>
<td>N</td>
<td>21.6</td>
<td>0.01</td>
</tr>
<tr>
<td>O</td>
<td>5</td>
<td>0.14</td>
</tr>
<tr>
<td>P</td>
<td>6.6</td>
<td>0.01</td>
</tr>
<tr>
<td>Q</td>
<td>21.3</td>
<td>0.07</td>
</tr>
<tr>
<td>R</td>
<td>5.6</td>
<td>0.16</td>
</tr>
<tr>
<td>S</td>
<td>5</td>
<td>0.12</td>
</tr>
<tr>
<td>T</td>
<td>4.4</td>
<td>0.21</td>
</tr>
<tr>
<td>U</td>
<td>8.2</td>
<td>0.05</td>
</tr>
<tr>
<td>V*</td>
<td>8</td>
<td>34.64</td>
</tr>
</tbody>
</table>
Figure 5-7: Flow rate at the node representing off-take D as predicted by SynerGEE Model (indicated by X) and using base demand profile apportioned by base demand factor in EPANET (indicated by the line).

Figure 5-8: Comparison of COLT flow rate data recorded at MS(3) (x) and flow rate modelled at MS(3) by the EPANET model (●) for the discoloured water event on 2 October 2001.
5.7.3 Critical shear stress estimate

The support for the Daily Peak Estimate (defined in Section 5.5.1) is greater than for the Weekly Peak Estimate (defined in Section 5.5.2) using the ANTU Method. Five of the 7 events between MS(3) and MS(5) shown in Figure 5-11 support the adoption of the Daily Peak Estimate whereas only 2 of the 7 events support the Weekly Peak Estimate.
shown in Figure 5-12. In the 5 events supporting the Daily Peak Estimate, no generated autochthonous turbidity is produced when $\tau_{xs}(3-5)$ is less than zero (fulfilling the conditions of Equation 5-15).

The Daily Peak Estimate is also supported when the ANTU Method is applied to data between MS(5) and MS(6). Figure 5-13 shows that 7 of the 10 events suitable for testing the critical shear stress estimates between MS(5) and MS(6) support the adoption of the Daily Peak Estimate. This is slightly more than the 6 out of 10 events supporting the adoption of the Weekly Peak Estimate shown in Figure 5-14. Therefore, overall the ANTU Method supports the adoption of the Daily Peak Estimate as a more accurate estimate of the critical shear stress for entrainment.

It should be noted that events when only one point of ANTU(A-B) greater than zero occurred when $\tau_{xs}(A-B)$ was just below 0 N.m$^{-2}$, and the remainder of the data points occurred when $\tau_{xs}(A-B)$ was above 0 N.m$^{-2}$, were considered to fulfil the conditions of Equation 5-15. This is because the majority of the event points did support the conditions of Equation 5-15.

Tables 5-3 and 5-4 show that the $\tau_c$ varied between 1.55 N.m$^{-2}$ and 0.00 N.m$^{-2}$, with the lower values corresponding to pipes which usually experience low shear stresses [as measured at MS(6)], and the higher values corresponding to pipes that typically experience higher shear stresses [as measured at MS(3)]. In addition, summer $\tau_c$ is generally greater than winter $\tau_c$, which corresponds to the typically higher applied shear stresses experienced in summer relative to winter. Variation in $\tau_c$ is greater with location (the maximum difference between MS(3) and MS(5) = 1.21 N.m$^{-2}$, and between MS(5) and MS(6) = 0.40 N.m$^{-2}$) than with seasonal variability (maximum difference at MS(3) = 0.58 N.m$^{-2}$, at MS(5) = 0.37 N.m$^{-2}$, and at MS(6) = 0.14 N.m$^{-2}$).

On the basis the Daily Peak Estimate, it can therefore be seen that the critical shear stress varies:
- Between monitoring sites (i.e. with location); and
- Between events (i.e. with time).
Figure 5-11: Relationship between ANTU(3-5) and $\tau_{xs}(3-5)$ using the Daily Peak Estimate for the critical shear stress.
Figure 5-12: Relationship between ANTU(3-5) and $\gamma_{ss}$ (3-5) using the Weekly Peak Estimate for the critical shear stress.
Figure 5-13: Relationship between ANTU(5-6) and $\tau_{c}(5-6)$ using the Daily Peak Estimate for the critical shear stress.
Figure 5-14: Relationship between ANITU(5-6) and $\tau_{x_5}(5-6)$ using the Weekly Peak Estimate for the critical shear stress.
Table 5-3: Summary of testing of critical shear stress using conditions of Equation 5-16 for discoloured water events between MS(3) and MS(5).

<table>
<thead>
<tr>
<th>Event</th>
<th>Daily Peak Estimate</th>
<th>Predicted $\tau_c$</th>
<th>$\tau_{c, \text{at point when ANTU} &gt; 0}$</th>
<th>Weekly Peak Estimate</th>
<th>Predicted $\tau_c$</th>
<th>$\tau_{c, \text{at point when ANTU} &gt; 0}$</th>
<th>Fulfil Eq. 5-16</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>2</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>3</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>4</td>
<td>1.04</td>
<td>0.22</td>
<td>-0.38</td>
<td>0.26</td>
<td>-0.06</td>
<td>No**</td>
<td>1.14</td>
</tr>
<tr>
<td>5</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>6</td>
<td>0.96</td>
<td>0.20</td>
<td>nt</td>
<td>nt</td>
<td>nt</td>
<td>nt</td>
<td>nt</td>
</tr>
<tr>
<td>7</td>
<td>0.97</td>
<td>0.20</td>
<td>-0.24</td>
<td>0.17</td>
<td>-0.03</td>
<td>Yes*,**</td>
<td>0.99</td>
</tr>
<tr>
<td>8</td>
<td>1.02</td>
<td>0.23</td>
<td>-0.05</td>
<td>0.33</td>
<td>0.14</td>
<td>Yes</td>
<td>1.03</td>
</tr>
<tr>
<td>9</td>
<td>0.71</td>
<td>0.25</td>
<td>nt</td>
<td>nt</td>
<td>nt</td>
<td>nt</td>
<td>nt</td>
</tr>
<tr>
<td>10</td>
<td>0.98</td>
<td>0.54</td>
<td>nt</td>
<td>nt</td>
<td>nt</td>
<td>nt</td>
<td>nt</td>
</tr>
<tr>
<td>11</td>
<td>0.98</td>
<td>0.22</td>
<td>-0.07</td>
<td>0.01</td>
<td>-0.03</td>
<td>No</td>
<td>1.14</td>
</tr>
<tr>
<td>12</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>13</td>
<td>1.24</td>
<td>0.31</td>
<td>1.35</td>
<td>0.16</td>
<td>0.76</td>
<td>Yes**</td>
<td>4.31</td>
</tr>
<tr>
<td>14</td>
<td>1.55</td>
<td>0.34</td>
<td>0.64</td>
<td>1.30</td>
<td>0.97</td>
<td>Yes</td>
<td>2.75</td>
</tr>
<tr>
<td>15</td>
<td>1.13</td>
<td>0.24</td>
<td>0.81</td>
<td>0.36</td>
<td>0.59</td>
<td>Yes</td>
<td>2.28</td>
</tr>
</tbody>
</table>

% of events that fulfil the conditions of Equation 5-16 71% 29%

Note:
- x = see Table 5-1
- * = one data point of positive ANTU(3-5) recorded when excess shear below zero.
- ** = not a discoloured water event between MS(3) and MS(5)
- nt = no turbidity generated
Table 5-4: Summary of testing of critical shear stress using conditions of Equation 5-16 for discoloured water events between MS(5) and MS(6).

<table>
<thead>
<tr>
<th>Event</th>
<th>Predicted $\tau_c$</th>
<th>$\tau_{cs}$ at point when ANTU &gt; 0</th>
<th>Fulfils Eq. 5-16</th>
<th>Predicted $\tau_c$</th>
<th>$\tau_{cs}$ at point when ANTU &gt; 0</th>
<th>Fulfils Eq. 5-16</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\tau_{c}(5)$</td>
<td>$\tau_{c}(6)$</td>
<td>$\tau_{cs}(5)$</td>
<td>$\tau_{cs}(6)$</td>
<td>$\tau_{cs}(5-6)$</td>
<td>$\tau_{cs}(5)$</td>
</tr>
<tr>
<td>1</td>
<td>0.20</td>
<td>0.00</td>
<td>-0.16</td>
<td>0.00</td>
<td>-0.08</td>
<td>0.27</td>
</tr>
<tr>
<td>2</td>
<td>0.22</td>
<td>0.00</td>
<td>0.25</td>
<td>0.10</td>
<td>0.18</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>0.22</td>
<td>0.00</td>
<td>-0.04</td>
<td>0.00</td>
<td>-0.02</td>
<td>Yes*</td>
</tr>
<tr>
<td>4</td>
<td>0.20</td>
<td>0.00</td>
<td>-0.09</td>
<td>0.00</td>
<td>-0.05</td>
<td>0.52</td>
</tr>
<tr>
<td>5</td>
<td>0.20</td>
<td>0.00</td>
<td>0.12</td>
<td>0.06</td>
<td>0.09</td>
<td>Yes</td>
</tr>
<tr>
<td>6</td>
<td>0.23</td>
<td>0.00</td>
<td>nt</td>
<td>nt</td>
<td>nt</td>
<td>0.44</td>
</tr>
<tr>
<td>7</td>
<td>0.25</td>
<td>0.02</td>
<td>-0.06</td>
<td>0.04</td>
<td>-0.01</td>
<td>Yes*</td>
</tr>
<tr>
<td>8</td>
<td>0.54</td>
<td>0.14</td>
<td>-0.48</td>
<td>-0.14</td>
<td>-0.31</td>
<td>No</td>
</tr>
<tr>
<td>9</td>
<td>0.22</td>
<td>0.00</td>
<td>nt</td>
<td>nt</td>
<td>nt</td>
<td>0.26</td>
</tr>
<tr>
<td>10</td>
<td>0.31</td>
<td>0.08</td>
<td>nex</td>
<td>nex</td>
<td>nex</td>
<td>0.90</td>
</tr>
<tr>
<td>11</td>
<td>0.34</td>
<td>0.00</td>
<td>1.30</td>
<td>0.69</td>
<td>0.99</td>
<td>Yes</td>
</tr>
<tr>
<td>12</td>
<td>0.24</td>
<td>0.00</td>
<td>0.36</td>
<td>0.02</td>
<td>0.19</td>
<td>Yes</td>
</tr>
</tbody>
</table>

% of events that fulfil the conditions of Equation 5-16: 70% 60%

Notes:
- $x$ = see Table 5-1
- * = one data point of ANTU(5-6) recorded when excess shear stress below zero.
- ** = not a discoloured water event between MS(5) and MS(6)
- nt = no turbidity generated
- nex = event not due to steady state shear stress.
Tables 5-3 and 5-4 also show that, using the ANTU method, exceptions for acceptance of \( \tau_c = \tau_{0,\max}(-1\text{d}) \) are observed between MS(3) and MS(5) for Events 4 and 11 and between MS(5) and MS(6) for Events 2, 6 and 10.

Event 4 was due to a flushing procedure, which involved a hydrant being opened fully to create an increased flow and associated shear stress within the main. A direct comparison of \( \tau_{xs}(3-5) \) and ANTU(3-5) using the Daily Peak Estimate indicates that the critical shear stress was not exceeded in the length of main between MS(3) and MS(5). Therefore solely on the basis of Equation 5-15, the event does not support the use of the Daily Peak Estimate. However, Table 5-3 shows that the flushing procedure resulted in positive excess shear being recorded at MS(5) (0.26 N.m\(^{-2}\)) and negative excess shear at MS(3) (-0.38 N.m\(^{-2}\)) with the resultant average excess shear being negative (-0.06 N.m\(^{-2}\)). These results indicate that autochthonous turbidity was predicted to have been generated in the section of main directly upstream of MS(5). These results at MS(5) can be used to accept this event as still being an indirect support of the conditions of Equation 5-15 and therefore as support for the acceptance of the Daily Peak Estimate. On the basis of this same argument, the \( \tau_{xs} \) results for each individual monitoring site [MS(3), MS(5) and MS(6)] for Events 11, 2 and 6 are also considered to indirectly support the acceptance of the Daily Peak Estimate.

Table 5-4 shows that, between MS(5) and MS(6), the cohesive layer for Event 10 is weaker than that which would be expected from the maximum shear stress from the previous day. This result appears to be in conflict with adopting the Daily Peak Estimate as the best estimate of \( \tau_c \) and the results of Grainger et al. (2003) which show that major strength increase due to consolidation occurs in the first 24 hours after the material is laid.

There are three possible explanations for this anomaly:

1. The applied shear stress for Event 10 increased and decreased quickly, as shown by the spiky nature of the temporal pattern of \( \tau_{xs} \) in Figure 5-16. This rapid change in applied shear stress may have resulted in a component of dynamic shear stress which is not taken into account in \( \tau_{xs}(5-6) \). This situation would
result in larger excess shear stress than that calculated from the steady state conditions alone.

2. Event 9 on the previous day may have resulted in more material than usual being deposited onto the pipe wall. Such a situation would suggest that, when a large amount of material is deposited, the material needs more than 24 hours to consolidate.

3. Event 9, which occurred on the day previous to Event 10, began to erode the cohesive layer but the layer was not exhausted. The existence of this condition is supported by the temporal pattern of ANTU(5-6) and $\tau_{xs}(5-6)$ in Figure 5-15 where the ANTU(5-6) continues to increase until $\tau_{xs}(5-6)$ is less than zero. This continual increase in turbidity may also indicate that with the sudden drop in applied shear stress, the cohesive layer stopped being eroded before equilibrium between the applied shear stress and the cohesive layer strength was reached. Such a situation would result in the layer strength being left weaker than that indicated by the maximum applied shear stress.

Determination of the true cause of this anomaly could not be determined using the data collected for this research and is therefore beyond the scope of this investigation.

Figure 5-15: Temporal pattern of discoloured water event on the 2 October 2001 for MS(5) to MS(6). (\(\bigstar\) = generated ANTU(5-6), X = slug ANTU(5-6), \(\bullet\) = $\tau_{xs}(5-6)$ using the Daily Peak Estimate.)
5.8 Results of analysis using SNTU Method

By comparing the scatter plots of maximum daily SNTU and maximum daily $\tau_{ex}$ shown in Figures 5-17 and 5-18, it can be seen that the SNTU Method also supports the use of the Daily Peak Estimate, rather than the Weekly Peak Estimate, for the critical shear stress. This conclusion can be reached because the Daily Peak Estimate using the SNTU Method (shown in Figure 5-17) produces scatter plots where there are more points of maximum daily spike turbidity greater than the Complaint Threshold when the maximum daily excess shear stress is greater than zero than is the case for the Weekly Peak Estimate (shown in Figure 5-18).

The Daily Peak Estimate has only two points at each monitoring site tested where maximum daily excess shear stress is less than zero when maximum daily spike turbidity is greater than the Complaint Threshold. The data points that are exceptions to the acceptance of the Daily Peak Estimate occur on 28 March 2001, 20 July 2001, 23 July 2001, 20 November 2001, 16 February 2002, and 4 April 2002. In Chapter 4, it can be seen that all these events were attributed to causes that did not result in escalated steady state shear stress. For example, Table 4-5 shows that the event on the 28 March 2001...
was attributed to being created by an unknown cause that was not flow related and therefore did not result in an increase in steady state shear stress.

Figure 5-17: Scatter plots of peak daily spike turbidity and peak daily excess shear stress for MS(3), MS(5) and MS(6) using the Daily Peak Estimate for the critical shear stress.
Figure 5-18: Scatter plots of peak daily spike turbidity and peak daily excess shear stress for MS(3), MS(5) and MS(6) using the Weekly Peak Estimate for the critical shear stress.

Table 4-5 also shows that the event on the 20 November 2001 was attributed to a mains repair that did not result in an increase in steady state shear stress in the transfer main (but may have at the point of the repair). The 4 April 2002 event at MS(5) was attributed to a valve closure (see Appendix 8). The discoloured water recorded in the transfer main in both these events may have been a result of dynamic shear stress from
water hammer and therefore the steady state shear stress used to calculate $\tau_{ss}$ would not indicate the true applied shear stress generated.

The event recorded at MS(6) on the 23 July 2001 was attributed to an unknown cause that did not result in an increase in flow that would cause an increase in steady state shear stress.

The event recorded at MS(6) on the 20 July 2001 was attributed to a hydraulic disturbance of an unknown cause in the reticulation system supplied by an off-take between MS(5) and MS(6). The discoloured water event created between MS(5) and MS(6) by the hydraulic disturbance then travelled downstream to MS(6). This is shown by an escalation in flow rate recorded at MS(5) but not MS(6) and an escalation in spike turbidity recorded at MS(6) and not MS(5). The turbidity recorded at MS(6) on the 19 February 2002, created from unusually high residential water demand between MS(5) and MS(6), also created a discoloured water event between MS(5) and MS(6) that subsequently was transported to MS(6).

Therefore, none of the above events are seen as a reason not to accept the Daily Peak Estimate as the better estimate of the critical shear stress. This conclusion is because the data points which counter acceptance of the Daily Peak Estimate are due to turbidity travelling down from further upstream or a cause that would not be indicated or predicted by steady state shear stress.

The scatter plots in Figures 5-17 and 5-18 can also be used to make general observations of discoloured water formation in the Wantirna WQZ. These scatter plots indicate that, due to higher flows in the transfer main nearer the source, shear stress in the transfer main, not unexpectedly, reached larger values closer to the Wantirna Service Reservoir (as represented by MS(3)) than at the end of the transfer main (as represented by MS(6)). However, the reverse is true for spike turbidity. More major turbidity events occurred at the extremity of the transfer main (as represented by MS(6)) than closer to the Wantirna Service Reservoir (as represented by MS(3)). Indeed, at
5.9 Discussion

5.9.1 Prediction of the occurrence of a discoloured water event
The mechanism proposed for the formation of discoloured water investigated in this chapter is one of particles entering the distribution system at low concentrations, collecting at the internal pipe wall via van der Waals forces, and forming cohesive layers. These cohesive layers are then eroded when a critical shear stress of entrainment is reached, creating discoloured water. The critical shear stress of entrainment is assumed to be equal to the strength of the cohesive layer at the water/layer interface. The critical shear stress of entrainment was proposed to be dependent on the peak applied shear stresses that had occurred in that section of pipe and the re-accumulation rate of the particles. This chapter examined whether the critical shear stress of entrainment can be estimated using the peak applied shear stress that had occurred in a preceding period of time, namely, the Daily Peak Estimate and the Weekly Peak Estimate, as described in Section 5.5.

The relationship of the critical shear stress to the applied shear stress can be explained by the mechanism of continual growth and erosion or sloughing of a cohesive layer on the walls of the pipes and increases due to consolidation in yield strength of the cohesive layer with distance from the water/layer interface toward the pipe wall. The strength increase of the cohesive layer with distance from the water/layer interface results in the cohesive layer being weakest (and more readily eroded) at the interface of the water and cohesive layer, and strongest at the pipe wall. Erosion continues at the interface until the applied shear stress and the cohesive layer yield strength are in equilibrium. The existence of this process results in a greater effective layer strength and therefore greater critical shear stress in pipes that experience prior and recent higher applied shear stresses.
Two methods were developed in this study to test estimates of critical shear stress of entrainment. The two methods developed were the SNTU Method and the ANTU Method and are key extensions to existing work. The ANTU Method is an in-depth analysis of only those discoloured water events that had previously been attributed to increases in water velocity. The SNTU Method is a general analysis using all COLT data. Use of these methods allowed a time and location dependent estimate of the critical shear stress of entrainment to be determined and increased the understanding of the way in which discoloured water is formed. Both methods use COLT of turbidity and flow rate. Two methods for estimating the critical shear stress of entrainment using these methods were based on the daily or weekly peaks in applied shear stress, as measured by COLT in a section of the Wantirna WQZ transfer main (Daily Peak Estimate and Weekly Peak Estimate, respectively).

Both the ANTU Method and the SNTU Method show that, when shear stresses caused by hydraulic conditions exceed a critical shear stress, discoloured water events occur. In this mechanism escalation in shear stress appears to cause the re-suspension of material previously collected in cohesive layers on the internal walls of the pipes.

The ANTU Method shows this causation effect by indicating that turbidity is generated between monitoring sites, indicated by positive ANTU, when the estimated critical shear stress is exceeded. The SNTU Method shows this causation effect by indicating that the majority of discoloured water events (as defined by SNTU$_{\text{max}}$ over the complaint threshold) occur when the estimated critical shear stress is exceeded. This expected result is consistent with accepted theory of cohesive layers in mudflats and rivers (Ravisanger et al. 2001, Black et al. 2002 and U.S. Army Corps of Engineers 2002) and findings in British water distribution systems (Boxall et al. 2001) and sewer systems (May et al. 1996).

Both the ANTU and SNTU methods found that, for a section of pipe, the maximum applied shear stress recorded on the previous day (the Daily Peak Estimate) is a better estimate of the critical shear stress of entrainment than the maximum shear stress over the preceding week (the Weekly Peak Estimate). The finding that the critical shear
stress of entrainment was best estimated by the peak shear stress on the preceding day is supported by the experiments of Grainger et al. (2003). Using particles collected from water systems in Melbourne, Australia (and of similar size and chemistry to those of Wantirna WQZ), experiments by Grainger et al. (2003) indicate that layers into which particles collect increased in consolidation strength over time but with very little strength increase occurring after the first day.

The variable magnitude of the critical shear stress identified within this study, and shown in Table 5-3, indicates that critical shear stress is unique to a location in the water distribution system. This table shows that critical shear stress is larger at MS(3) than at MS(5) and MS(6). MS(5) and MS(6) are sequentially further down the system than MS(3) and experience lower daily maximums in shear stress. The same table also indicates that, at a particular location, the critical shear stress varies with time, as shown by the variance in critical shear stress between events at each monitoring site. This result is expected from an approach which uses a critical shear stress that is estimated through a maximum prior applied shear stress. Applied shear stress experienced in a pipe varies with location and time in the same way as the flows, and their associated velocities, vary with time throughout the distribution network.

A natural extension of this finding is that the critical shear stress estimate methods can be applied to other parts of the water distribution system. Under this approach system hydraulics cause the critical shear stress to vary in each pipe segment each day. Therefore, for a given hydraulic disturbance the critical shear stress might be exceeded in some areas of the system and not others, causing discoloured water to be formed in some areas and not others.

This conclusion is substantiated by a comparison of discoloured water events recorded in the Wantirna WQZ transfer main and customer complaints concerning discoloured water (as discussed in Section 4.14). Fifty % of complaints occurred in areas off, but supplied by, the transfer main, when no or low turbidity was recorded in the transfer main. This situation indicates that discoloured water was most likely generated in the reticulation system and not in the transfer main. Therefore, local hydraulic conditions in
a specific pipe are an important factor in that pipe producing discoloured water. It also explains why some of the DWCCs reported in Section 2.6.8 still occurred when flow rates recorded at the outlet of the Wantirna Service Reservoir were low.

The work of Boxall et al. (2001) supports the dependence of the critical shear stress on local hydraulic conditions, proposing that the cohesive layer is both “conditioned” by past hydraulic events in the pipe and does not have a constant value. This characteristic would explain the seemingly random and episodic nature of discoloured water described by some authors (Walski 1991). The work by Boxall et al. (2001), unlike this study, did not however link past hydraulic events to a particular time frame.

This study also concludes that an area is therefore affected by discoloured water under two main scenarios. The first scenario, and apparently the most common, occurs when local critical shear stresses are exceeded and there is material at the pipe wall to entrain. The second scenario occurs when discoloured water is transported from upstream, as indicated by the 5 complaints that occurred when high turbidity was recorded in the part of the transfer main supplying those locations and the 5 allochthonous discoloured water events recorded entering the Wantirna WQZ through the Wantirna Service Reservoir (as reported in Chapter 4).

5.9.2 Self-Cleaning Threshold

Results from analysis of the SNTU Method suggest that a section of the network at the top of the transfer main (near MS(3)) did not always produce discoloured water when the critical shear stress was exceeded. For example, excess shear stress at MS(3) can be greater than 1 N.m$^{-2}$ and SNTU$_{\text{max}}$ still equal to 0 NTU. These points all occur in summer when the maximum daily velocity is greater than that typically used for mains cleaning (1 m.s$^{-1}$). Table 4-7 indicates that events in summer may require more than 5 days for sufficient material to cause a discoloured water event to be deposited. This situation may indicate that these pipes are ‘swept’ clean at certain periods of the year on a daily basis by daily high shear stress events which prevent the significant build up of accumulation material to cause discoloured water. Hence the pipe is effectively “self-cleaning”.
The self-cleaning concept is consistent with theory developed by van den Boomen and van Mazijk (2002), and van den Boomen et al. (2004) for the design of self-cleaning networks. Investigation of a self-cleaning threshold, defined as the maximum daily shear stress required to ensure daily scouring of the pipe, would be useful for maximising the time between mains cleaning programs. It would also reduce the number of pipes identified as needing cleaning by identifying those pipes within the system where the severity of discolouration will be low even when critical shear stress is exceeded. Self-cleaning thresholds have been defined in terms of both shear stress and water velocity (van den Boomen and van Mazijk 2002, and van den Boomen et al. 2004).

The determination of the exact self-cleaning threshold for the Wantirna WQZ has been further investigated by Boxall and Prince (2006) using the Sheffield University PODDS model. Boxall and Prince (2006) determined a consistent self-cleaning threshold value of 1.15 N.m⁻² for all the events examined. This modelling supports the findings in this study that a self-cleaning threshold exists. This modelled value of the self-cleaning threshold is larger than the experimental self-cleaning threshold of 0.47 N.m⁻² suggested by Slaats (2002) for Dutch water systems. The difference of the self-cleaning threshold reported by Slaats (2002) could be because the Dutch self-cleaning threshold was derived from laboratory studies with non-cohesive sediments, and differences in material characteristics between the Wantirna and Dutch distribution systems.

Quantification of the self-cleaning threshold has significant implications without the need for further model development. For example, system management, operation and design can be optimised to maximise the occurrence of shear stresses in excess of the threshold to prevent sufficient accumulation of material to lead to a discoloured water event. This optimisation would maximise the area of the system maintained in a clean state. Cleaning programs could then be planned to target only potentially dirty pipes and a “clean water front” for spot flushing readily identified. A clean water front is defined as the systematic cleaning a pipe network using unidirectional flushing or air scouring of mains by always drawing water through clean mains Slaats (2001).
5.9.3 Effect on operating procedures

An operational procedure is defined as a physical action (for example the use of a hydrant) taken by a party (for example the water company or fire department) that affects the pipe network or water flowing in the pipe network.

It would appear from the conclusions of this study that a discoloured water event will be created by an operational procedure that causes an applied shear stress that exceeds the critical shear stress of entrainment. As the critical shear stress has been found to be best estimated using the Daily Peak Estimate, the likelihood of operational procedures creating discoloured water is minimised when the resulting peak shear stress generated in the pipe from the procedure and underlying water demand is kept below the maximum shear stress of the previous day. Hence, based on the critical shear stress concept, there may be a lower risk of causing a discoloured water event if an operational procedure is carried out at times of the day in which low flows occur so that the additional demand created by the operational procedure over and above the underlying demand does not exceed the Daily Peak Estimate.

Areas that experience low peak daily shear stresses are at more risk of discoloured water for a specific operational procedure than those areas that experience high maximum daily shear stresses. This conclusion is supported by the greater number of discoloured water events created at MS(6) (where the daily shear stresses are low) than MS(3) (where the daily shear stresses are much higher).

The recommendation of when to schedule operational procedures cannot, however, be applied to flushing procedures. Flushing procedures to clean pipes need to be conducted so that the critical shear stress is exceeded, otherwise no material will be removed. However, it is recommended that flushing procedures should be conducted using a “clean water front” so that discoloured water is not created in an uncontrolled way in the system.

Less water would be required to clean pipes with typically high values of critical shear stress if flushing procedures are conducted during times of high demand and associated
pipe shear stresses, as only a minimal additional flow would be needed to exceed the critical shear stress. However, as high demands are likely to be associated with larger numbers of customers using the water, this could also result in the maximum number of customers receiving the discoloured water. Therefore, to reduce customer complaints it would be preferable to conduct flushing procedures during low flow times and use more water.

If isolated flushing is required for system management, for example, to rectify localised low chlorine levels or high coliform counts, it is suggested that hydraulic modelling be performed to determine if the critical shear stress can be exceeded in the pipe to be cleaned while not exceeding the critical shear stress for transfer mains elsewhere in the system. This would limit the area in which discoloured water is formed and limit to where it is transported.

However, the results of this study pose questions on the actual usefulness of flushing procedures to reduce the likelihood of discolouration. Flushing is effectively using a deliberate hydraulic disturbance to exceed the existing critical shear stress, removing material collected at the pipe wall and increasing the critical shear stress at the pipe wall to a point at which it is unlikely to be exceeded in the immediate future. The time between flushing procedures is dependent on the time it takes for enough material to collect in the pipe wall to create a risk of causing discoloured water. The conclusion in this study that: (1) the Daily Peak Estimate, rather than, the Weekly Peak Estimate is the best indicator of the critical shear stress; and (2) discoloured water events have occurred within days of one another, may indicate that significant material is collecting ($R_c$ is significant) within one week in the large pipes investigated. Hence, the benefit of flushing to reduce the severity of an event would appear to be relatively short term. These observations may also explain why customer complaints were not reduced in the following year after block mains cleaning (as discussed in Section 2.6.10).

Furthermore, Kjellberg (2007), in a study on the application of the Resuspension Potential Method (RPM) as a means of mains cleaning, reported that RPM measurements gathered two weeks after mains cleaning in the Yarra Valley Water
system produced turbidity levels above the customer complaint threshold of 5 NTU. Although Kjellberg (2007) notes that the RPM may not have been applied appropriately in the Yarra Valley Water system and therefore the results were not particularly useful, the study does give an indication that material which gives rise to discoloured water events gathers relatively quickly – in terms of periods of time of two weeks or less rather than months. Further research is needed to predict quantitatively the length of time needed for sufficient material to recollect at the pipe wall to have the potential to cause discoloured water.

5.9.4 Limitations of ANTU and SNTU Methods

A potential limitation of both the ANTU and SNTU Methods used in this study is the way in which the turbidity parameters ANTU and SNTU are calculated. There is not necessarily a linear relationship between the number of particles present in a water sample and the turbidity readings. Thus it is not strictly correct to subtract turbidity values to determine how much turbidity is “left over”, which is effectively what is done when calculating ANTU and SNTU values. In addition, turbidity readings will alter with different particle sizes. Hence, if particle conglomerates break up with transport through the system, turbidity readings have the potential to change for the same bulk mass of particles. Different particle materials may also produce varying turbidity readings.

However, the limited studies on the particles in the SE Water system have found approximately consistent particle physical and chemical characteristics over the whole system (Ekanayake et al. 2003; Grainger et al. 2002; and Johnson and Gianchino 2000). In this study, it was therefore assumed that the mix of particle size and materials causing discoloured water had little effect on the calculation of ANTU and SNTU. Further research on the effect of transport on particle characteristics and the corresponding effect on turbidity readings would nevertheless aid in interpretation of both ANTU and SNTU.

Both the SNTU and ANTU Methods also had some unique limitations. Although considerable information was generated from the ANTU Method, substantial time was
required to perform the analysis, in excess of four hours set-up time for each event. This
time requirement is the result of the need for both a calibrated hydraulic model and
development of a chemical trace pattern for each discoloured water event investigated.
In addition, analysis of a number of discoloured water events was required to determine
if the results were consistent. The sampling period required for this method was itself
lengthy and depended on the frequency of random and relatively infrequent discoloured
water events occurring in the pipe being analysed. Therefore, the sampling period could
not be predetermined. Even with 16 months of monitoring, only 7 events between
MS(3) and MS(5), and 10 events between MS(5) and MS(6) were suitable for analysis
using the ANTU Method.

The number of off-takes from the transfer main between COLT monitoring sites also
created some limitations to the ANTU Method. The off-takes created variance in the
flow rate between monitoring sites which in turn created great variability of the critical
shear stress. The variability in the critical shear stress resulted in the value of the
average excess shear stress between the two monitoring sites not indicating the overall
potential of that section of pipe to create discoloured water in 6 cases. For example,
investigation of the individual excess shear stress values at each site showed that a
portion of the section of pipe between the two sites might have produced turbidity when
use of the average excess shear stress would not have predicted it. This limitation could
be overcome by selecting a section of pipe with no off-takes. This would reduce the
longitudinal shear stress variation and cause the average excess shear stress to be a more
exact measure of conditions at all points along the section of pipe.

The distance between monitoring sites may have also affected the accuracy of the
ANTU Method, and thus the determination of the critical shear stress. The ANTU
Method relies on identifying when erosion of the cohesive layer starts and stops from
the shape of ANTU with time. At low flow times the travel time between monitoring
sites becomes very large, over 5 hours in some cases. It is conceivable that during this
time re-deposition of particles and travel time of the turbidity event may have masked
the exact point at which erosion stopped. Furthermore, erosion may have been occurring
at one end of the section of pipe and re-deposition occurring further down stream. This
is particularly the case between MS(5) and MS(6), as the flows recorded at MS(6) were typically below the detection limit of the flow meter. Therefore adventive transport may not have always occurred between MS(5) and MS(6).

A limitation of the SNTU Method was that $SNTU_{\text{max}}$ values are a combination of turbidity generated in the pipe being monitored (autochthonous turbidity) and turbidity transported from upstream (allochthonous turbidity). This limitation results in an ambiguous relationship between $\tau_{s,s,\text{max}}$ and $SNTU_{\text{max}}$ for some days and locations. The limitation is particularly evident when the component of allochthonous turbidity was large compared to the autochthonous turbidity component, such that the $\tau_{s,s,\text{max}}$ value recorded against the $SNTU_{\text{max}}$ value was not the shear stress that created the event but only an indicator of the flow conditions that transported the discoloured water event from upstream. Therefore caution should be used when interpreting results when using the SNTU Method and some research into individual discoloured water events may be required.

In summary, the SNTU Method requires an investigation of each data point that does not support the acceptance of the critical shear stress estimate. Alternatively, the ANTU Method requires more manipulation of data before analysis can be conducted. The SNTU Method was considered to be the better of the two methods in predicting the critical shear stress of entrainment, as: (1) the method gave similar results to the ANTU method; (2) all data (excluding events associated with turbidimeter errors) are included in the analysis; (3) the time required to conduct the analysis is less due to the reduced data manipulation and that the use of a hydraulic model is not required.

A COLT sampling rate of 10 minutes allowed the turbidity of discoloured water events to be measured adequately. However, the frequency of monitoring of flow rate essentially only allowed steady state shear stress to be determined and therefore the magnitude of any dynamic component could not be established. Attributed causes of discoloured water events reported in the study suggest that the dynamic shear stress (for example, from water hammer) may have created 4 out of 33 discoloured water events. However, this observation is in conflict with theoretical analysis reported by van den
Boomen and van Mazijk (2002) who stated that the dynamic component of shear stress would be negligible for large pipes. It is therefore recommended that further empirical research be conducted to determine the actual effect of the dynamic component of the shear stress on discoloured water formation. The dynamic component of shear stress could be calculated from COLT data if pressure was measured every 1 second. It is suggested that data collection of COLT of pressure be triggered when a certain level of pressure is exceeded, as this would reduce the electronic data storage requirement for data logging.

**Limitations of using “natural” discoloured water events**

By not artificially producing the shear stress events that occur in the system, only “natural” discoloured water events were recorded. An indication of the type of procedures that cause discoloured water could therefore be determined without presuming causes or creating additional discoloured water events over and above those that would have already occurred. This situation also meant that discoloured water events could not be predicted and were not frequent prolonging the period of time that monitoring was required.

A major limitation of not artificially producing the shear stress events was that some variables, such as the shear stress of an event, could not be held constant. The effect of the variability of the shear stress resulted in some aspects of discoloured water formation, such as the entrainment mechanism of particles, not adequately investigated. In short, due to the constantly changing hydraulics in the pipe network, it was impossible to use the existing data set to determine if the entrainment mechanism of particles from the cohesive layer causing the turbidity was due to time dependent erosion or instant sloughing of the layer to a particular distance toward the pipe wall.

The following procedure could be used to adequately investigate whether the entrainment mechanism could be best described by time dependent erosion or instant sloughing of the layer to a particular distance toward the pipe wall.
A procedure that uses live systems to determine the re-suspension mechanism could be modelled on the Re-suspension Potential Method (RPM) developed by Kiwa Water Research. The RPM involves the continuous measurement of turbidity when an induced disturbance is created. It is recommended this procedure be modified so that two sites in series are used, with turbidity being measured at each site. A sustained stepwise increase in shear stress would be applied to the pipe. Each step should be of sufficient duration to allow for at least 1 pipe turnover\textsuperscript{88} to occur so that any material mobilised by the flow travels to the downstream monitoring site as shown in Figure 5-19. This approach would enable the point at which turbidity begins to increase to be identified.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure5-19.png}
\caption{Sustained stepwise increase in shear stress recommended to determine the critical shear stress.}
\end{figure}

Assuming consistent particle size and characteristics, and a linear relationship between turbidity and particle concentration, a linear increase in turbidity over a pipe turnover would suggest a constant and sustained erosion rate. A sharp increase in turbidity at each increase in shear stress followed by a constant turbidity over a pipe turnover, would suggest the instant mobilisation of particles from the cohesive layer (sloughing) that are subsequently transported to the monitoring site.

This approach would also allow for the verification of whether the strength of the layer of material at the pipe wall increases with distance toward the pipe wall by comparing results between the time steps. Results of monitoring that indicate an increase in

\textsuperscript{88} Pipe turnover is defined as the time taken for the volume of water in a pipe section to be replaced by water flowing from upstream.
turbidity occurring with each step in shear stress would suggest the strength of the layer increases with distance toward the pipe wall. This result is particularly strong if the previous step in shear stress has been conducted until turbidity had begun to reduce.

The same procedure of using an altered RPM could be used to verify the methods for calculating an estimate of the critical shear stress for different pipe sizes and materials. Using the flow rate and turbidity data collected, the ANTU or SNTU Method outlined in this study can be used to verify the estimate of the critical shear stress.

The monitoring sites for such studies should be placed closer together than was the case for this study. The close proximity of sites is recommended because the hydraulic differences in the system due to major off-takes between monitoring sites, and the long travel times between the sites, impacted on analysis of the COLT data. The use of in situ COLT of live systems is recommended for these tests, rather than laboratory investigation. The use of live systems is recommended because of the limitations of laboratory studies using collected particles or artificial particles, such as that the effect of reconstituted cohesive layers, has not clearly been identified (as discussed in the literature review).

5.9.5 Collection of Particles

Based on the literature review the main origin for particles causing discoloured water events in the unfiltered water distribution system investigated was hypothesised to be the surface source water. It was proposed that, because of their small size and physical properties, and observations in laboratory experiments, these particles collect via van der Waals forces onto the pipe wall forming cohesive layers. Although the origin and the way in which particles collect in the water distribution system was not a focus of this study, the analysis conducted to determine the hydraulic triggers of discoloured water events lends support to the hypothesised collection mechanism.

The hypothesis that the source water is the origin of particles causing discoloured water is supported by two factors: firstly by the surface source water having a high turbidity of 0.7 to 2.3 NTU; and secondly, by the median reading of background turbidity that
entered the Wantirna WQZ from the Wantirna Service Reservoir also being high, at 1.4 NTU. These two factors indicate that particles were continually being supplied from upstream of the Wantirna Service Reservoir. The hypothesis that particles are collecting onto the pipe wall during turbulent flow due to van der Waals forces is supported by discoloured water events being generated in sections of the Wantirna WQZ that continually experienced turbulent flow at a level that would theoretically prevent sedimentation due to gravitational forces.

Furthermore, results in this study indicate that particles collect onto the pipe wall at a rate high enough to create a discoloured water event in a period less than a week and, at times, within a day. This conclusion is based on: (1) the result that the peak shear stress on the previous day is a better estimate of the critical shear stress of entrainment than the peak shear stress in the previous week. The prediction of the critical shear stress using the maximum shear stress from the previous week overestimates the critical shear stress and therefore the strength of the cohesive layer, indicating that the layer is weakening in some way; and (2) that 11 discoloured water events out of 33 events identified occurred within seven days of a previously larger shear stress event indicating that this effective weakening of the cohesive layer, at a rate greater than the strengthening of the layer due to consolidation, is likely to be due to the accumulation of new material. In fact, some discoloured water events occurred within two days of the previous event indicating a very rapid rate of particle accumulation.

The collection rate and mechanism for particle accumulation under different conditions justifies further investigation. Laboratory experiments using test rigs where aspects such as pipe size, roughness and hydraulic regime can be controlled are recommended to investigate the collection mechanism further. The work of Wu et al. (2003) which discusses a particle sediment model based on sediment accumulation through van der Waals forces represents the start of this type of investigation. The theory examined by Wu et al. (2003) resulted in a good fit to the limited laboratory based experimental data. However, the wall deposition mechanism in that model requires the measurement of a wall mass coefficient that appears able to be practically measured only with a laboratory test rig. The limited investigations to date of the wall mass coefficient have found that it
varies with flow velocity and particle physical and chemical properties and thus is likely to be unique to a system. While only one pipe size and one material was used in the Wu et al. (2003) experiments, particles collected from a number of different water companies were investigated. However, the results have not been validated using data taken from within actual water distribution systems.

Boxall et al. (1991) present a theoretical “black box” computer model, which is calibrated using turbidity measurements measured in situ, for regeneration of corrosion layers. The model may be applicable to cohesive layer regeneration formed by other materials as the equations used are not based on the physics of particle corrosion. The equations are instead based on correlation with measurements of the additional turbidity stored at the pipe wall over a period in a particular system. The correlation is conducted by varying the relative contribution of coefficients of regeneration, such as time since last discoloured water event, temperature and cohesive layer condition. A process of validation of the model on filtered and unlined systems in the United Kingdom has recently begun. However, the results of that validation study have not yet been published. Further research to compare and verify the accuracy of the models reported by Wu et al. (2003) and Boxall et al. (2001) is required.

A possible method for verifying these theoretical models would be the resuspension potential method (RPM) reported by Slaats (2002). By repeating RPM measurements at the same locations over different periods, the re-accumulation rate of particles could be determined. To this end, water systems in the Netherlands present a ready-made data source as they have been routinely conducting RPM for a number of years.

### 5.10 Conclusion

Despite the limitations in the use of COLT to measure discoloured water, the turbidity and flow rates obtained from this monitoring system were used successfully to identify both the operational procedures and the hydraulic events causing discoloured water. It is therefore concluded that COLT can be used to identify discoloured water events and that monitoring sites in series can be used to gain an understanding of discoloured water
formation. From this understanding, COLT of flow rate and a hydraulic model should be able to determine those areas likely to receive discoloured water for a specific operational procedure.

Most discoloured water events (turbidity at a level a customer may notice) were found to occur when the applied steady shear stress from the velocity of water exceeds a critical shear stress of entrainment. The maximum applied shear stress recorded on the previous day is the best estimate of this critical shear stress. Due to the spatial and temporal patterns of the flow in the network the magnitude of the critical shear stress is unique in location and time. However, using the existing data set was not possible to determine if the entrainment mechanism of particles from the cohesive layer causing the turbidity was due to time dependent erosion or instant sloughing of the layer to a particular distance toward the pipe wall.
CHAPTER 6 : SYNTHESIS AND RECOMMENDATIONS

6.1 Synthesis

Throughout the world, the most common water quality issue reported to water companies by customers is of discoloured water. In Melbourne, Australia, discoloured water complaints are also a Key Performance Indicator (KPI) used to compare the performance of the three water retail companies. Customer complaints are used as a KPI because the customer charter common to all water retail companies in Melbourne requires delivery of water that is aesthetically pleasing, and the Safe Drinking Water Act (2003) requires that the level of water quality not cause widespread complaints and requires reporting of all customer complaints.

Discoloured water events are defined in this study as incidents where a Discoloured Water Customer Complaint (DWCC) has been reported to the water company or incidents where turbidity exceeds the complaint threshold of aesthetic water quality. In agreement with other research into discoloured water events, the characteristics of discoloured water events observed in this study suggest that discoloured water in the unfiltered and lined water distribution system investigated is created by particulate matter rather than true colour. This result is consistent with previous findings.

When the causes of discoloured water events are understood, a system can be proactively managed to prevent discoloured water events. This philosophy is supported by contemporary water system management, practices and operations. Contemporary practices such as those outlined in the 2004 Australian Drinking Water Guidelines, require a preventative management approach to water quality management that takes into account aspects from catchment to customer through the Framework for the Management of Drinking Water Quality. This approach is in line with Quality
Management (ISO 9001), Environmental Management (ISO14001), Risk Management (AS/NZS 4360) and Hazard Analysis and Critical Control Point (HACCP) systems.

The Framework for the Management of Drinking Water Quality is developed specifically for the water industry and requires water companies to incorporate problem minimisation strategies that consist of multiple barriers, monitoring at critical points in the system, and outlining appropriate action that is required if barriers are breached. Although this system has been primarily built for health related water quality, it can also be used successfully for aesthetic water quality as “in terms of reliability, there is no substitute for understanding a water supply system from catchment to consumer, how it works and its vulnerabilities to failure” (NHMRC and NRMMC 2004). The challenge for water companies is therefore to move toward management practices that are based on an understanding of how discoloured water is formed. Better approaches to discoloured water event management therefore require an improved understanding of discoloured water formation so that appropriate barriers, monitoring and actions can be determined.

World wide, the most widely adopted management practices for identifying and managing problem areas for discoloured water events are not based on a comprehensive understanding on how discoloured water is formed. The management practices tend to use a retrospective analysis of the frequencies of DWCCs and/or the frequency that water quality measurements collected by grab samples at sampling tap sites exceed aesthetic guideline levels. A new and promising measuring technique for improved management practices involves continuous on-line testing (COLT) of turbidity. In this study the new COLT method and existing measurement techniques were compared to determine the most effective measurement technique for capturing discoloured water events and to assist in the understanding the mechanisms of how discoloured water is formed. Investigations were preformed in an unfiltered and lined water distribution system controlled by South East Water (SE Water) in Melbourne, Australia. Detailed monitoring was performed on a transfer main in the Wantirna Water Quality Zone (Wantirna WQZ) controlled by SE Water.
COLT of turbidity at 6 locations within the Wantirna WQZ is found to be more
effective at measuring and characterising discoloured water events than either water
quality grab samples taken at sampling frequencies recommended by the 1996
Australian Drinking Water Guidelines or reported DWCCs. COLT of flow rate and
turbidity, measured every 10 minutes at 6 locations, allows for the identification of
discoloured water events and the determination of both hydraulic and operational causes
in the unfiltered water distribution system investigated.

The shortcomings of the grab sample approach relate to the episodic and sporadic nature
of discoloured water events. Grab samples cannot economically or logistically be
collected frequently enough to capture discoloured water events reliably. Furthermore,
test results of grab samples cannot be used to determine the characteristics or causes of
discoloured water events. Even a sampling program at 10 times the frequency
recommended by the 1996 Australian Drinking Water Guidelines only characterised
underlying water quality and did not measure discoloured water events.

Customer complaints are considered inferior to COLT as customers do not experience
every discoloured water event and then do not reliably report every discoloured water
event they experience. Hence, although it is valid to assume that a discoloured water
event has occurred when a DWCC is reported, it is not valid to conclude that no
discoloured water has occurred if no complaints occur. COLT of turbidity is more
accurate and reliable than customer complaints at identifying discoloured water events
that have occurred at a specific location and provides a basis for a method of predicting
discoloured water complaints. However, it is not economically feasible to place COLT
of turbidity in every pipe of the water distribution system for the use of direct system
management. It is therefore valid to use complaints as a trigger for immediate
investigation and action for localised discoloured water events. The use of complaints
for a trigger for immediate action is consistent with the Risk Management Framework
in the 2004 Australian Drinking Water Guidelines.

Many earlier studies suggest that complaints be used as a confirmation or validation
parameter of areas at high risk of receiving discoloured water. However, it is
recommended that complaints only be used as a confirmation or validation parameter if the water company is confident that the conversion rate of reported complaints to actual discoloured water events is known and consistent over time and location. This recommendation is made because, even as a secondary parameter, there is a temptation to assess an area as having lower risk of receiving discoloured water events when few or no complaints were reported. It is suggested that the conversion rate of reported complaints to actual discoloured water events be determined from a comparison of discoloured water events identified using COLT and complaints in the areas supplied from the pipe under monitoring.

COLT of flow rate and turbidity was used to determine the system operations and understand the steady state hydraulics that cause discoloured water events in a transfer main of the unfiltered Wantirna WQZ. COLT of turbidity provides a temporal pattern of water quality at a specific location and therefore can be used to determine the magnitude and duration of discoloured water events. Monitoring sites in series can then be used to determine the movement of such events through the system. This approach distinguishes between discoloured water transported from upstream (allochthonous turbidity) and discoloured water formed within the pipe being monitored (autochthonous turbidity).

Although not a primary focus of this study, some insight was developed into the antecedent conditions needed for formation of discoloured water events. Background COLT of turbidity readings indicate that few discoloured water events originate directly from allochthonous discoloured water events in the source water. The background turbidity readings suggest that, for the majority of discoloured water events, the particulate matter is from source water supplied to the water distribution system at low concentrations and subsequently accumulated in the system.

COLT of flow rate indicates that it is likely that the transfer main being monitored only experiences turbulent flow such that, due to the characteristics (size etc) of the particles originally from the source water, sedimentation due to gravity is unlikely to occur. It appears therefore that particles collect on the pipe wall during turbulent flow, possibly
due to van der Waals forces. The behaviour and clay content of particle samples taken from the study area, as reported by other authors, also supports the particles forming cohesive layers at the pipe wall.

Standard cohesive layer theory proposes that cohesive layers are held in a relatively stable condition and only begin to be entrained when the surface layer shear strength is exceeded by the applied shear stress from the water. The cohesive layer strength can be due to a number of physical, chemical and biological factors. The point at which a significant entrainment occurs is known as the critical shear stress of entrainment. This resulting entrainment process is hypothesised to continue until equilibrium between the applied shear stress and the strength of the cohesive layer has occurred. Under an assumption that the cohesive layer is not totally removed by this process, and knowing from other researchers that the strength of the cohesive layer increases with distance toward the pipe wall, for a certain applied shear stress there will be a point at which the cohesive layer stops being entrained and a new critical shear stress equal to the currently applied shear stress has been created. Therefore, predicting when a cohesive layer begins to be entrained to create a discoloured water event, lies in the ability to estimate the critical shear stress for a particular section of pipe within the water distribution system at any given time.

Two methods were developed in this study to determine the critical shear stress of entrainment using COLT of flow rate and turbidity. The two methods developed were the SNTU Method and the ANTU Method and constitute key extensions to existing work. The ANTU Method is an in-depth analysis of only those discoloured water events that had been attributed to increases in water velocity from temporal patterns in flow rate and turbidity. The ANTU Method requires the use of EPANET to determine travel time between monitoring sites. The SNTU Method is a general analysis using maximum daily flow rate and turbidity data obtained from COLT.

Both the ANTU and SNTU Methods allow a time and location dependent estimate of the critical shear stress of entrainment to be determined and increase the understanding of the way in which discoloured water is formed. Two estimates of the critical shear
stress of entrainment were examined using these methods. These two estimates were based on the daily or weekly peaks in applied shear stress measured by COLT in a section of the Wantirna WQZ transfer main (Daily Peak Estimate and Weekly Peak Estimate, respectively). The SNTU Method was considered to be the better of the two methods in predicting the critical shear stress of entrainment, as the method gave similar results to the ANTU method, all data is included in the analysis, the time to conduct the analysis is less, and no hydraulic model is required.

Both the SNTU and ANTU Methods using COLT of flow rate and turbidity, and analysis of DWCCs, suggest that the majority of discoloured water events in the system were created when a critical shear stress of entrainment was exceeded. Both the ANTU and SNTU Methods concluded that this critical shear stress is best estimated by the Daily Peak Estimate. Analysis of COLT data found that this critical shear stress of entrainment varies in time and location across the transfer main monitored.

The finding that discoloured water events also occur within a day or two of previous events suggests that significant amounts of particles are collecting in the cohesive layer within periods less than one week. As discussed in the literature review it has been proposed that the collection of particles onto a cohesive layer effectively weakens the cohesive layer surface strength, and thereby lowers the critical shear stress of entrainment. However, consolidation of a cohesive layer over time can increase the critical shear stress of entrainment. The conclusion that the best estimate of the critical shear stress of entrainment is the Daily Peak Estimate can be explained by the effective weakening of the cohesive layer surface strength within 24 hours due to particles collecting being minimal compared to the strength increase of the layer due to consolidation. This result is consistent with the laboratory work of Grainger et al. (2002) who showed significant increase in strength due to consolidation within 24 hours.

During summer months the section of the transfer main near the Wantirna Service Reservoir appears to be self-cleaning, due to the frequency and magnitude of the shear stresses imposed. The exact determination of what constitutes the self-cleaning
threshold was beyond the scope of this study. However, work conducted by Boxall and Prince (2006) on the Wantirna WQZ determined a self-cleaning threshold of 1.15 N.m\(^{-2}\).

[Particular details of this work could not be included in this thesis as the parameters used within the modified PODDS model were unable to be published due to confidentiality conditions.]

There are two ways in which this increased understanding of the way in which discoloured water is formed in water distribution systems can be used in prevention strategies. These are: (1) imbed parameters into a hydraulic model (real time or predictive) for the use in identifying areas at risk of receiving discoloured water; and (2) develop new, or alter existing, operational procedure policies to minimise or manage the likelihood of discoloured water events.

Computer simulations can be used to predict the likelihood of hydraulic conditions which give rise to the generation of discoloured water in an unfiltered water distribution system for a given operational procedure. Two aspects would need incorporation into the model: (1) the critical shear stress for each pipe segment; and (2) the self-cleaning threshold of the system. As both these elements were only calculated for the 450 mm transfer main in the Wantirna WQZ, further work should be conducted to verify the critical shear stress estimate and self-cleaning threshold more generally.

Detailed knowledge of the hydraulics of each individual pipe is required to adequately determine the critical shear stress for each pipe segment. Two simulations are required to obtain this information. The first simulation is required to determine the critical shear stress value for each pipe segment. For the system under investigation the critical shear stress of entrainment was found to be the maximum applied shear stress reached on the previous day. The hydraulic model is calibrated to the hydraulic conditions on the previous day (or the time period determined to best estimate the critical shear stress for the system being investigated). The peak shear stress reached in each pipe segment for this simulation is the estimate of the critical shear stress in that section of pipe. The number and location of flow monitoring sites needed to achieve the necessary accuracy and precision requires detailed and specific analysis.
The second simulation models the specific operational procedure to be undertaken. This simulation determines the maximum applied shear stress in each segment resulting from the specific procedure. The pipe segments in which the critical shear stress has been exceeded can then be determined by comparing results from the first simulation, which give the critical shear stress, and results from the second simulation which give the applied shear stress of a specific operational procedure. The self-cleaning threshold of the system would also need to be taken into account by identifying those pipes with consistently higher shear stresses than the self-cleaning threshold and setting their likelihood for discoloured water formation to zero. Pipes which experience velocities and associated shear stresses that are normally below the self-cleaning threshold and where the critical shear stress has been exceeded would be considered at high risk of generating discoloured water. Such a modelling approach can be used in proactive management to ‘red flag’ those sections of the water distribution system at risk of generating discoloured water from an operational procedure. Alternative scenarios can be modelled to determine the best method of conducting a procedure to minimise ‘red flag’ areas. Alternatively, certain sections of the water system may be targeted for cleaning prior to the specific operational procedure, taking into account that flushing may only have a short term effect and that the flushing must not itself cause shear stresses which exceed the critical shear stress elsewhere in the system.

This approach of using linked hydraulic model simulations is similar to the procedures used by the PODDS water quality model for unlined systems, described in Boxall et al. (2001). The PODDS model similarly uses a conditioning hydraulic model and an event model. However, in the PODDS model, the critical shear stress is a parameter requiring calibration by optimisation techniques and the self-cleaning threshold is not taken into account. The PODDS model has been used successfully to model discolouration in the Wantirna WQZ with the incorporation of a self-cleaning threshold (Boxall and Prince 2006). [It should be noted that the results of this application of the PODDS model are not reported in this thesis due to requirements of the collaborative work.]
A factor requiring consideration when using this linked hydraulic model approach is that it is virtually impossible to calibrate a model adequately for those areas furthest from the source water with few customers due to the averaged demand profiles used to model customer demand. These averaged demand profiles more accurately reflect the true demand of a number of customers, not individual or a limited number of customers. However, as each customer does not use water continuously, a risk based approach to determine the level of calibration required, whereby a trade off between the number of customers in an area and hydraulic model accuracy, could be conducted.

As the critical shear stress varies on a daily basis, the flow data needed for such modelling is beyond the capacity of most water companies at present. It is, however, becoming more common for water companies to have hydraulic models of the systems under their control, have an idea of the seasonal average hydraulic conditions in the system, and the water demands of specific operational procedures they conduct. Theoretically, this more general information could be used to gain some idea of areas under risk of generating discoloured water. However, perhaps the most effective use of COLT data at present is to optimise operating procedures to minimise discolouration.

Systems operational procedures conducted by the water company were a major trigger of discoloured water. The system operational procedures with the highest likelihood of generating discoloured water are mains cleaning by flushing, valve closures during main repairs, and changes in water supply causing higher than usual shear stresses and reverse flows. It is recommended that these procedures be reviewed to determine if they can be preformed in a manner that reduces the likelihood of the critical shear stress being exceeded. For example, this study suggests that flushing, which is accepted practice in industry in preventing discoloured water, can be a contributor to creating discoloured water events. It is recommended that further research be conducted that specifically investigates the time interval in which flushing is beneficial for reducing discoloured water occurrence for different pipe sizes and system characteristics.

Long term continuous on-line monitoring of flow rates within the water distribution system would be useful in assisting in the prevention of discoloured water events as the
measurements obtained can identify hydraulic changes in the system that may affect the
critical shear stress in the system. Examples of such changes are: (1) the reduction in the
maximum daily shear stress due to changes in water consumption from water
restrictions, such as those that have occurred in Melbourne, Australia, since the
monitoring reported in this study; and (2) the increase in maximum daily shear stress
due to the installation of a new major water consumer within a water quality zone.

Long-term strategies to prevent or minimise discoloured water should also be
investigated. Options include designing new and replacement water distribution systems
as self-cleaning water systems such as those proposed by van den Boomen et al. (2004)
and to limit the material available to be entrained by preventing particles entering water
distribution systems from upstream of the service reservoir. However, it should be noted
that even the Netherlands, with some of the highest levels of treatment in the world
cannot avoid discoloured water because inevitably some particles get through.

A range of discoloured water events that were investigated demonstrate that, although
there is a low likelihood of events caused by aspects other than increased steady state
shear stresses, their severity can be high, and therefore warrant further investigation.
Such causes of discoloured water include water hammer and direct provision of
discoloured water from upstream of the service reservoir. These causes of discoloured
water are relatively ignored by literature as a significant cause and it is recommended
that further research be conducted into these types of events.

Another issue needing investigation for other pipe sizes is the role of biofilm. Biofilm
may form a more important role in the mechanism of formation of discoloured water
events for smaller pipes. There is a greater biofilm potential component for smaller
pipes due a greater surface to water volume ratio.

6.2 Recommendations relevant to industry

Based on the results of this study the following recommendations related to industry can
be made:
1) DWCCs and water quality grab samples are not adequate for full analysis of discoloured water formation and therefore should not be used for this purpose.

2) COLT of turbidity and flow rate is an effective technique to gather information for analysis of discoloured water formation. However further work is needed to determine the optimal placement of COLT sites.

3) The size and chemistry of particles found in water distribution systems effect their behaviour in the pipe network. Particles in the system in Melbourne, Australia, form cohesive layers that are eroded to create discoloured water events. This erosion begins when a critical shear stress of entrainment is exceeded by the applied shear stresses created by flow conditions in the pipes. The shear stresses are calculated at the interface between the water and the material accumulated on the pipe wall. The critical shear stress of entrainment can be estimated using COLT of flow rate and turbidity together with the SNTU method (as outlined in Section 5.6.2 and summarised below). This critical shear stress is best estimated by the maximum applied shear stress on the previous day for the Wantirna WQZ.

4) The number of discoloured water events created by operational procedures can be lowered in the following ways.
   a. By altering the way in which high risk operational procedures are conducted. These procedures need to be altered so that the risk of exceeding the critical shear stress in any part of the system that is not self-cleaning (as defined in the previous section) is reduced.
   b. By cleaning those areas of the system that have the potential of creating discoloured water when a specific operational procedure is conducted, taking into account that the long-term effectiveness of flushing is itself questionable in this unfiltered water system and that the flushing procedure itself must not exceed the critical shear stress elsewhere in the system.
   c. More work is required to confirm the effectiveness of traditional operating procedures designed to address discoloured water, and identify modifications that could reduce their potential to cause additional discoloured water. For example, the way in which isolated flushing is
conducted is in need of investigation as flushing has been found to cause discoloured water.

5) Using data from COLT of turbidity and flow rate, a water company can utilise a hydraulic model to determine those areas likely to create discoloured water under a specific operational procedure. Two aspects would need incorporation into the model: (1) the critical shear stress for each pipe segment, (2) the self-cleaning threshold of the system.

6) Development of a computer simulation model of discoloured water severity incorporating the prediction of the critical shear stress and the self-cleaning threshold. These findings may be able to be incorporated into the Particle Suspension Model described by Wu et al. (2003) or the PODDS model described by Boxall et al. (2001) to enhance the ability of those models to identify areas at risk of generating and receiving discoloured water.

The SNTU method consists of the following steps:

Step 1: Use continuous online monitoring to measure turbidity and flow rate over a number of months.

Step 2: From the monitored data calculate the spike turbidity and applied shear stress in the main being monitored (according to Section 4.6).

Step 3: For each day of monitoring, determine the estimate of the critical shear stress. For example, in this study two estimates of the critical shear stress were tested, namely, maximum recorded applied shear stress in the preceding 24 hours, and maximum recorded applied shear stress in preceding week.

Step 4: For each day of monitoring, calculate the maximum daily spike turbidity (SNTU\textsubscript{max}) and maximum daily excess shear stress ($\tau_{\text{xs,max}}$) \[ where, \tau_{\text{xs,max}} = \tau_0 - \tau_c \] using each of the estimates of the critical shear stress ($\tau_c$).

Step 5: Correlate the maximum daily spike turbidity and the maximum daily excess shear stress for each estimate of the critical shear stress. A result where the majority of discoloured water events occur (defined as when SNTU\textsubscript{max} exceeds the spike turbidity complaint threshold described in Section 4.11.2) when $\tau_{\text{xs,max}}$ is greater than zero suggests that the best estimate of $\tau_c$ is being used.
Step 6: Conduct an investigation into individual values of SNTU\textsubscript{max} that are over the complaint threshold when \(\tau_{xs,\text{max}}\) is below zero to confirm or deny the validity of the method and the estimate of the \(\tau_c\)

### 6.3 Recommendations for further research

Further research is required on the use of hydraulic models and the estimate of the critical shear stress to predict areas within a water distribution system that cause discoloured water. For completeness this research will involve:

1. Verification of critical shear stress for different pipe sizes, materials and roughness;
2. Determination of the re-suspension mechanism (for example, time dependent erosion or instant sloughing);
3. Investigation of the importance of dynamic shear stress in different pipe sizes; and
4. Determination of the self-cleaning threshold for different pipe sizes, materials and roughness.

Items (1) and (2) could be investigated a number of ways. However, it is recommended that they initially be investigated in the field with standardised induced disturbance, such as a modified version of Re-suspension Potential Method using two turbidimeters in series with no off-takes between them. The procedure should be conducted at night when there is minimal additional water demand so that the magnitude of the excess shear stress can be controlled for more than 1 pipe turnover. Conducting the procedure at night may also eliminate the issues found by Polychronopoulos \textit{et al.} (2001) who could not produce a small enough initial disturbance in small pipes using a hydrant. The ANTU Method could then be used to verify the critical shear stress estimate.

The modified Re-suspension Potential Method described above would also allow the mechanism, and rate, of erosion of the cohesive layer to be determined. Once the erosion rate and mechanism are known a method to determine details of the severity of
the response of a water pipe in relation to the excess shear stress (defined as the applied shear stress minus the critical shear stress) may be able to be developed.

The approach in this study relied upon shear stress estimates based on steady state conditions and established a link of these conditions to discoloured water generation. However, the study also found that events that were likely to have aspects of water hammer, which causes significant dynamic shear stress, also appeared to cause discoloured water in the transfer main. It is therefore recommended that further research be conducted to determine the actual effect of the dynamic component of shear stress on discoloured water formation. The dynamic component of shear stress could be calculated from COLT data if pressure is measured every 1 second. It is suggested that COLT collection of pressure at these 1 second intervals be triggered when a certain level of pressure is exceeded, thereby reducing the electronic storage required for data logging. However, the practical aspect of collecting data at 1 second intervals may prevent this.

Assuming the data collection can occur, based on work by van der Boomen and Mazijk (2002), the dynamic component of shear stress may be of particular significance for smaller pipe sizes. The capturing of discoloured water events in small pipes by measuring a real system under ‘natural’ conditions may need a long monitoring period as the frequency of discoloured water events is unknown. Re-suspension Potential Method using two COLT sites in series measuring turbidity, flow rate and pressure would allow effective short term monitoring to be conducted. ‘Natural’ hydraulic procedures could be simulated using the discoloured water events characterised in this study.

Research into calculating the self-cleaning threshold was begun by Boxall and Prince (2006) whose study used the Sheffield University PODDS model, calibrated with COLT data from this study, to determine the self-cleaning threshold for the transfer main in the Wantirna WQZ. It is recommended that the PODDS model, calibrated with COLT data collected by the night procedure described earlier in relation to verification of the critical shear stress, could be used to determine the self-cleaning threshold for
other pipe sizes and roughness. The critical shear stress estimate method used in this study could be used in the PODDS model as the ‘conditioning’ shear stress parameter. However, the limiting factor in using the PODDS model is that it is quite data intensive and therefore widespread application may be limited.
CHAPTER 7: PAPERS PRODUCED

All papers and reports listed below were produced in the course of this thesis.

7.1 Journal papers


7.2 Conference papers

All conference papers were presented by Rachael Prince.


7.3 Technical reports


CHAPTER 8 : REFERENCES


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US EPA , R9 Laboratory SOP 507, Determination of Trace Elements by Inductively


<table>
<thead>
<tr>
<th>Symbol</th>
<th>Acronym or term</th>
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<tbody>
<tr>
<td></td>
<td>Allochthonous particles</td>
<td>Autochthonous particles are defined as those that are entrained from within the water distribution system.</td>
<td>1.2.2, 2.5.2</td>
</tr>
<tr>
<td>$\tau_0$</td>
<td>Applied shear stress</td>
<td>The shear stress at the water interface with the particles collected on the internal pipe wall created by the water flowing in the pipe.</td>
<td>1.3.2, Eq 1-1</td>
</tr>
<tr>
<td>ADWG</td>
<td>Australian Drinking Water Guidelines</td>
<td>Water quality management system used in Australia.</td>
<td>3.2</td>
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<td>ANTU</td>
<td>Autochthonous turbidity</td>
<td>Autochthonous turbidity is turbidity that has been created by particles that are derived from outside the water distribution system such as those that occur direct from source water</td>
<td>1.2.2, 5.6.1</td>
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<tr>
<td>ANTU method</td>
<td>Autochthonous turbidity method</td>
<td>Method of terming the best estimate of the critical shear stress by using autochthonous turbidity, calculated by modelling selected discoloured water events.</td>
<td>5.6.1</td>
</tr>
<tr>
<td>COLT</td>
<td>Continuous online testing</td>
<td>An in-situ water quality measurement technique where a device continuously, or very frequently, monitors the water parameters. The frequency of measurement may range from a few seconds to daily.</td>
<td>1.4.3, Ch 4</td>
</tr>
<tr>
<td>$\tau_c$</td>
<td>Critical shear stress of entrainment</td>
<td>The shear stress needed at the water interface with particles collected on the internal pipe wall for significant entrainment of particles into the bulk water phase to occur.</td>
<td>1.3.2, Eq 1-1</td>
</tr>
<tr>
<td>DWCC</td>
<td>Discoloured Water Customer Complaint</td>
<td>Complaints of discoloured potable water supply registered by a customer with a water company or utility.</td>
<td>1.4.1, Ch 2</td>
</tr>
<tr>
<td></td>
<td>Daily Peak Estimate</td>
<td>Estimate of the critical shear stress of entrainment based on the peak shear stress that has occurred in a pipe in the previous 24 hours.</td>
<td>5.5.1</td>
</tr>
<tr>
<td>$\tau_{xs}$</td>
<td>Excess shear stress</td>
<td>The amount by which the critical shear stress is exceeded by the applied shear stress at the interface between the water and the particles collected on the internal pipe wall.</td>
<td>1.3.2, Eq 1-1</td>
</tr>
<tr>
<td>SNTU</td>
<td>Spike turbidity</td>
<td>The value of measured turbidity remaining after the subtraction of background turbidity readings.</td>
<td>4.6</td>
</tr>
<tr>
<td>SNTU method</td>
<td>Spike turbidity method</td>
<td>Method of terming the best estimate of the critical shear stress by using spike turbidity values.</td>
<td>5.6.2, 6.2</td>
</tr>
<tr>
<td>V</td>
<td>velocity</td>
<td>Average velocity of water in the cross section of a pipe.</td>
<td>4.6.1</td>
</tr>
<tr>
<td>-------</td>
<td>----------</td>
<td>----------------------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>WQZ</td>
<td>Water Quality Zone</td>
<td>A water quality zone is supplied by water that would be expected to be of similar water quality (for example, from the same source) and contains up to 100,000 people (NHMRC and ARMC 1996).</td>
<td>2.2.1 2.5.5 2.6.5</td>
</tr>
<tr>
<td></td>
<td>Weekly Peak Estimate</td>
<td>Estimate of the critical shear stress of entrainment based on the peak shear stress that has occurred in a pipe in the previous week.</td>
<td>5.5.2</td>
</tr>
</tbody>
</table>
### Appendix 1: Coding system of customer complaint database

<table>
<thead>
<tr>
<th>Type</th>
<th>Code</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>DW/Brown</td>
<td>1</td>
<td>Customer Complaint of Brown Water</td>
</tr>
<tr>
<td>DW/Black</td>
<td>2</td>
<td>Customer Complaint of Black Water</td>
</tr>
<tr>
<td>DW/Yellow</td>
<td>3</td>
<td>Customer Complaint of Yellow Water</td>
</tr>
<tr>
<td>DW/White</td>
<td>4</td>
<td>Customer Complaint of White Water</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Action</th>
<th>Code</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flushed</td>
<td>1</td>
<td>Main was flushed in isolation</td>
</tr>
<tr>
<td>Investigate</td>
<td>2</td>
<td>Contractor did not report back as to action taken</td>
</tr>
<tr>
<td>Now Clear</td>
<td>3</td>
<td>Water was clear on arrival</td>
</tr>
<tr>
<td>Customer Advised</td>
<td>4</td>
<td>Customer informed of the problem and no action taken by SEWL</td>
</tr>
<tr>
<td>Block flushed</td>
<td>5</td>
<td>Area flushed, as part of a block flushing program</td>
</tr>
<tr>
<td>Repaired</td>
<td>6</td>
<td>Main was repaired. Main flushed before reinstated</td>
</tr>
<tr>
<td>Test Water/Samples taken</td>
<td>7</td>
<td>Only action taken was samples taken for testing and customer advised of results</td>
</tr>
<tr>
<td>Other</td>
<td>11</td>
<td>Other action taken such as replacement of filter</td>
</tr>
<tr>
<td>No entry</td>
<td>99</td>
<td>No action listed</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Attributed Cause</th>
<th>Code</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWI pipe</td>
<td>1</td>
<td>Galvanised wrought iron internal plumbing</td>
</tr>
<tr>
<td>Internal problem/ private extension</td>
<td>2</td>
<td>Internal plumbing problem such as copper internal pipes</td>
</tr>
<tr>
<td>Hot Water Service</td>
<td>3</td>
<td>Hot water service such as corrosion</td>
</tr>
<tr>
<td>Burst Main/ hydrant/ service</td>
<td>4</td>
<td>Includes knocked hydrant, burst fire plug</td>
</tr>
<tr>
<td>Main flushing/airscouring</td>
<td>5</td>
<td>Main is flushed or air-scoured</td>
</tr>
<tr>
<td>Works in area - SEWL</td>
<td>6</td>
<td>Specific works not specified</td>
</tr>
<tr>
<td>Works in area - other</td>
<td>7</td>
<td>I.e. Road works. Specific works not specified.</td>
</tr>
<tr>
<td>Mains shutdown/ water off</td>
<td>8</td>
<td>Water is turned off in main. Main flushed before reinstated</td>
</tr>
<tr>
<td>Change of Supply</td>
<td>9</td>
<td>Alternate supply of water used i.e. from neighbouring WQZ</td>
</tr>
<tr>
<td>Hydrant used</td>
<td>10</td>
<td>By a contractor, fire-fighter, unauthorised access</td>
</tr>
<tr>
<td>Valve shut/opened</td>
<td>11</td>
<td>A valve is shut or opened</td>
</tr>
<tr>
<td>Main Renewal</td>
<td>12</td>
<td>Main is replaced. Main flushed before reinstated</td>
</tr>
<tr>
<td>Air in main</td>
<td>13</td>
<td>Air is found to be present in the main</td>
</tr>
<tr>
<td>Other</td>
<td>14</td>
<td>Algae, possible GWI pipe but not confirmed, flushing devise needed new timer, choked meter</td>
</tr>
<tr>
<td>MW Main recharge/connection</td>
<td>15</td>
<td>Wholesaler conducting works upstream of the WQZ</td>
</tr>
<tr>
<td>Caste iron, no lining</td>
<td>16</td>
<td>Main found to be caste iron. Only present in post 2001 data</td>
</tr>
<tr>
<td>Dead end main</td>
<td>17</td>
<td>Main is a dead end. Only present in post 2001 data</td>
</tr>
<tr>
<td>No entry</td>
<td>99</td>
<td>No attributed cause listed</td>
</tr>
</tbody>
</table>

Note: Data entry of “not in our area” removed from data set.
Appendix 2: Measles plots of Discoloured Water Customer Complaints in the Wantirna WQZ
Appendix 3 : Plans of Locations of Continuous Online Testing Monitoring Sites

Figure A3-1: Schematic of the Wantirna WQZ showing the location of the six Monitoring Sites (MS)
Figure A3-2: Location of Monitoring Sites 1 and 2
Figure A3-3: Location of Monitoring Site 3
Figure A3-5: Location of Monitoring Site 5
Figure A3-6: Location of Monitoring Site 6
Appendix 4 : Test results for verification of calibration of Low Range Turbidity Meter (HACH 1720 D) using hand held turbidity meter (HACH 2100P)

<table>
<thead>
<tr>
<th>Date</th>
<th>Test</th>
<th>MS(3) 1720D</th>
<th>MS(3) 2100P</th>
<th>Diff</th>
<th>MS(4) 1720D</th>
<th>MS(4) 2100P</th>
<th>Diff</th>
<th>MS(5) 1720D</th>
<th>MS(5) 2100P</th>
<th>Diff</th>
<th>MS(6) 1720D</th>
<th>MS(6) 2100P</th>
<th>Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/03/2001</td>
<td>1</td>
<td>1.6</td>
<td>1.9</td>
<td>-0.3</td>
<td>1.7</td>
<td>1.7</td>
<td>0.0</td>
<td>*Biofilm present, samples not taken</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.6</td>
<td>1.5</td>
<td>0.0</td>
<td>1.6</td>
<td>1.5</td>
<td>0.1</td>
<td>*Biofilm present, samples not taken</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.6</td>
<td>1.4</td>
<td>0.2</td>
<td>1.7</td>
<td>1.5</td>
<td>0.2</td>
<td>*Biofilm present, samples not taken</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*Biofilm present, samples not taken</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/04/2001</td>
<td>1</td>
<td>0.0</td>
<td></td>
<td></td>
<td>1.2</td>
<td>1.3</td>
<td>-0.1</td>
<td>*Biofilm present, samples not taken</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.0</td>
<td></td>
<td></td>
<td>2.0</td>
<td>1.8</td>
<td>0.1</td>
<td>*Biofilm present, samples not taken</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.0</td>
<td></td>
<td></td>
<td>1.5</td>
<td>1.4</td>
<td>0.1</td>
<td>*Biofilm present, samples not taken</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*Biofilm present, samples not taken</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/08/2001</td>
<td>1</td>
<td>1.0</td>
<td>1.2</td>
<td>-0.1</td>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
<td>*broken lock, couldn’t get into cabinet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.2</td>
<td>1.1</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td>*broken lock, couldn’t get into cabinet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.1</td>
<td>1.0</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td>*broken lock, couldn’t get into cabinet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*broken lock, couldn’t get into cabinet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/06/2002</td>
<td>1</td>
<td>0.0</td>
<td></td>
<td></td>
<td>1.3</td>
<td>1.4</td>
<td>-0.1</td>
<td>1.4</td>
<td>1.6</td>
<td>-0.2</td>
<td>1.4</td>
<td>1.6</td>
<td>-0.2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.0</td>
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<td>1.3</td>
<td>1.4</td>
<td>0.0</td>
<td>1.4</td>
<td>1.4</td>
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<td>1.4</td>
<td>1.5</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.0</td>
<td></td>
<td></td>
<td>1.3</td>
<td>1.4</td>
<td>0.0</td>
<td>1.4</td>
<td>1.5</td>
<td>-0.1</td>
<td>1.4</td>
<td>1.5</td>
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<td>4</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix 5 : Results from verification of calibration of GLI flow meters

Flow meter checked on 1 May 2001. The expected flow rates were measured using the online turbidity meters at high flows at MS(3) and MS(5) (Figure A5-1). Flow meters at MS(4) and MS(2) could not be verified as meters were offline. MS(3) online flow meter recorded a little more flow than that which was induced by the disturbance which may have been due to demand within the system. The flow meter at MS(6) seemed to have high inaccuracies at high flows and did not record the flow rate of 17.5 l.s\(^{-1}\) at all. One reading was recorded at the online flow meters at MS(5) and MS(3) when the total induced disturbance was at 17.5 l.s\(^{-1}\), showing that these sites were recording flow rates at this level. It was concluded that the online flow meter at MS(6) was not operating correctly. The flow meter and data logger were replaced which resulted in accurate results being obtained.

It must be noted that the portable flow meter that was used to record the flow rates at Site A and B is not highly accurate (± 20 %) so that the flow rates measured at Site A and B are only an indication of actual values.
Figure A5-1: Flow meter verification results showing the flow rate of the induced disturbance at Site A, the total induced disturbance (Site A&B) and the online flow rate measurements taken at each monitoring site.
Appendix 6 : Monitoring site visitation log

No Monitoring Site Visitation Log was kept by Melbourne Water for Monitoring site 1 and 2. Table 6-1 represents events known to have occurred for Monitoring Site 2 from post event investigations.

Monitoring Site Visitation Logs for Monitoring Site 3, 4, 5, and 6 are represented by Tables 6-2 to 6-5 respectively. In addition to the information recorded, turbidimeters at Monitoring Site 3, 4, 5, and 6 were checked each fortnight by C-Tech and calibration checked with “IcePic” device on date listed as “Start Date”.
### Table A6-1: Monitoring Site 2

<table>
<thead>
<tr>
<th>Start Date</th>
<th>Finish Date</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>17/11/2000</td>
<td>19/01/2000</td>
<td>Turbidity meter installed on wrong main</td>
</tr>
<tr>
<td>20/11/2000</td>
<td>6/12/2000</td>
<td>Turbidity meter located on wrong main</td>
</tr>
<tr>
<td>4/12/2000</td>
<td>16/12/2000</td>
<td>Turbidity meter located on wrong main</td>
</tr>
<tr>
<td>18/12/2000</td>
<td>28/12/2000</td>
<td>Turbidity meter located on wrong main</td>
</tr>
<tr>
<td>29/12/2000</td>
<td>4/01/2001</td>
<td>Turbidity meter located on wrong main</td>
</tr>
<tr>
<td>15/01/2001</td>
<td>28/01/2001</td>
<td>Turbidity meter located on wrong main</td>
</tr>
<tr>
<td>29/01/2001</td>
<td>11/02/2001</td>
<td>Turbidity meter located on wrong main</td>
</tr>
<tr>
<td>12/02/2001</td>
<td>25/02/2001</td>
<td>Turbidity meter located on wrong main</td>
</tr>
<tr>
<td>26/02/2001</td>
<td>13/03/2001</td>
<td>Turbidity meter located on wrong main</td>
</tr>
<tr>
<td>14/03/2001</td>
<td>25/03/2001</td>
<td>Turbidity meter located on wrong main</td>
</tr>
<tr>
<td>26/03/2001</td>
<td>8/04/2001</td>
<td>Turbidity meter located on wrong main</td>
</tr>
<tr>
<td>9/04/2001</td>
<td>22/04/2001</td>
<td>Turbidity meter located on wrong main</td>
</tr>
<tr>
<td>23/04/2001</td>
<td>6/05/2001</td>
<td>Turbidity meter located on wrong main</td>
</tr>
<tr>
<td>7/05/2001</td>
<td>20/05/2001</td>
<td>Turbidity meter located on wrong main</td>
</tr>
<tr>
<td>21/05/2001</td>
<td>31/05/2001</td>
<td>Turbidity meter located on wrong main</td>
</tr>
<tr>
<td>2/06/2001</td>
<td>17/06/2001</td>
<td>Turbidity meter located on wrong main</td>
</tr>
<tr>
<td>18/06/2001</td>
<td>1/07/2001</td>
<td>Turbidity meter located on wrong main</td>
</tr>
<tr>
<td>2/07/2001</td>
<td>15/07/2001</td>
<td>Turbidity meter located on wrong main</td>
</tr>
<tr>
<td>17/07/2001</td>
<td>29/07/2001</td>
<td>Turbidity meter located on wrong main</td>
</tr>
<tr>
<td>30/07/2001</td>
<td>12/08/2001</td>
<td>Turbidity meter located on wrong main</td>
</tr>
<tr>
<td>13/08/2001</td>
<td>26/08/2001</td>
<td>Turbidity meter located on wrong main</td>
</tr>
<tr>
<td>26/08/2001</td>
<td>28/08/2001</td>
<td>Turbidity meter located on wrong main</td>
</tr>
<tr>
<td>28/08/2001</td>
<td>9/09/2001</td>
<td>5/9 to 12/9 - white water incident proving meter on wrong main</td>
</tr>
<tr>
<td>9/09/2001</td>
<td>17/09/2001</td>
<td>5/9 to 12/9 - white water incident proving meter on wrong main</td>
</tr>
<tr>
<td>17/09/2001</td>
<td>23/09/2001</td>
<td>22/9/01 Wantirna turbidity meter moved to right location</td>
</tr>
<tr>
<td>24/09/2001</td>
<td>7/10/2001</td>
<td></td>
</tr>
<tr>
<td>8/10/2001</td>
<td>21/10/2001</td>
<td></td>
</tr>
<tr>
<td>22/10/2001</td>
<td>4/11/2001</td>
<td></td>
</tr>
<tr>
<td>19/11/2001</td>
<td>2/12/2001</td>
<td>Chlorine Dosing began at the Wantirna Res, inflow from the Boronia Res</td>
</tr>
<tr>
<td>3/12/2001</td>
<td>16/12/2001</td>
<td></td>
</tr>
<tr>
<td>17/12/2001</td>
<td>30/12/2001</td>
<td></td>
</tr>
<tr>
<td>31/12/2001</td>
<td>13/01/2002</td>
<td></td>
</tr>
<tr>
<td>14/01/2002</td>
<td>27/01/2002</td>
<td></td>
</tr>
<tr>
<td>28/01/2002</td>
<td>10/02/2002</td>
<td></td>
</tr>
<tr>
<td>11/02/2002</td>
<td>24/02/2002</td>
<td></td>
</tr>
<tr>
<td>25/02/2002</td>
<td>10/03/2002</td>
<td></td>
</tr>
<tr>
<td>11/03/2002</td>
<td>24/03/2002</td>
<td></td>
</tr>
<tr>
<td>25/03/2002</td>
<td>7/04/2002</td>
<td></td>
</tr>
<tr>
<td>8/04/2002</td>
<td>21/04/2002</td>
<td></td>
</tr>
<tr>
<td>22/04/2002</td>
<td>5/05/2002</td>
<td></td>
</tr>
<tr>
<td>6/05/2002</td>
<td>19/05/2002</td>
<td></td>
</tr>
<tr>
<td>19/05/2002</td>
<td>3/06/2002</td>
<td></td>
</tr>
</tbody>
</table>
## Table A6-2: Monitoring Site 3

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<tr>
<th>Start Date</th>
<th>Finish Date</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>17/11/2000</td>
<td>19/01/2000</td>
<td>Logger errors 17/11/00 11:30 to 19/11 23:40, flow data only</td>
</tr>
<tr>
<td>20/11/2000</td>
<td>6/12/2000</td>
<td>Logger errors 20/11 0:00 to 20/11 12:20, flow data only</td>
</tr>
<tr>
<td>4/12/2000</td>
<td>16/12/2000</td>
<td>Flow data only</td>
</tr>
<tr>
<td>18/12/2000</td>
<td>28/12/2000</td>
<td>Flow data only</td>
</tr>
<tr>
<td>29/12/2000</td>
<td>4/01/2001</td>
<td>Logger errors in all turbidity data</td>
</tr>
<tr>
<td>15/01/2001</td>
<td>28/01/2001</td>
<td>15/1/01 0:00 - 11:40 data error due to ID logger change</td>
</tr>
<tr>
<td>29/01/2001</td>
<td>11/02/2001</td>
<td>Turbidity meter errors, flow data only</td>
</tr>
<tr>
<td>12/02/2001</td>
<td>25/02/2001</td>
<td></td>
</tr>
<tr>
<td>26/02/2001</td>
<td>13/03/2001</td>
<td></td>
</tr>
<tr>
<td>14/03/2001</td>
<td>25/03/2001</td>
<td></td>
</tr>
<tr>
<td>26/03/2001</td>
<td>8/04/2001</td>
<td>3/4 Biofilm found in turbidimeters, inflow stopping due to blocking of valves</td>
</tr>
<tr>
<td>9/04/2001</td>
<td>22/04/2001</td>
<td>Resetting valves every 2 weeks is not sustaining inflow to turbidimeter</td>
</tr>
<tr>
<td>23/04/2001</td>
<td>6/05/2001</td>
<td>Globe blown in turbidity meter 1/5/01 2:20, flow data only</td>
</tr>
<tr>
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</tr>
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<td>17/06/2001</td>
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</tr>
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<td>Globe blown in turbidity meter 1/5/01 2:20, flow data only</td>
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<td>Globe fixed 11/7/01 17:20</td>
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<td>29/07/2001</td>
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<td>13/08/2001</td>
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<tr>
<td>28/08/2001</td>
<td>9/09/2001</td>
<td>5/9 to 12/9 - white water incident</td>
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<tr>
<td>14/01/2002</td>
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</tr>
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<td>8/04/2001</td>
<td>Biofilm found in turbidimeters, inflow to turbidity meter stopping due to blocking of valves</td>
</tr>
<tr>
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<td>22/04/2001</td>
<td>Blocked valve to turbidity meter</td>
</tr>
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<td>23/04/2001</td>
<td>6/05/2001</td>
<td>Blocked valve to turbidity meter</td>
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<td>20/05/2001</td>
<td>Blocked valve to turbidity meter</td>
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<td>Blocked valve to turbidity meter</td>
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<td>17/06/2001</td>
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<td>1/07/2001</td>
<td>Blocked valve to turbidity meter</td>
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<tr>
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<td>15/07/2001</td>
<td>Blocked valve to turbidity meter</td>
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<td>29/07/2001</td>
<td>1 hour behind MS(3) and MS(5) due to day light saving time</td>
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<td>03-08-2001 dead ants cleaned from bottom of turbidimeter, inlet flow had to be reduced. 1 hour behind ms(3) and ms(5) due to day light saving time</td>
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<td>1 hour behind MS(3) and MS(5) due to day light saving time</td>
</tr>
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<td>1 hour behind MS(3) and MS(5) due to day light saving time</td>
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<td>5/9 to 12/9 - white water incident. 1 hour behind ms(3) and ms(5) due to day light savings</td>
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<td>1 hour behind MS(3) and MS(5) due to day light saving time</td>
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<td>1 hour behind MS(3) and MS(5) due to day light saving time</td>
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<tr>
<td>19/11/2001</td>
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<td>16/12/2001</td>
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</tr>
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<td>1/2/02 drainage pipe is running into pit and is repaired this day</td>
</tr>
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<td>24/02/2002</td>
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</tr>
<tr>
<td>25/02/2002</td>
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<tr>
<td>11/03/2002</td>
<td>24/03/2002</td>
<td></td>
</tr>
<tr>
<td>25/03/2002</td>
<td>7/04/2002</td>
<td>1 hour behind MS(3) and MS(5) due to day light saving time</td>
</tr>
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<td>21/04/2002</td>
<td>1 hour behind MS(3) and MS(5) due to day light saving time</td>
</tr>
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<td>1 hour behind MS(3) and MS(5) due to day light saving time</td>
</tr>
<tr>
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<td>19/05/2002</td>
<td>1 hour behind MS(3) and MS(5) due to day light saving time</td>
</tr>
<tr>
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<td>Meter off line 20/5/02 16:00, 1 hour behind MS(3) and MS(5) due to day light saving time</td>
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<td>Finish Date</td>
<td>Comments</td>
</tr>
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<td>--------------------------------------------------------------------------</td>
</tr>
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</tr>
<tr>
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<td>Flow meter only</td>
</tr>
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<td>4/12/2000</td>
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<td>29/01/2001</td>
<td>11/02/2001</td>
<td>Flow meter only</td>
</tr>
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<td>25/02/2001</td>
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<td>26/02/2001</td>
<td>13/03/2001</td>
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<td>26/03/2001</td>
<td>8/04/2001</td>
<td>3/4 Biofilm found in turbidimeters, inflow stopping due to blocking of valves</td>
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<td>Resetting valves every 2 weeks is not correcting inflow problem to turbidimeter</td>
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<td>Sample water turned off to turbidity meter due to drainage problem</td>
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<td>20/05/2001</td>
<td>Sample water turned off to turbidity meter due to drainage problem</td>
</tr>
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<td>21/05/2001</td>
<td>31/05/2001</td>
<td>Sample water turned off to turbidity meter due to drainage problem</td>
</tr>
<tr>
<td>2/06/2001</td>
<td>17/06/2001</td>
<td>Sample water turned off to turbidity meter due to drainage problem</td>
</tr>
<tr>
<td>18/06/2001</td>
<td>1/07/2001</td>
<td>20/6/01 sample water turned back on</td>
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<td>29/07/2001</td>
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<td>28/08/2001</td>
<td></td>
</tr>
<tr>
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<td>9/09/2001</td>
<td>5/9 to 12/9 - white water incident</td>
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<td>8/10/2001</td>
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<td>16/12/2001</td>
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<td>30/12/2001</td>
<td>Download procedure error, data lost</td>
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<td>25/02/2001</td>
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<td>Suspect data logger</td>
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<td>Suspect data logger</td>
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<td>26/03/2001</td>
<td>8/04/2001</td>
<td>Suspect data logger, 3/4 biofilm found in turbidimeters, inflow stopping due to blocking of valves</td>
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<td>9/04/2001</td>
<td>22/04/2001</td>
<td>Flow results change 17/4 but still look wrong, possible polarity problem</td>
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<td>6/05/2001</td>
<td>Error in data 23/4 11:30 to 1/5 15:50, flow check 1/5/01</td>
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<td>7/05/2001</td>
<td>20/05/2001</td>
<td>No data recorded 9/5 12:00 to 10/5 11:50</td>
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<td>21/05/2001</td>
<td>31/05/2001</td>
<td>Turbidity meter error 22/5 13:10 to 2/6 23:50, zero reading, globe blown</td>
</tr>
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<td>2/06/2001</td>
<td>17/06/2001</td>
<td>Turbidity meter globe blown</td>
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<td>20/06/2001</td>
<td>2/07/2001</td>
<td>Data logger changed to hob data logger</td>
</tr>
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<td>2/07/2001</td>
<td>16/07/2001</td>
<td>MS(6) seems to be 2 hours behind MS(5), time on data logger altered</td>
</tr>
<tr>
<td>16/07/2001</td>
<td>31/07/2001</td>
<td>MS(6) 1 hour behind MS(3) and MS(5), in accordance with day light saving time</td>
</tr>
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<td>31/07/2001</td>
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<td>3/8/01 turbidimeter checked, cleaned and inflow corrected. Down load error resulting in data missing</td>
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<td>13/08/2001</td>
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<td>MS(6) 1 hour behind MS(3) and MS(5)</td>
</tr>
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<td>9/09/2001</td>
<td>5/9 to 12/9 - white water incident. MS(6) 1 hour behind MS(3) and MS(5)</td>
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<td>24/09/2001</td>
<td>5/9 to 12/9 - white water incident. MS(6) 1 hour behind MS(3) and MS(5)</td>
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Appendix 7: Selection of raw data from Continuous Online Testing of turbidity and flow rate

Figure A7-1: Monitoring Sites 1 and 2 raw data
Figure A7-2: Monitoring Site 3 raw data
Figure A7-3: Monitoring Site 4 raw data
Figure A7-4: Monitoring Site 5 raw data
Figure A7-5: Monitoring Site 6 raw data
Appendix 8 : Diurnal profiles of major turbidity events

Major turbidity event 26/2/01

- Turbidimeters cleaned and calibrated on this day.
- No operational procedures recorded on this day.
- No DWCC recorded on this day.
- Not a discoloured water event; assumed to be due to the turbidimeter being cleaned/maintained.
Major turbidity event 1/3/01

- Monitoring site not visited on this day
- No operational procedures near spike
- Brown water complaint between MS(4) and MS(5) on 2/3/01, dead end
- Brown water complaint between MS(5) and MS(6) on 4/3/01, dead end
- Discoloured water event in the pipe system; not velocity related.
Major turbidity event 14/3/01

- Turbidimeters cleaned and calibrated on this day.
- Hydrant use collecting turbidity samples between MS(4) and MS(5).
- No increase in velocity at time of turbidity event
- No DWCC within three days.
- Disregard event; may be due to meter being cleaned/maintained.
Major turbidity event 28/3/01

- Turbidimeters not cleaned/maintained on this day.
- Valves to turbidimeter were stopping regularly at this time.
- No information from MS(2) to determine if this event came through service reservoir.
- No DWCC recorded within three days after the event.
- **Discoloured water event in the pipe system; no known cause.**
Major turbidity event 3/4/01

- Monitoring site was visited this day. Algae were found in turbidimeter and flow to turbidimeter had stopped due to a valve blockage.
- No operational procedure was recorded on this day in this area.
- A Brown DWCC was recorded in a court (suspect dead end) on the 5/4/01 between MS(5) and MS(6)
- Disregard event; assumed to be due to problems with turbidity meter.
Major turbidity event 11/4/01

- Turbidimeters not cleaned/maintained on this day
- Inlet valves to turbidimeters blocked, resetting valves every two weeks is not correcting problem.
- No operational procedures this day
- One brown DWCC recorded between MS(5) and MS(6), main was flushed.
- **Discoloured water event in system; not flow related.**
Major turbidity event 24/4/01

- Turbidimeters not cleaned/maintained on this day.
- Only one monitoring site in operation.
- Mains burst between MS(4) and MS(5).
- Brown DWCC in a court (suspected dead end) on 24/4/01 between MS(5) and MS(6).
- **Discoloured water event within the system; caused by high flow event.**
**Major turbidity event 28/6/01**

<table>
<thead>
<tr>
<th>Time</th>
<th>Water Velocity (m.s⁻¹)</th>
<th>Spike Turbidity (NTU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21:00</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>0:00</td>
<td>0</td>
<td>0.2</td>
</tr>
<tr>
<td>3:00</td>
<td>0.0</td>
<td>0.4</td>
</tr>
<tr>
<td>6:00</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>9:00</td>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>12:00</td>
<td>0.6</td>
<td>1.0</td>
</tr>
<tr>
<td>15:00</td>
<td>0.8</td>
<td>1.2</td>
</tr>
<tr>
<td>18:00</td>
<td>1.0</td>
<td>1.4</td>
</tr>
<tr>
<td>21:00</td>
<td>1.2</td>
<td>1.6</td>
</tr>
<tr>
<td>0:00</td>
<td>1.4</td>
<td>1.8</td>
</tr>
<tr>
<td>3:00</td>
<td>1.6</td>
<td>2.0</td>
</tr>
</tbody>
</table>

- Turbidimeters not cleaned/maintained on this day.
- Event only occurred at MS(6). No data available for MS(1) through MS(4).
- Flushing was conducted below MS(6) resulting in high velocities recorded at MS(6).
- No DWCC were recorded in the three days after the event.
- **Discoloured water event in system due to high flow event.**
Major turbidity event 4/7/01

- Turbidimeters not cleaned/maintained on this day.
- Spike turbidity recorded at more than one monitoring site.
- Routine flushing between MS(4) and MS(5) but this is in a different location and time based on velocity and turbidity profile.
- No DWCC recorded within three days of event.
- **Discoloured water event in system due to high flows from unrecorded event below MS(6).**
Major turbidity event 18/7/01

- Turbidimeters not cleaned/maintained on this day.
- Spike turbidity recorded at MS(5) and MS(6). No data available from MS(2,4)
- Event at 5:00am occurs at time of scheduled flush below MS(6).
- No recorded operations coincide with the velocity event at 1:50 PM.
- No DWCC recorded in the three days after the event.
- **Discoloured water events in the system due to high velocities.**
Major turbidity event 20/7/01

- Turbidimeters not cleaned/maintained on this day.
- Spike turbidity recorded at 2 sites (MS(6) and just visible at MS(5)).
- No operational procedure recorded on this day.
- No DWCC recorded within three days of this event.
- Discoloured water event in the system; assumed to be due to increases in velocity as there is an increase velocity at MS(5) at time of turbidity event.

Flow event occurred as a result of an event between MS(5) and MS(6) or an event below MS(6) but below detection level of flow meter (0.06m/s).
Major turbidity event 22/7/01

- Turbidimeters not cleaned/maintained on this day.
- Flow event can be seen at MS(3,5,6). Turbidity Event only occurred at MS(6).
- Hydrant use in reticulation system downstream of MS(6) and hydrant left leaking at 15:00. Hydrant flushed at 15:30.
- No DWCC recorded within three days after event.
- **Discoloured water event in system; caused by an increase in water velocity.**
Major turbidity event 23/7/01

- Turbidimeters not cleaned/maintained on this day.
- Turbidity event recorded at only at one monitoring site (MS(6)).
- No operational procedure recorded in area and time of event.
- Small increase in velocity was recorded at MS(5) but not of MS(6) at time of event.
- No DWCC within three days of event.
- Discoloured water event in system; cause unknown.
Major turbidity event 25/7/01

- Turbidimeters not cleaned/maintained on this day.
- Increase in velocity was recorded at MS(3) to MS(6).
- Increase in turbidity recorded MS(5) and MS(6).
- Hydrant cover found 26/7/01 near MS(6); suspect unrecorded hydrant use on the 25/7/01.
- No DWCC within three days of event.
- **Discoloured water event in the system; due to increased water velocity.**
- Turbidimeters were cleaned and calibrated on this day.
- Turbidity spike only occurs at one monitoring site.
- No operational procedures recorded on this day.
- No DWCC within three days after event.
- Major turbidity event due to interference with the meter.
Major turbidity event 23/8/01 to 24/8/01

- Turbidimeters not cleaned/maintained on this day.
- Increase in velocity occurs at MS(3) through MS(5) at time of increase in turbidity, with turbidity event arriving at MS(6) later.
- Burst hydrant between MS(5) and MS(6) at 21:00 hours and repair between 22:00 and 0:00 hours.
- Brown DWCC on 23/8/01 between MS(4) and MS(5).
- Discoloured water event in system caused by high velocity due to hydrant burst.
- Turbidimeters not cleaned/maintained on this day.
- Increase in spike turbidity recorded at two monitoring sites.
- No DWCC at this time, major event on same day that resulted in DWCC in next three days (See 7/9/01 B).
- Discoloured water event in system that came through the Wantirna Service Reservoir.
Major turbidity event 7/9/01

- Turbidimeters not cleaned/maintained on this day.
- Mains repair on Melbourne Water asset above the Wantirna Service Reservoir resulting in saturated air entering the Wantirna WQZ.
- 1 white water complaint between MS(2) and MS(3) on the 7/9/01. 36 white water complaints between MS(2) and MS(3) on 8/9/01. 1 brown water complaint between MS(5) and MS(6) on the 9/9/01.
- Discoloured water event caused by a mains repair to a Melbourne Water asset.
Major turbidity event 21/9/01

- Turbidity meters not cleaned/maintained on this day.
- Turbidity event only occurred at MS(1).
- Operational procedure (mains flush for localised discoloured water) recorded between MS(2) and MS(3) at 12:00 to 13:00 hours unlikely to have caused spike at MS(1). Unfortunately no data from MS(2) to know if this spike entered the water distribution system. No DWCC recorded in the three days after this event
- Assumed to be not a discoloured water event or did not have an effect of the water distribution system.
Major turbidity event 24-09-01, 26-09-01, 27-09-01

24-9-01

See text on following page.
26-9-01 to 27-9-01

- Turbidity meter at MS(2) infested with ants and relocated on 21-09-01.
- Major turbidity event only occurred at one site.
- No operational procedures at time and location of event.
- One DWCC of brown water occurred between MS(5) and MS(6) on 25-09-01.
- Assumed to be due to ants and not discoloured water event.
- Turbidimeter not cleaned/maintained on this day.
- Turbidity event occurred at more than one site [MS(1) and MS(2)].
- No operational procedures recorded at the time of the turbidity event.
- No DWCC at this time.
- **Discoloured water event entering through the Wantirna Service Reservoir, however, event did not reach MS(3)**
- Turbidimeter not cleaned/maintained on this day.
- Major turbidity event recorded at more than one site, namely, MS(1) and MS(2).
- No operational procedures recorded at this time.
- No DWCC within three days of event.
- Discoloured water event entering through the Wantirna Service Reservoir, however, event did not reach MS(3).
Major turbidity event 8/12/01

- MS(2) infested with ants around this time.
- Event occurred only at one site MS(2).
- No operational procedures at this time.
- No DWCC within three days.
- Therefore, not a discoloured water event and due to infestation of ants.
- Turbidimeters not cleaned/maintained on this day.
- Increases in turbidity recorded at more than one site [MS(2), MS(3), and MS(5)].
- No operational procedures recorded at the time of the turbidity increases.
- No DWCC within three days.
- Discoloured water event that entered the system through the Wantirna Service Reservoir.
Major turbidity event 30-01-02

- Faulty drainage pipe for turbidimeter at MS(4).
- Turbidity event occurred at only MS(4).
- Flushing procedure conducted between MS(5) and MS(6) between 9:15 hours and 9:45 hours due to a DWCC of brown water. However no increase in velocity recorded from the flushing.
- Assumed not to be a discoloured water event and due to faulty drainage from the turbidimeter.
Major turbidity event 19-02-02

- Turbidimeters not cleaned/maintained on this day.
- Event occurred at more than one site.
- No operational procedures recorded at this time, however, although water velocity profile is a standard shape, the peak velocity is higher than the previous week.
- No DWCC within three days of event,
- Discoloured water event due to typical residential water demand higher than in previous days.
- Turbidimeters not cleaned/maintained on this day.
- Increase in water velocity recorded at all sites.
- Increase in turbidity recorded at one site.
- Country Fire Authority (CFA) attended a motor vehicle accident at 12:50 and used a hydrant to wash down the road (Richards, 2003).
- No DWCC recorded within three days of the event.
- Discoloured water event; flow related, attributed to hydrant use by CFA.
Major turbidity event 3/10/01

- Turbidimeters not cleaned/maintained on this day.
- Increases in water velocity recorded at all sites, increase in turbidity recorded at one site.
- Routine flushing and valve fixed below MS(6).
- Many complaints of no water, but no DWCC complaints.
- Discoloured water event, attributed to high water velocity caused by flushing of mains.
Major turbidity event 15/11/01

- Turbidimeters not cleaned/maintained on this day.
- Increase in turbidity occurred at more than one site.
- No operational procedures recorded at time of event.
- No DWCC recorded within three days of event.
- **Discoloured water event attributed to increase in water velocity caused by morning peak.**
Major turbidity event 20/11/01

- Turbidimeters not cleaned/maintained on this day.
- Increase in turbidity recorded at more than one site.
- Mains repair from 11:00 to 16:00 in reticulation system supplied by off-takes between MS(4) and MS(5). Also, the Wantirna WQZ was supplied partially from Boronia WQZ between MS(2) and MS(3) and chlorine boosting put on the Wantirna WQZ. No DWCC reported in three days after the event.
- Two discoloured water events; first event attributed to a mains repair, second event attributed to change of supply between MS(2) and MS(3).
Major turbidity event 24/11/01

- Turbidimeters not cleaned/maintained on this day.
- Increase in turbidity occurs at more than one site.
- The Wantirna WQZ supplied Boronia WQZ resulting in reverse flows in some mains.
- No DWCC within three days of event.
- Discoloured water event attributed to change in supply causing an event that travelled down the system.
- All sites visited and turbidimeters cleaned on this day.
- Increases in turbidity at MS(3), MS(4) and MS(5), not in a pattern that suggests an event that has travelled down the transfer main.
- Service main renewed in reticulation system between MS(4) and MS(5) at 8:00 to 13:30 hours. This should not effect meters MS(3) and MS(4).
- No DWCC within three days.
- Not a discoloured water event, due to interference with the turbidimeters.
- Turbidimeters not cleaned/maintained on this day.
- Increase in water velocity is recorded at all sites, increase in turbidity is recorded at only MS(6).
- Turbidimeters at MS(3) and MS(5) offline.
- Flushing recorded to have occurred in the reticulation system below MS(6) to reduce coliform counts and increase chlorine residual.
- No DWCC within three days of event.
- **Discoloured water event attributed to high water velocity from flushing procedure.**
Major turbidity event 5/1/02

- Turbidimeters not cleaned/maintained on this day.
- Mains repair recorded because of burst in the reticulation system between MS(5) and MS(6) between 4/1/02 22:30 and 5/1/02 3:00.
- Increase in turbidity recorded at MS(6) starting when mains repair was completed.
- No DWCC within three days of event.
- Discoloured water event attributed to a valve closure as part of a mains repair which may have caused water hammer.
- Turbidimeters not cleaned/maintained on this day.
- Increase in turbidity occurred at more than one site at time of afternoon peak in water velocity.
- No operational procedures recorded at time and location of event.
- No DWCC within three days of spike.
- Discoloured water event attributed to high water demand at MS(2) to MS(5) with the event being transported to MS(6).
Major turbidity event 19/2/02

- Turbidimeters not cleaned/maintained on this day.
- Increase in turbidity recorded at more than one site.
- No operational procedure recorded for time and location of event.
- No DWCC within three days of event.
- Discoloured water event attributed to high flows from high normal demand.
- MS(6) visited on this day therefore potential that meter was cleaned/maintained.
- Increase in turbidity recorded at twice at MS(6) and MS(3).
- Routine mains flushing occurred in a dead end main in the reticulation system supplied by off-takes between MS(4) and MS(5) at 9:00 hours.
- No DWCC within three days of spike.
- Turbidity event at 9:00 hours is attributed to routine flushing, major turbidity event at 13:30 hours attributed to interference with the turbidimeter at MS(6).
Major turbidity event 28/2/02

- Turbidimeters not cleaned/maintained on this day.
- Increase in turbidity recorded at MS(4) and MS(5).
- No operational procedures recorded at this time or location.
- No DWCC reported within three days.
- Discoloured water event created in the water distribution system but not attributed to increases in water velocity.
- Turbidimeters not cleaned/maintained on this day.
- Increase in turbidity and velocity recorded at MS(3) to MS(6).
- Mains burst reported at 15:20 hours in the reticulation system below MS(6) followed by a mains repair at 17:40 hours. The water was turned off and ended with a mains flush at 19:10 hours.
- No DWCC within three days of event.
- **Discoloured water event attributed to increase in water velocity from a burst main.**
- Turbidimeters not cleaned/maintained on this day.
- Flush to collect samples in the reticulation system between MS(5) and MS(6) occurred at 12:00 - 14:04 hours. Flush as part of a mains repair occurred in the reticulation system between MS(3) and MS(4) at 12:48 - 16:18 hours (water was turned off at 13:12 hours and on again at 14:32 hours). Main was repaired in reticulation system between MS(5) and MS(6) at 8:51 – 13:20 hours.
- No DWCC recorded within three days of event.
- **Discoloured water event recorded at MS(6) caused by flushing.** Discoloured water event at MS(3), MS(4) and MS(5) caused by water hammer in main when water was turned off to repair a hydrant.
- Turbidimeters not cleaned/maintained on this day.
- Increase in turbidity recorded at more than one site.
- Country Fire Authority brigade attended a sprinkler malfunction at a protected premises in the reticulation system below MS(6) at 18:17 hours.
- No DWCC recorded within three days of event.
- Discoloured water event due to high velocities in mains, attributed to sprinkler malfunction.
- MS(3) to MS(6) cleaned and data downloaded on this day.
- Increase in turbidity recorded at MS(3), MS(5) and MS(6). Increase in velocity recorded at MS(6) at time of turbidity event.
- No operational procedures recorded at this time.
- No DWCC recorded within three days of this event.
- Discoloured water event at MS(6) at 9:00 hours due to velocity increase.
- Major turbidity event at other sites at about 12:00 hours attributed to interference with the turbidimeters.
- Turbidimeters not cleaned/maintained on this day.
- Increase in turbidity recorded at MS(3), only one data point.
- MS(1) and MS(2) off line so can not verify if event entered through the service reservoir.
- No operational procedure at time and location of spike.
- No DWCC recorded within three days of event.
- Not a discoloured water event; no known cause.
- MS(3) to MS(6) were visited for routine cleaning, data download and calibration.
- Increase in turbidity at MS(4).
- No operational procedures at time or location of spike.
- No DWCC recorded within three days of event.
- Not a discoloured water event, attributed to cleaning/maintenance of turbidimeter.