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Particles in Water Distribution Systems
Particles in Water Distribution Systems

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Research Report 33
PARTICLES IN WATER DISTRIBUTION SYSTEMS

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Particles in Water Distribution System: Characterisation of particulate matter in drinking water supply systems

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FOREWORD

Title: Particles in Water Distribution Systems: Characterisation of Particulate Matter in Drinking Water Supplies

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CRC for Water Quality and Treatment Project No. 1.0.0.4.3.6 – Particles in the Water Distribution System
EXECUTIVE SUMMARY

Background and Relevance

One of the key performance and compliance indicators for the water industry is customer complaints about discoloured or “dirty water”. Such discoloration is frequently caused by particulates from the reticulation system appearing at the customer tap. In Australia, little is understood of the origins of such material, yet it may cause between 60 and 80% of water quality related customer complaints.

How these particles behave in distribution systems was not adequately understood. The aim of Research Project 1.0.2.4.3.6 “Particles in the Distribution System” was to determine the origins and characteristics of particulate material within a reticulated water system that generated dirty water complaints.

Research Approach

Particles from the distribution systems of six water utilities around Australia were collected and characterised to determine the key components. This investigation confirmed the similarities in physical and chemical properties of particles from different distribution systems. The results of this research are given in Part 1 of this report.

Particle movement was studied using two laboratory pipe test loops of ductile iron lined with PVC and concrete respectively. The movement of particles from each water utility was observed under different flow conditions to develop equations that would describe their movement. The equations developed from the pipe test loop were incorporated into a computer simulation that could predict particle movement within a reticulated water supply network. This research is detailed in Part 2.

Outcomes

The similarities between the particles sourced from different distribution systems around Australia confirmed the usefulness of a modelling approach. The characterisation work also indicated that most particles appeared to originate from the source water, upstream of treatment. The chemical properties of the particles differed between utilities and this difference may present a challenge for particle modelling if it proves significant in affecting particle settling and movement.

The laboratory test loops investigated the movement of particles in water tested from different water utilities and observed consistency in several factors affecting particle movement. These factors included the velocity required to start moving particles into suspension, the velocity for all particles to move into the water phase, and the effect of constant velocity in allowing particles to adhere to the pipe wall.

Research Design

This report summarises the outcomes of field monitoring to characterise particles within the distribution and reticulation systems of the seven water utilities involved in the study: Brisbane City Council, Melbourne Water, Sydney Water, South East Water, United Water, Water Corporation, and Yarra Valley Water. Investigations were to determine:

- Where do particles in the distribution system originate?
- Was the material observed in the water supply similar for each water utility?
- Was there any consistency in differences observed between water supply systems?
- Could these differences be used to assist in understanding particle behaviour in each system?

In addressing these questions an initial sampling program was devised for each utility. This consisted of obtaining samples from five locations in a clearly defined water quality supply zone with a single source of supply. The sites were located:

1) Immediately downstream of treatment;
2) Immediately downstream of a water storage tank supplying the zone of interest;
3) In a large (>100 mm) diameter pipe further into the zone;
4) On a 100 mm diameter through main within the zone; and
5) On a 100 mm diameter or smaller dead-end main at the end of the system.

Parameters analysed for each site included:
• General field parameters of turbidity, suspended solids, pH and chlorine, to assist in differentiating each distribution system.

• Particle size distribution – to determine the range of particle sizes encountered and the general applicability of the computer simulation developed by CSIRO (the PSM) as part of this project.

• Mass of particulate material as total and volatile suspended solids.

• Elemental composition of particulate and dissolved material to assist in evaluating the likely origins and possible changes in particles with distance into the water supply system. These included:
  - Iron (Fe) – possible corrosion products, soil inputs or treatment chemicals
  - Aluminium (Al) – clay or water treatment inputs
  - Silica (Si) – clay or soil inputs and possible corrosion of cement lining of pipes
  - Manganese (Mn) – to investigate possible precipitation of this element within the water supply systems
  - Organic carbon – assessing biofilm growth and carbon inputs including treatment polymers

The results of this analysis can be summarised as follows:

Field Parameters
Field parameters differed between utilities. Two consistent but not surprising trends emerged:

• pH became elevated towards the ends of each system, but there was no association between pH and the number or mass of particulates released, turbidity or chlorine concentration; and

• Chlorine concentrations declined with distance into each system, with total chlorine declining at a slower rate in chloraminated systems, relative to chlorinated systems.

It has been suggested by a number of authors that chlorine may oxidise suspended solids, affecting the mass of sediment or turbidity found in the system. No such correlation was observed in this investigation.

There was no observed correlation between suspended solids (TSS) and turbidity, with the exception of Sydney Water for samples taken between April and November 2003. The amount of TSS and turbidity generally increased with distance into water supply system and decreased as source water quality and the level of water treatment increased.

Solids accumulation
Analysis of TSS in the water column of each utility confirmed the mass of particles to be consistent with treatment type. Unfiltered systems had greatest mass of solids, whereas those with filtration had a lower mass, with the observed mass decreasing based on source water and level of treatment. Accumulation of material as sediment found in mains was not in proportion to the amount of material found in the water column, with similar concentrations of material found after 30 seconds flushing of water from a hydrant at 10L/s, from South East Water, Yarra Valley Water and United Water, less from Brisbane City Council and lowest amounts from Sydney Water and Water Corporation (note the absence of flushing by Water Corporation because of water restrictions is likely to have contributed to this result). There was up to a 10-fold difference in the amount of sediment accumulated at high and low concentration sites. The proportion of sediment after settling relative to the mass in the water column was much greater at sites in Brisbane and Adelaide compared to other locations, possibly because of denser material settling out of solution or formation of manganese slimes on the pipe wall (primarily observed in CSIRO pipe loop tests involving the Adelaide system).

There was a trend in the percentage TVSS as TSS at Sites 4 and 5 relative to Sites 1-3, which was different for each utility. The majority of utilities had less TVSS with distance into the water supply system (Brisbane City Council, South East Water, Sydney Water, Yarra Valley Water) – implying degradation of organic material possibly through biological activity, one utility showed no change in TVSS with distance (Water Corporation) possibly indicating minimal biological activity in the distribution system, and one utility showed an increase in TVSS (United Water), which may indicate that the material entering the water supply system may be of a more complex organic material than...
observed in other systems, and result from degradation of this more complex organic material. Differences in TSS and TVSS for each system indicated that the material was most likely derived from treatment or upstream of the treatment plant.

**Organic Content**

Carbon was almost exclusively found in dissolved form for all water utilities, with only very small amounts of particulate carbon present.

Variations in both DOC and TOC were concluded to be unrelated to the distance into the water distribution system. However when high inlet dissolved organic carbon concentrations were observed, there were often higher concentrations further into the water supply system, suggestive of material from the water treatment plant entering the system and passing through to upstream sites. All sites were sampled on the same day, so only short-term effects could be observed.

There was a significant monthly variation of DOC in source water, upstream of Site 1, in all cities, except for Sydney, which had consistently low organic carbon concentrations that did not vary significantly over time. April and May, and in some cases June and July were found to be the dominant months for high average organic carbon concentrations in almost all other cities. The reason for this was suspected to be from increased infiltration of detritus e.g. dead leaves, into the catchments during this time of year. In many cases organic carbon also increased around September. These seasonal differences increased the organic carbon concentration significantly. Consistently low organic carbon concentrations were observed during late spring and summer. Thus possible impacts from organic carbon were concluded to vary from season to season for all systems with the exception of Sydney.

**Variation of Particle Sizes**

There was no association between particle size distributions and the concentration of TSS obtained in any sample. On average, the modal size of particles decreased with distance from the treatment plant, and there appeared to be some consistency in modal sizes towards end of system. Most of the time the size of particles and sediment at Sites 4 and 5 were found between 5 and 20 microns, with some exceptions. There was often a second local mode or saddle point occurring on the particle size distribution, for Sites 4 and 5 and resuspended particles at these locations. This second mode occurred at variable particle sizes, averaging at around $37 \mu m$, for all water utilities. These features were independent of treatment process, treatment chemicals and source water.

Sediment particle sizes were similar, if not slightly smaller, than the bulk water particle sizes for Sites 4 and 5 for most water quality zones. This suggested that particles do not strongly clump together when they attach to the walls of the reticulation system or when they settle to the bottom of the reticulation mains. Some form of action (mechanical, chemical and/or microbiological) must have occurred to reduce particle size, as particles were carried through the system from Site 1 to Site 5. The differences in particle characteristics observed in this study would suggest that the fundamental particle sizes and their chemical nature are likely to be similar and that similar processes act in each water supply system to produce particles of similar sizes.

Chemically treated, filtered and chlorinated water from all sources, catchment, riverine and ground water possessed particles equally as large as those of water in Melbourne which is not filtered and is subjected only to pH correction and chlorination. There was seasonal variation in particle sizes, for all utilities, however the pattern was slightly different for each. In many cases particles appeared to be flushed into or formed within the reticulation systems around winter/spring, and summer. It was hypothesized that these occurrences may match times of heavy rains or the occurrence of high demands on the supply system.

There was no observed correlation between TOC or DOC and TVSS. Note that this is not unexpected for two reasons: most of the carbon was in the dissolved phase; and the concentration of TVSS was at least an order of magnitude lower than for organic carbon. The low concentration of TVSS relative to dissolved organic carbon meant that the background variation in DOC measurements did not allow sufficient resolution of changes in particulate carbon to determine any correlation with TVSS. However, values for particulate carbon were such that it could account for virtually all TVSS in many samples.
Elemental Concentrations
In looking at the elemental composition of material from each water utility the following was observed:

**Water column**
- There was little difference in the concentration of each element in the water phase through the water supply system on each sampling occasion, with two notable exceptions which appeared to be related to possible inputs of corrosion product – iron.
- Si was the predominant element at all sites. Its origin was uncertain because it could be derived from either corrosion of cement from lined assets or from the catchment upstream of treatment because it is a major soil component. There was remarkable similarity in the Si concentration in water from Sydney, Melbourne and Adelaide, and much higher content from Perth – where the water table sits in a sandy aquifer, and much lower in Brisbane. Suggesting the origin of this material is likely to be upstream of treatment.
- Despite alum being used as flocculant in the systems from Adelaide, Brisbane and Perth, ferric as a flocculant in Sydney, and no flocculant being used in Melbourne, there was no clustering of data between water quality zones that use flocculant and those that do not, nor any association between the type of flocculant and material in the downstream water quality zones. It appears that the water source and perhaps the presence of clay particles had a greater influence on the dissolved elemental concentration, than the impact of flocculants used in treatment.

**Sediment**
- The order of decreasing elemental concentration was different to that found in the water entering each water quality zone, with Fe being the predominant element, followed by Al and Si (no significant difference) and then Mn. The low abundance of Mn was consistent with low concentrations entering each system. The Brisbane Bracken Ridge and Sydney Bringelly zones differ from all other zones in that the Mn concentration was more significant, appearing as the second most abundant element in dissolved form. The high concentrations of Fe and Al relative to Si would most likely be because over 50% of Si was in the dissolved form and hence unlikely to settle.
- It was clear that the particulate composition of the Brisbane Bracken Ridge and Sydney Bringelly zones was different to the other water quality zones. The difference appears to be the absence of Si and Al. This suggests that clay particles may not play a part in the formation of particles in these zones. The Sydney Bringelly zone had Si present, but little Al in the dissolved fraction. The Brisbane, Bracken Ridge zone had Al present but little Si.

Chemical analysis indicated that on the majority of sampling occasions the material found in the water main most likely originated upstream of treatment. Further samples of material from the catchments and treatment plants should be undertaken to confirm this.

**Elemental Ratios**
Mass ratios for Si:Al and Fe:Mn were calculated for water and sediments found in the reticulation system of each water utility to provide an indication of the origins of the material detected. The range for these ratios was consistent between cities. However, it was notable that very low concentrations of particulate Si were observed in the Sydney samples, which were at or below the limits of detection.

There appeared to be possible corrosion issues at one or two sites (sampled only once during this investigation), which were represented by unusually elevated Fe/Mn ratio’s, in the solid form. This was evident for the Wantirna (Melbourne) and Bringelly (Sydney) zones, where a peak in Fe/Mn ratio was clearly observed in January and July respectively.

It was notable that the soluble Si:Al ratio was high for Sydney, while the particulate reactive component for Sydney was comparatively the lowest of the cities. This was consistent with the much of the Si from the Sydney supply being in a colloidal form, which was different from the experience of other water utilities.

There was no common association between Fe/Mn or Si/Al between the different water utilities. Also, there was no relationship between elements in the two ratios at any site in the dissolved form. Sites from the same water source showed differing correlations for particulate elemental ratios, indicating
either that observed correlations were due to material from within the individual pipe network or that the correlations do not indicate significant cause and effect, most likely the latter.

**Application of particle characterisation information to particle movement**

The information derived from Part 1 of this study was compared to data gathered from laboratory investigations of particle movement, undertaken by the CSIRO as a separate component of this project, to determine the widespread applicability of the particle movement theory and the associated particle sediment model (PSM). It was intended to indicate whether significant differences in the nature of particulate material existed between the water supply systems involved in the study and to assist in explaining differences in particle behaviour observed in the pipe test loop developed by CSIRO. This part of the project is considered in Part 2.

![Figure 1 Cross-section of a pipe illustrating the elements of the PSM.](image)

CSIRO investigations indicated that particles from each water utility behaved in a similar manner with respect to the velocity at which particles start to move due to the bulk water flow and the velocity at which all particles are resuspended into the bulk water. The similarities in particle movement reflect the similarities observed in particle composition, and indicate that the differences observed between utilities did not significantly affect particle behaviour, despite the material observed in the pipe test loop being from water storage tanks or hydrant flushing from within the reticulation system.

Therefore the models and theory developed by the laboratory investigations of particle movement should be applicable to all water quality zones from utilities that participated in the study, and are likely to be applicable to the majority of water utilities in Australia with respect to settling due to gravity. However, this may not be the case for particle adhesion to the pipe wall based on the observed manganese precipitation observed in samples from the Adelaide system. However, this phenomenon was not predicted from the form of manganese investigated through this study i.e. the total or dissolved concentration. These were consistent with other systems. It is more likely the oxidation state of the manganese that would have dictated its ability to precipitate. Future studies should look to identify the oxidation state of such compounds where there are known to be a problem in particular water supply systems.

**General limitations of the study**

1) Limited sample size – only a single water quality zone was examined for each water utility, with monthly samples taken over a 12-month period. The samples obtained were grab samples and so only isolated points in time could be analysed. It was not possible to confirm the movement of material from the source through each system only to speculate that material located within each system originated from the same source based on its characteristics and spatial distribution.

2) The method of particle concentration used to detect particles settled after a 24-hour period i.e. to allow collection of sufficient material to undertake detailed chemical analysis of particulates from the water column, did not produce consistent results either because of the highly colloidal nature of the particulates or variations in sample collection technique. A review of the method
indicated the most likely cause was the colloidal nature of the particulate material because the proportion of material obtained was consistent. However, this prevented direct comparison of particulate material from Sites 1 to 3 with that from Sites 4 and 5. Hence this prevented confirmation that the material observed entering each system was identical to that removed during mains flushing.

Summary

- The majority of particulate material observed in the water supply systems examined in this study appeared to originate from the catchment upstream of the treatment plant. Samples of source water should be taken by each water utility involved in this study to confirm this hypothesis.

- Analysis of TSS in the water column of each utility confirmed that the mass of particles to be consistent with treatment type. Unfiltered systems had greatest mass of solids, whereas those with filtration had a lower mass, with the observed mass appearing to depend on a combination of source water and level of treatment. Differences in TSS and TVSS for each system indicated that material was most likely derived from treatment or upstream of the treatment plant.

- Organic carbon was predominantly in the dissolved form and was greatest during autumn and winter, lowest in spring and summer. It was hypothesised that these trends were associated with plant senescence in autumn and winter, and increased biological degradation activity during spring and summer.

- It appears that the water source and perhaps the presence of clay particles, had a greater influence on the dissolved elemental concentration, than the impact of flocculants used in treatment. Si was the dominant element in both dissolved and particulate forms for all except one water utility.

- Data from laboratory investigations of particle movement indicated that the differences in particle characteristics observed between the water utilities participating in this study did not significantly affect particle movement due to water velocity or gravitational settling.

Recommendations from Part 1

- Further samples are required upstream of and at the outlet of each water treatment plant to confirm the origins of particles found in the water supply system. Analysis of this material should be to determine TSS, TVSS, TOC, DOC, and total and dissolved Fe, Al, Mn, and Si.

- Development of an improved method of sample collection to allow direct comparison to confirm that the material observed in the water column of each system was identical to that removed during mains flushing.

- Future studies should look to identify the form of manganese and possibly Fe e.g. manganese 3, 4 or 7, where there are known to be a problem in particular water supply systems to determine whether such information can be used to predict the likelihood of discoloured water in such systems.

Recommendations from Part 2

- Repeat suspension, transport and settling tests with Cast Iron Cement Lined pipes and establish the suspension, re-suspension, transport and settling performance of sediments for that type of pipe.

- Examine the sediment samples under a microscope to investigate the shape of the particles.

- Further refine and calibrate the model for the PSM computer program.

- Repeat the suspension, transport, settling and re-suspension tests for sediment samples from other Water Authorities.
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1.1.1 Introduction

One of the key performance and compliance indicators for the water industry is customer complaints about discoloured or “dirty water”. Such discoloration is frequently caused by particulates from the reticulation system appearing at the customer tap. In Australia, little is understood of the origins of such material, yet it may cause between 60 and 80% of water quality related customer complaints. There is little information on how or whether the occurrence of this material can be predicted and managed.

This review report updates the 4th Progress Report and documents the current status of the research carried out by the project team at CSIRO MIT (CMIT) to understand the “dirty water” problem and predict the movement of particles in water distribution systems. The 4th Progress Report followed on from the literature review report of June 2002 which documented relevant literature data and theory and presented an analysis of published data to establish a basic theoretical framework for the settling, re-suspension and transport of particles. The aim of the research is to develop a Particle Sediment Model (PSM) to add to the existing hydraulic models used by the water authorities for the purpose of tracking the transport, settling, and re-suspension of particles in the water distribution systems, and thus guide the water authorities in hydrant flushing programs or other pipe cleaning methods. The PSM would take the form of software which would be added onto the hydraulic model software packages used by the water authorities.

1.1.2 Particle characterisation

The first step of the practical research has been to obtain samples of particulates; and to this end, a field sampling program has been established to obtain samples from the water distribution systems (WDS) of Melbourne, Adelaide, Sydney and Brisbane. These samples are being analysed, both physically and chemically to characterise them. Samples of sediment have already been extracted from pipes (through hydrant flushing) and storage tanks of the water distribution systems of Yarra Valley Water (YVW) and South East Water Limited (SEWL) in Melbourne, and to a limited extent, from Adelaide and Sydney. The samples have been analysed to establish their specific gravity, carbon content, biological plate count, particle size distribution and mineral composition (by X-ray Diffraction Analysis). A database of the particle characteristics is being built.

1.1.3 Mass concentration measurements

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

1.1.4 Laboratory tests

The third step of the research has focussed on measurements of the suspension, settling, transport and re-suspension of the particulate samples. A calibrated water tunnel at CMIT has been used to establish the fluid shear stress to suspend samples consolidated under water for a period of time. A Particle Sediment Test Loop (PSTL) comprising 41 m of 100 mm pipe in a loop driven by a low turbulence pump has also been developed to establish the settling, transport and re-suspension characteristics of the samples in an environment similar to the WDS. It is equipped with a particle counter. Further characteristics of the samples have also been investigated because particulate samples in sample bottles have been observed to exhibit a gel-like behaviour, which could inhibit the re-suspension of the sediments. Samples have been subjected to auto-claving, gamma rays and immersion in chlorine to kill off bacteria and thus to determine if the gel effect was caused by biological bonding.
1.2 Methods

1.2.1 Hydrant and tank sampling
The complementary report by Prem Mathes (SEWL) et al (2002) covers the fine detail of the hydrant and tank sampling methods.

1.2.2 Particle Size Distributions (PSD’s)
Size analyses were carried out with a Coulter LS130 instrument at external laboratory Microns to Measure. The samples were dispersed in water using sonication. The distribution was calculated using a Mie Theory optical model (RI 1.55/0.01) suitable for quartz, clays and other common soil minerals.

1.2.3 X-ray Diffraction measurements
In the initial stages before the 4th report, three sediment samples were sent to X-ray Vision Australia Pty Ltd for XRD analysis of crystalline structure. Diffraction patterns were collected on a Siemens D-5000 automated diffractometer and analysed to determine the crystalline phases present. The Standard ICDD JCPDS Data File contains over 100,000 phases which have been accurately recorded or calculated and can be compared with each unknown pattern to identify the phases present in it. Because of the presence of amorphous components, Zincite (ZnO) was added in a known amount to enable the amounts of the other compounds to be established.

1.2.4 Specific Gravity
The density of many of the sediment samples was measured as follows. First, accurate measurements were made of the volume (V₁) and weight (W₁) of the wet samples, then the water was dried off at 40 degrees to enable the weight (W₂) of the dry sediment sample to be measured. Then the density was calculated using the following steps:
- The weight of water dried off was W₁ – W₂.
- The volume of water dried off was V₂ = 1000 / (W₁ – W₂).
- The volume of the sediment sample was V₃ = V₁ – V₂.
- The density of the sediment sample was W₂ / V₃, and the SG was W₂ / (1000 V₃)
An error analysis of this technique was used to establish that we could measure specific gravity to within 0.05 with the weighing and volume measuring equipment on hand. Typically, a sample of 60 mL was used, and this was measured accurate to 0.1 mL (as established by weighing samples of water). Weights were measured accurate to within 0.0002 gm.

1.2.5 Carbon content
Carbon or organic compounds in the sample could affect the Specific Gravity (SG) results significantly. Further investigation was carried out to determine whether carbon was present in the sample or not. Organic carbon will be burnt at 560°C, therefore the samples dried for the S.G measurement were heated at 560°C for 2 hours in a muffle furnace.
Initially the dried samples were ground into very fine particles and weighed before being placed into a ceramic boat. When the sample was weighed the initial weight was recorded as W₃. The sample was then inserted in the muffle furnace at 560°C for 2 hours. Repeated weighings showed that after 2 hours the weight remained the same, and did not decrease if the sample was heated for more than 2 hours. This meant all the organic compound was completely burnt. Immediately after 2 hours, the sample was removed from the muffle furnace for weighing and sample weight recorded as W₄. Normally W₄ is smaller than W₃; this is due to the organic contents in the sample being liberated as gaseous carbon dioxide and water vapour.

Carbon content is determined by:
\[
\% C = 100 \times \frac{(W₃ - W₄)}{W₃}
\]
1.2.6 Biological activity in the samples
Pipe and tank sediment samples which had settled for a day or so separated into a dense, gel-like fraction with a watery supernatant above. The strength of the gel was such that the sample jar could be turned almost 90 degrees off-vertical without the gel breaking and allowing the sediment sample to slump. This gel-behaviour would give strength to the settled components in the water distribution system pipes and would thus affect suspension behaviour, so further investigation of the biological activity in the samples was carried out.

To destroy bacteria and biological cells, three approaches were used:
1. Irradiation with gamma rays
2. Autoclaving
3. Dosing with chlorine

Bacterial plate counts were obtained before and after these treatments, which were carried out by the company WATER ECOscience. After treatment, the gel-nature was assessed simply by tilting the sample jar again. There was negligible change to the tilt-test, indicating that the gel-like behaviour was not caused by biological activity.

![Sediment gel-like behaviour established by tilt-test.](image)

1.2.7 Particle mass concentration in the Water Distribution System
A novel method was devised (Bon Nguyen et al. 2002) for obtaining estimates of the concentration of particles in the WDS to calibrate the PSM software. Twenty-two devices were installed at customer properties across the WDS in Doncaster for measuring the mass concentration of particles in water delivered to the customers (Figure 1.3). A small flow (0.02 L/s) of water is bled off from the customers supply before the water meter via a special fitting, and passed through both a water flow meter and a 1 micron filter of known dry weight. After a period of approximately 7 days, the dirty filter is removed, dried and weighed. The nett increase in filter weight yields the mass concentration of particles in the water:

\[
\text{Mass concentration (mg/ L)} = \frac{\text{Change in filter weight (mg)}}{\text{Volume of water (L)}}
\]
1.2.8 Re-suspension measurements in a water tunnel

Tests were devised for establishing the fluid shear stress required to re-suspend sediment samples which had a substantial thickness of approximately 2 mm. This represents thick sediments accumulated in pipes in the WDS where sedimentation has been steadily building up thick sediment by a simple vertical settling process.

1.2.8.1 Equipment and basic method

The water tunnel shown in Figure 1.4 was used for the suspension tests. Particle samples from the WDS were deposited in trays, which were, in turn, held in a cut-out in a PVC plate which was situated in a channel in the water tunnel. Water flowing through the channel flowed over the particle samples in the trays and particles were eroded and re-suspended by the flowing water. The fluid wall shear stress was used to quantify the conditions causing erosion and re-suspension of the particles. This is the shear stress which the fluid exerts on the surface of the particle samples, and it is denoted by $\tau_0$. 
For calibration, the wall shear stress was measured with a Preston tube located on a dummy tray in place of the sample tray and a calibration was obtained in which the wall shear stress was measured as a function of the water flow rate through the water tunnel. The Preston tube is shown in Figure 1.5.

Individual suspension tests were then carried out with each sample in its tray in the water tunnel, at increments of water tunnel flow rate. The degrees of suspension were determined by visual observation of the cloud of particles carried downstream from the sample. The wall shear stress at each flow rate was then obtained from the calibration.

**Figure 1.5** The 4.5 mm diameter Preston tube on the dummy tray inserted into the flat PVC plate in the water tunnel. Water flows to the right.

### 1.2.8.2 Wall Shear stress calibration.

The theory of how a Preston tube measures wall shear stress is detailed by Patel (1965). The calibration of the Preston tube was checked first by measuring the wall shear stress developed over the PVC plate and comparing it with the shear stress predicted by the standard theory for the development of a turbulent boundary layer over a flat, smooth plate. Close agreement was obtained. This work was done with the flat PVC plate at half height in a water depth of 240 mm in the water tunnel channel (Figure 1.6).
For suspension tests, the plate was moved down to 30 mm above the channel floor and the water depth reduced to 100 mm (Figure 1.6) in order to obtain a water speed adequate to suspend test samples requiring wall shear stresses as high as 2 Pa. The Preston tube was again used to calibrate the wall shear stress against the flow rate. The calibration curve is shown below in Figure 1.7. It should be noted that the water level reduced as the water speed increased in the channel, and this caused the waviness in the calibration curve. (The usual relationship that wall shear stress is proportional to water velocity squared was obtained for the flat plate boundary layer test).

**Figure 1.6** Cross-sections of the water tunnel, for boundary layer test and for re-suspension test.

Although the water in the WDS appears clear in most occasions, there are some particles which accumulate in pipes and tanks before disturbances such as demand increases or system maintenance distribute them to the customers. To understand these particles behaviour; re-suspension tests were done with real samples provided by YVW and SEWL. To partially simulate the processes of deposition of the particles in the reticulated system, the samples of particles with water were introduced into a tubular shaker (Figure 1.8) and the mixture shaken thoroughly and allowed to settle into the sample tray.

**Figure 1.7** Wall shear stress as a function of water tunnel flow rate squared

**1.2.8.3 Suspension sample preparation**

Although the water in the WDS appears clear in most occasions, there are some particles which accumulate in pipes and tanks before disturbances such as demand increases or system maintenance distribute them to the customers. To understand these particles behaviour; re-suspension tests were done with real samples provided by YVW and SEWL. To partially simulate the processes of deposition of the particles in the reticulated system, the samples of particles with water were introduced into a tubular shaker (Figure 1.8) and the mixture shaken thoroughly and allowed to settle into the sample tray.
After allowing approximately one day for consolidation, the volume of the particles sample was adjusted to make the surface flush with the sample tray surface. The sample was re-shaken and allowed to settle again then moved to the consolidation tank for the rest of the consolidation period; either 1 day, 1 week, or 1 month.

1.2.9 Particle Suspension Test Loop

In order to simulate and investigate conditions of particle suspension, transport, settling and re-suspension in pipes in the Water Distribution System (WDS), a particle suspension test loop (PSTL) has been built and installed in the CMIT laboratory at Highett, Melbourne (Figure 1.9 and Figure 1.10).

Figure 1.8 Shaker used to create settled sample in suspension trays. The end of tray no.3 is visible at the bottom

Figure 1.9 Schematic of Particle Suspension Test Loop at Highett, Victoria.
Figure 1.10 Particle Suspension Test Loop at Highett

It comprises a specially designed pump and 41 metres of 100 mm internal diameter PVC pipe into which samples of pipe or tank sediment particles are injected. The pump is an axial flow type and was designed to create low swirl and turbulence so that particle distributions entering it are not grossly changed on their way through the pump. A variable speed controller and Magflow flow-meter facilitate operation of the PSTL over a range of measured water velocities.

1.2.9.1 Measurement of Particle Size Distribution in the PSTL

In order to measure the concentration and sizes of particles in the PSTL, a sample flow of 100 mL/min is drawn through a Hach 2200 PCX Particle Counter by a peristaltic pump and re-injected into the PSTL further downstream. The Hach particle counter has been connected to a personal computer to log counts of particles in specified bin sizes (of less than 3 micron, 3-5, 5-7, 7-10, 10-14, 14-18, 18-22, 22-26, 26-30 and greater than 30 micron) at specified time intervals of 15 or 30 seconds.

Data thus logged is entered into an Excel spreadsheet to compute and draw Particle Size Distributions (PSDs). As an alternative presentation, particle concentration data may be drawn as changes of concentration as a function of time, for specified particle sizes. The Hach particle counter can detect particles in the range 2 – 100 microns in concentrations up to 17,000 particles/mL. Concentrations greater than 17,000 particles/mL are measured by measuring the concentration of a sample bled from the PSTL and diluted by a known amount in a small tank from which the Hach takes its sample.
1.3 Results and Discussion

1.3.1 Hydrant and tank sampling

Sediment samples were taken from the Melbourne reticulation system by South Eastern Water (SEW) and Yarra Valley Water (YVW) from both tanks and pipes, and later from Adelaide, Sydney and Brisbane. These first samples were obtained in advance of the systematic monthly sampling by all the water authorities participating in this project. These samples have been used to gain an initial insight into the nature and behaviour of the sediments.

Table 1.1 Locations from which tank or pipe sediment samples have been taken.

<table>
<thead>
<tr>
<th>Locations:</th>
<th>Water Authorities</th>
<th>Tank or Pipe</th>
<th>Date of Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birts Hill wrs36</td>
<td>YVW</td>
<td>Tank</td>
<td>6/05/02</td>
</tr>
<tr>
<td>Growler Hill wrs 59</td>
<td>YVW</td>
<td>Tank</td>
<td>6/05/02</td>
</tr>
<tr>
<td>Warbuton wrs60</td>
<td>YVW</td>
<td>Tank</td>
<td>8/05/02</td>
</tr>
<tr>
<td>Mt Cuelyn Wrs140</td>
<td>YVW</td>
<td>Tank</td>
<td>7/05/02</td>
</tr>
<tr>
<td>Montrose High Level</td>
<td>YVW</td>
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<td>7/05/02</td>
</tr>
<tr>
<td>Nth emerald</td>
<td>YVW</td>
<td>Tank</td>
<td>14/05/02</td>
</tr>
<tr>
<td>Sherbrooke</td>
<td>YVW</td>
<td>Tank</td>
<td>8/05/02</td>
</tr>
<tr>
<td>Panton hill wrs93</td>
<td>YVW</td>
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<td>13/05/02</td>
</tr>
<tr>
<td>Memorial P wrs97</td>
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<td>Olinda Wrs50</td>
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<td>18/07/02</td>
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<td>Watts Court Temp 48hrs</td>
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</tr>
<tr>
<td>Pinewood drive temp</td>
<td>YVW</td>
<td>Pine</td>
<td>18/07/02</td>
</tr>
<tr>
<td>Watts Court Temp</td>
<td>YVW</td>
<td>Pine</td>
<td>18/07/02</td>
</tr>
<tr>
<td>YVW panorama tank</td>
<td>YVW</td>
<td>Pipe</td>
<td>4/09/02</td>
</tr>
<tr>
<td>SEW Site 4</td>
<td>SEW</td>
<td>Pipe</td>
<td>15/07/02</td>
</tr>
<tr>
<td>Templemore Drve draining line</td>
<td>SEW</td>
<td>Pipe</td>
<td>5/08/02</td>
</tr>
<tr>
<td>Owen st. Doncaster</td>
<td>SEW</td>
<td>Pipe</td>
<td>6/08/02</td>
</tr>
<tr>
<td>Templemore drive. During scouring</td>
<td>SEW</td>
<td>Pipe</td>
<td>7/08/02</td>
</tr>
<tr>
<td>Beresford Court Doncaster</td>
<td>SEW</td>
<td>Pipe</td>
<td>8/08/02</td>
</tr>
<tr>
<td>Tucker rd Doncaster</td>
<td>SEW</td>
<td>Pipe</td>
<td>9/08/02</td>
</tr>
<tr>
<td>Loxley Court Doncaster</td>
<td>SEW</td>
<td>Pipe</td>
<td>10/08/02</td>
</tr>
<tr>
<td>Woodlea St. Doncaster</td>
<td>SEW</td>
<td>Pipe</td>
<td>11/08/02</td>
</tr>
<tr>
<td>Unknown 1</td>
<td>SEW</td>
<td>Pipe</td>
<td>12/08/02</td>
</tr>
<tr>
<td>Unknown 2</td>
<td>SEW</td>
<td>Pipe</td>
<td>13/08/02</td>
</tr>
<tr>
<td>SEW</td>
<td>SEW</td>
<td>Pipe</td>
<td>13/08/02</td>
</tr>
<tr>
<td>SEW( Wantirna + Cranbourne)</td>
<td>SEW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>United Water</td>
<td>UW</td>
<td>Pipe</td>
<td>Jul-02</td>
</tr>
<tr>
<td>Brisbane Water</td>
<td>Brisbane Water</td>
<td>Pipe</td>
<td>Jul-02</td>
</tr>
<tr>
<td>Brisbane Water Repeat</td>
<td>Brisbane Water</td>
<td>Tank</td>
<td>Jul-02</td>
</tr>
<tr>
<td>Sydney Water</td>
<td>Syd Water</td>
<td>Pipe</td>
<td>Jul-02</td>
</tr>
</tbody>
</table>
Table 1.1 lists the locations of the samples collected between May and September 2002. Watts Court and Pinewood Drive pipe sediment samples were obtained by collecting 2-4 m$^3$ of water by flushing from a fire hydrant into a water tanker. Samples were then allowed to settle in a large vessel at CMIT. However, some of the larger particles were observed to settle in the bottom of the water tanker, before sediment samples could be obtained. This would have affected the PSD, XRD and SG measurements.

1.3.2 Particle Size Distributions

Six particle size distributions have been carried out at the locations listed in Table 1.2. The full PSDs for the six locations are shown graphically in Appendix A. A typical example is reproduced in Figure 1.11.

The PSD sub-contractor, ‘Microns to Measure’ reported that sediment samples were sonicated to disperse them before measurements of the PSD were made. They found that the Whittlesea sample, in particular, as well as the others, was slow to disperse. They chose a sonication time of 5 minutes but noted that sediment continued to become finer with extended sonication (eg. the mode moved from 25 micron initially, to 18 micron after 5 minutes sonication, to 12 microns after 9 minutes for the Whittlesea sample, which is a filtered supply).

<table>
<thead>
<tr>
<th>Location</th>
<th>Tank or pipe</th>
<th>Size range (micron)</th>
<th>Modal Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whittlesea</td>
<td>Tank</td>
<td>0.5 - 300</td>
<td>18 micron</td>
</tr>
<tr>
<td>Birts Hill</td>
<td>Tank</td>
<td>0.8 - 500</td>
<td>22 micron</td>
</tr>
<tr>
<td>Growler Hill</td>
<td>Tank</td>
<td>0.6 - 400</td>
<td>27 micron</td>
</tr>
<tr>
<td>Wantirna No.2</td>
<td>Tank</td>
<td>0.8 - 110</td>
<td>8 micron</td>
</tr>
<tr>
<td>Watts Court</td>
<td>Pipe</td>
<td>0.9 - 220</td>
<td>11 micron</td>
</tr>
<tr>
<td>Pinewood Drive</td>
<td>Pipe</td>
<td>0.9 - 280</td>
<td>11 micron</td>
</tr>
</tbody>
</table>

It can be seen from Table 1.2 that the first three tank samples contained mostly particles of greater than 18 microns size, whereas the pipe samples and the Wantirna tank sample contained particles of approximately 8 microns size, although the pipe samples would have lost large particles from the PSD as explained in section 1.3.2 above.

**Figure 1.11** Particle size distribution for sediment from Wantirna Tank No.2.
1.3.3 Xray Diffraction measurements

In order to gain an appreciation of the nature of the sediments and of the information revealed by the Xray Diffraction analysis, three sediment samples were analysed. The samples were supplied in water, which meant that a drying step was required to produce the crystalline form suitable for XRD analysis. The results of these analyses are presented in Table 1.3.

<table>
<thead>
<tr>
<th>Component</th>
<th>Pinewood Drv pipe</th>
<th>Wantirna tank</th>
<th>Whittlesea tank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscovite Kal2(AlSi3O10)(OH)2</td>
<td>6.7 %</td>
<td>8.8 %</td>
<td>---</td>
</tr>
<tr>
<td>Quartz SiO2</td>
<td>17.4 %</td>
<td>31.9 %</td>
<td>2.9 %</td>
</tr>
<tr>
<td>Kaolin – Bish Al2Si2O5(OH)4</td>
<td>6.4 %</td>
<td>9.2 %</td>
<td>---</td>
</tr>
<tr>
<td>Calcite-R CaCO3</td>
<td>---</td>
<td>---</td>
<td>45.4 %</td>
</tr>
<tr>
<td>Unidentified est. 10 %</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Amorphous</td>
<td>69.5 %</td>
<td>50.1 %</td>
<td>51.7 %</td>
</tr>
</tbody>
</table>

Whittlesea sediment, which came from a filtered supply, is quite different from the other two, and it is interesting that the PSDs were quite different too.

1.3.4 Specific Gravity

Specific gravity estimates are presented in Table 1.4. To validate the method used, the SG of standard type Al Ballotini glass (SG approximately 2.5) was measured. As seen from Table 1.4, satisfactory agreement was obtained.

<table>
<thead>
<tr>
<th>Location</th>
<th>Specific Gravity</th>
<th>Tolerance +/-</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al glass (standard)</td>
<td>2.43</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Al glass (standard)</td>
<td>2.41</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Pinewood</td>
<td>1.18</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>Watts</td>
<td>1.20</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>Whittlesea</td>
<td>1.92</td>
<td>0.08</td>
<td>YVW tank</td>
</tr>
<tr>
<td>Growler Hill</td>
<td>1.39</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Montrose HL</td>
<td>1.62</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>Wantirna R</td>
<td>1.63</td>
<td>0.06</td>
<td>YVW mains</td>
</tr>
<tr>
<td>Wantirna O</td>
<td>1.78</td>
<td>0.07</td>
<td>YVW mains</td>
</tr>
<tr>
<td>Mt Cuelyn</td>
<td>1.73</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Birts Hill</td>
<td>1.81</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Sherbrook</td>
<td>1.80</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>Panton Hill</td>
<td>1.71</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>Olinda</td>
<td>2.04</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Memorial park</td>
<td>1.30</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Nth Emerald</td>
<td>1.99</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>YVW mixed tank sed.</td>
<td>1.48</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>Pinewood Drv</td>
<td>1.65</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Watts Crt</td>
<td>1.65</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Pinewood Drv</td>
<td>1.50</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Watts Crt</td>
<td>1.37</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>Brisbane</td>
<td>1.97</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>1.64</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Several repeats of SG estimates were made to check the accuracy of the measurements (e.g. Watts, Pinewood, AI Ballotini glass). It appears that samples with different density were obtained in some circumstances (e.g. Watts Court).

The mean specific gravity of particles collected in the Melbourne water supply system was 1.64. The low values for Watts Court and Pinewood Drive (approximately 1.2) can be discarded as inaccurate because some of the larger, heavier, quicker-settling particles were lost during the sample collection process (see section 1.2.1).

### 1.3.5 Carbon content

Carbon content measurements for a range of samples are presented in Table 1.5. The mean percentage of volatile carbon is 18.3%.

#### Table 1.5 Carbon content of sediment samples.

<table>
<thead>
<tr>
<th>Location</th>
<th>Carbon content % w/w</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pinewood</td>
<td>21.8</td>
</tr>
<tr>
<td>Watts</td>
<td>19.5</td>
</tr>
<tr>
<td>Whittlesea</td>
<td>30.1</td>
</tr>
<tr>
<td>Growler Hill</td>
<td>24.4</td>
</tr>
<tr>
<td>Montrose Hill</td>
<td>7.4</td>
</tr>
<tr>
<td>Wantirna Rwanti</td>
<td>28.0</td>
</tr>
<tr>
<td>Wantirna Olindale</td>
<td>11.1</td>
</tr>
<tr>
<td>Mt Cuelyn</td>
<td>18.7</td>
</tr>
<tr>
<td>Birts Hill</td>
<td>17.1</td>
</tr>
<tr>
<td>Sherbrook</td>
<td>16.8</td>
</tr>
<tr>
<td>Panton Hill</td>
<td>2.7</td>
</tr>
<tr>
<td>Olinda</td>
<td>31.9</td>
</tr>
<tr>
<td>Memorial Park</td>
<td>13.4</td>
</tr>
<tr>
<td>North Emerald</td>
<td>13.9</td>
</tr>
<tr>
<td>YVW mixed tank sample</td>
<td>18.1</td>
</tr>
<tr>
<td>Mean</td>
<td>18.3</td>
</tr>
</tbody>
</table>

### 1.3.6 Biological activity in the samples

Samples from Whittlesea and Olinda tanks were selected for analysis and treatment to assess the biological impact for the observed gel-like behaviour of the sediment samples. Plate counts were measured before and after treatment (Table 1.6).

#### Table 1.6 Sequence of treatments of sediment samples to destroy biological activity.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Treatment</th>
<th>Plate count 22°C (orgs/mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whittlesea tank #1</td>
<td>Untreated</td>
<td>14000</td>
</tr>
<tr>
<td>&quot;</td>
<td>Chlorine</td>
<td>&gt; 480</td>
</tr>
<tr>
<td>Whittlesea tank #2</td>
<td>Untreated</td>
<td>12000</td>
</tr>
<tr>
<td>&quot;</td>
<td>Autoclave</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>&quot;</td>
<td>Gamma ray irradiated</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>Olinda tank #1</td>
<td>Untreated</td>
<td>38000</td>
</tr>
<tr>
<td>&quot;</td>
<td>Chlorine</td>
<td>&gt; 780</td>
</tr>
<tr>
<td>Olinda tank #2</td>
<td>Untreated</td>
<td>36000</td>
</tr>
<tr>
<td>&quot;</td>
<td>Autoclave</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>&quot;</td>
<td>Gamma ray irradiated</td>
<td>&lt; 10</td>
</tr>
</tbody>
</table>
It was expected that auto-claving and gamma-ray irradiation would destroy the cell walls, and thus break down any biological cohesion in the samples. However, it was concluded that the gel-like behaviour was not caused by biological activity because when the reaction of the samples to this treatment was assessed by tilting the sample vials, the samples remained gel-like. It is more likely that Van De Waals forces cause the cohesion of the samples. Organic matter comprised 5% of the sample.

1.3.7 Particle mass concentration in the Water Distribution System

CMIT measured the particle concentrations at several locations at the Highett, Victoria site for several months. The results are shown in Figure 1.12: particle mass concentrations vary between 0.18 ppm and 0.5 ppm. Figure 1.12 also shows a comparison between back-to-back meters, installed on the same hydrant, revealing excellent agreement. The only discrepancy was at month 4 when a sudden increase in flow through unit 2 would have flushed some particles out. This was rectified by fitting restrictors in the flow lines to restrict the change in flow rate.

\[\text{Comparison of back-to-back mass concentration meters}\]

Figure 1.12 Mass concentration of particles from hydrants at the Highett test site.

Yarra Valley Water installed these devices for measuring the mass concentration of particles at 20 locations across its WDS (Figure 1.13).
Figure 1.13 Locations of mass-concentration meters in the YWW WDS.

The results of several months of measurements are presented in Figure 1.14 and Figure 1.15. The range is 0.16 – 0.9 ppm. These concentrations are similar to those measured at CMIT.
Figure 1.14 Mass concentration measurements for locations east of the source (Doncaster tank).

Figure 1.15 Mass concentration measurements for locations west of the source (Doncaster tank)
1.3.8 Re-suspension measurements in the water tunnel

All the re-suspension results are tabulated in Appendix B. Tank re-suspension shear stresses measured in the water tunnel are shown in Figure 1.16 as equivalent velocities to re-suspend in 100 mm pipes. The higher and lower values indicate the range over which re-suspension gradually increases from partial to full suspension. It can be seen that a velocity of 0.25 – 0.35 m.s⁻¹ is adequate to suspend these agglomerated samples from the tanks. The Wantirna tanks samples required the greatest shear stress to re-suspend. These are in the SEWL reticulation system, whereas the others are from the YVW reticulation system.

![Velocity to re-suspend in 100mm pipe at different locations](images/velocities.png)

**Figure 1.16** Velocity to re-suspend tank sediment samples in a 100 mm pipe, calculated from shear stress measurements in the water tunnel. Sediment sample consolidation period = 1 day.

Figure 1.16 also shows that autoclaving and gamma-ray treatment marginally reduced the re-suspension velocity for the Whittlesea and Olinda samples.

The effect of consolidation period is shown in Figure 1.17. As an approximate rule, the increases of consolidation period beyond one day create increases in sediment sample strength, and increased shear stress and velocity are then required to re-suspend the samples, but there is not much difference between one week and one month consolidation. A velocity of approximately 0.4 m.s⁻¹ is able to re-suspend all the samples. It is remarkable that this is the same velocity as KIWA had reported as the daily minimum velocity required to maintain clear water in 100 mm pipes in their WDS system in Holland (Ryan and Grainger (2002).

Figure 1.18 shows the velocity to re-suspend sediment particles in 100 mm pipe for sediment samples from pipes in various water distribution systems, obtained by flushing through hydrants. These velocities are all a little less than the velocities for tank sediment samples.
### Velocity to re-suspend in 100mm pipe at 4 locations after different consolidations

**Figure 1.17** Velocity to suspend sediment samples from tanks as a function of consolidation period.

### Velocity in 100 mm pipes to re-suspend samples from pipes for various locations.

**Figure 1.18** Velocity in 100 mm pipes to re-suspend samples from pipes for various locations.

#### 1.3.9 Particle Suspension Test Loop (PSTL)

A special axial-flow pump had been designed and constructed for the PSTL. The first experiments with the PSTL established that the pump did not create swirl about the axis of the pipe. However, although it had been hoped that the pump might allow fully laminar flow to pass through without being made turbulent, it did not.
1.3.9.1 Measurement of Particle Size Distribution with the Hach 2200 PCX

Before beginning to use the Hach particle counter to measure particle size distributions in the PSTL, some calibration experiments were carried out. These began with tap water samples. It was quickly found that filtered tap water was not clean, and contained approximately 1000 particles per millilitre greater than 2 microns in size. However, with scrubbed, de-ionised water and clean tubing, particle counts of 291/mL greater than 2 micron, and 17/mL greater than 5 micron were obtained. These levels were adequate to work with as background levels for the suspension tests planned for the PSTL because the Hach has an upper limit of 17,000 particles per millilitre.

The next calibration experiments were carried out with a few drips of Pinewood Drive sediment samples in water in a stirred vessel. The peristaltic pump drew the particles through the Hach particle counter then discharged them back to the stirred vessel. It was of concern that the pulsations of flow caused by the peristaltic pump could influence the reading of the Hach counter, so a gravity feed system was tried. This made negligible changes to the readings, so it was concluded that the peristaltic pump could be used.

With this set-up, the Hach counter was configured to measure particle counts >3, >5, >7, >10, >14, >18, >22, >26, >30 micron. The Hach counter reported these particle counts obtained over 6 second counting periods at 30 second (programmable) intervals. These readings were automatically stored in a text file and later down-loaded to an Excel spreadsheet for processing. Thus PSDs could be drawn from the Hach data. Figure 1.19 below shows the PSD from the Hach data of Test 29 compared with the PSD obtained by a Coulter LS130 on another Pinewood Drive sample.

Although both PSDs show a peak at approximately 10 microns, the Hach data shows no particles above 20 microns.

To investigate the cause of this discrepancy, some type AI Ballotini glass particles of approximately 40 microns size were suspended in the mixing vessel but again the Hach registered none greater than 20 microns. Type AH1 particles with nominal size 60 microns were also tried with the same result. Then it was noticed that particles were falling out of suspension as they travelled along the tubing into the Hach counter. At the recommended flow-rate of 100 mL/min through the Hach, the flow in the 4 mm ID tubing is laminar, not turbulent, and thus the particles fall out of suspension. To overcome this problem, both smaller tubing and a greater flow-rate were tried, but still nothing greater than 25 micron could be detected.

It was decided to work with the detectable particles in the range 1 – 20 micron.
Repeated sampling with different sampling periods with the Hach produced the same three peaks in the PSD distribution shown in Figure 1.19.

### 1.3.9.2 Background particle concentration in the PSTL

In Test 39, the background concentration of particles in the PSTL was measured with the Hach in order to establish that it was low enough compared to the particle concentrations of sediment samples which were to be added for suspension, settling and re-suspension tests. Figure 1.20 shows this concentration as a function of pipe Reynolds number: the pump speed was increased in steps to find the point at which significant re-suspension occurred. This was at Reynolds number 2800, which corresponds to the well-known value of 2200 which divides laminar flow from turbulent flow. The pipe velocity is only 0.028 m.s\(^{-1}\) at this point.

Peak concentrations were approximately 1000 particles per millilitre, which is low enough compared to the intended use of concentrations of approximately 17,000 counts per millilitre.

![Figure 1.20 Background level of particles in the PSTL as a function of pipe Reynolds number before additional sediment samples were added.](image-url)

**Table 1.7 Sediment samples inserted into the PSTL**

<table>
<thead>
<tr>
<th>Sample number</th>
<th>1A</th>
<th>1B</th>
<th>1C</th>
<th>1D</th>
<th>1E</th>
<th>2A</th>
<th>3A</th>
<th>3B</th>
<th>4A</th>
<th>5A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beginning test number</td>
<td>Test 42</td>
<td>Test 49</td>
<td>Test 53</td>
<td>Test 58</td>
<td>Test 70</td>
<td>Test 76</td>
<td>Test 76</td>
<td>Test 76</td>
<td>Test 90</td>
<td>Test 102</td>
</tr>
<tr>
<td>Sample source</td>
<td>Pinewood</td>
<td>Pinewood</td>
<td>Pinewood</td>
<td>Pinewood</td>
<td>Sample 1D</td>
<td>Olinda</td>
<td>YVW</td>
<td>YVW</td>
<td>Tank mix</td>
<td>Tank mix</td>
</tr>
<tr>
<td>Sample volume - wet mL</td>
<td>15</td>
<td>10</td>
<td>15</td>
<td>3</td>
<td>30</td>
<td>1000</td>
<td>1500</td>
<td>40</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Sample volume - mL packed</td>
<td>9</td>
<td>6</td>
<td>9</td>
<td>1.8</td>
<td>18</td>
<td>600</td>
<td>900</td>
<td>24</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Sample volume - mm(^3)</td>
<td>9000</td>
<td>6000</td>
<td>9000</td>
<td>1800</td>
<td>18000</td>
<td>600000</td>
<td>900000</td>
<td>240000</td>
<td>3600</td>
<td></td>
</tr>
<tr>
<td>Concentration in PSTL ppm v/v</td>
<td>27.9</td>
<td>18.6</td>
<td>27.9</td>
<td>5.6</td>
<td>55.9</td>
<td>1863.3</td>
<td>2794.9</td>
<td>74.5</td>
<td>11.2</td>
<td></td>
</tr>
<tr>
<td>Mean count / mL</td>
<td>17700</td>
<td>14000</td>
<td>20000</td>
<td>12000</td>
<td>16500</td>
<td>4861000</td>
<td>2794.9</td>
<td>4661000</td>
<td>4661000</td>
<td></td>
</tr>
<tr>
<td>Total particles into PSTL</td>
<td>5.70E+09</td>
<td>4.51E+09</td>
<td>8.44E+09</td>
<td>1.03E+09</td>
<td>3.88E+09</td>
<td>5.31E+09</td>
<td>1.50E+12</td>
<td>4.46E+10</td>
<td>6.44E+10</td>
<td></td>
</tr>
<tr>
<td>Volume per particle in mL</td>
<td>1.57E-09</td>
<td>4.51E-09</td>
<td>8.44E-09</td>
<td>1.03E-09</td>
<td>3.88E-09</td>
<td>5.31E-09</td>
<td>1.50E-12</td>
<td>4.46E-10</td>
<td>6.44E-10</td>
<td></td>
</tr>
<tr>
<td>Particle diameter in micron</td>
<td>1.28</td>
<td>1.19</td>
<td>1.21</td>
<td>1.31</td>
<td>1.63</td>
<td>0.80</td>
<td>0.91</td>
<td>0.88</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>Particles per square mm of wall</td>
<td>443</td>
<td>350</td>
<td>500</td>
<td>80</td>
<td>300</td>
<td>413</td>
<td>116525</td>
<td>116525</td>
<td>3465</td>
<td></td>
</tr>
<tr>
<td>Particles deep on wall</td>
<td>0.000554</td>
<td>0.000381</td>
<td>0.000577</td>
<td>0.000107</td>
<td>0.000000</td>
<td>0.000858</td>
<td>0.058342</td>
<td>0.076450</td>
<td>0.002114</td>
<td>0.000313</td>
</tr>
</tbody>
</table>

**NB:** For Tank mix flushed samples 4A and 5A, Sample particles mL is estimated, based on mean counts/mL.

**NB:** Samples 3A and 3B have estimated sample volumes.
1.3.9.4 Performance of Pinewood Drive sediment sample 1A in PSTL

The objective of Test no. 49 was to suspend a sample, transport it around the test loop for a few cycles, then allow it to settle before re-suspending it. Approximately 10 mL of settled sediment from the Pinewood Drive hydrant sample was injected into a quiescent pipe-flow 500 mm downstream of the pump and allowed to settle for 1.5 hours. It formed a patch of approximately 50 mm diameter on the bottom of the pipe (Figure 1.21).

![Figure 1.21 50 mm patch of sediment inserted into the PSTL.](image)

The water was fresh (the water from the previous test had been replaced). This section of the pipe was transparent. During these processes, the sediment load in the water was studied by sampling with the Hach particle counter.

To initially suspend the sample, the pump was run slowly for several minutes and any suspension of the sample was observed before further increases of the pump speed. This process was repeated until all the sample had been suspended. Results are summarised in Table 1.8 below. As can be seen from the table, the shear stress to fully suspend the sample was approximately 0.14 Pa, which compares well with the measurement of 0.16 Pa – 0.25 Pa in the water tunnel for the stronger sample consolidated for 1 day (see Appendix B). Note also that it took a few minutes at that shear stress to fully suspend the sample – i.e. there was a suspension rate rather than an immediate full suspension at a distinct velocity.

![Cross section](image)

Table 1.8 Suspension of Pinewood Drive sample in PSTL

<table>
<thead>
<tr>
<th>Time hr:min</th>
<th>Velocity m/s</th>
<th>Reynolds No.</th>
<th>Shear stress Pa</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:32</td>
<td>0.05</td>
<td>4800</td>
<td>0.011</td>
<td>No suspension</td>
</tr>
<tr>
<td>1:34</td>
<td>0.07</td>
<td>7300</td>
<td>0.022</td>
<td>Tractoring of small particles</td>
</tr>
<tr>
<td>1:35</td>
<td>0.12</td>
<td>11800</td>
<td>0.05</td>
<td>Initial suspension which stopped</td>
</tr>
<tr>
<td>1:41</td>
<td>0.16</td>
<td>16400</td>
<td>0.091</td>
<td>Cloudy suspension of fines</td>
</tr>
<tr>
<td>1:46</td>
<td>0.21</td>
<td>21000</td>
<td>0.138</td>
<td>Rapid suspension rate</td>
</tr>
<tr>
<td>1:48</td>
<td>0.21</td>
<td>21000</td>
<td>0.138</td>
<td>All suspended</td>
</tr>
</tbody>
</table>

Figure 1.22 shows the change with time of the particle concentrations measured on the pipe centre-line near the pump in the PSTL as the dense concentration (or ‘puff’) of suspended sediment moved around the loop. The cycle time was approximately 3.25 minutes at a pipe velocity of 0.21 m.s⁻¹. Note that the particle peak concentration reduced, but the width of the peaks does not change much, nor does the bottom of the troughs rise. This indicates that there is little axial extension of the puff of sediment in the pipe.
However, the shape of the PSD changes with time, as shown in Figure 1.23. The effect is that the particles in suspension become smaller. This may be caused by fluid turbulence, the pump, or wall friction.

This pattern of slowly decaying, oscillating particle concentration with time is characteristic of the initial suspension of sediment samples in the PSTL, and is shown in other figures from subsequent tests (eg. Figure C.3 and Figure C.41 in Appendix C).

After 5 cycles of transport around the PSTL, the pump was slowed (at time=31 minutes) to allow settling of the particles in laminar flow, which required a pipe velocity of less than 0.2 m.s⁻¹, so a pipe velocity of 0.018 m.s⁻¹ was chosen (Re=1800). Figure 1.24 shows the concentration of the various size
fractions of the sediment sample during this time and up to 100 minutes. The high concentration “puff” of particles continued to move around the pipe loop. Particle concentrations reduced for the size ranges 7 – 22 microns, but were relatively constant for the size range 3 – 7 micron. Figure 1.25 shows these concentrations for elapsed times up to 300 minutes.

Figure 1.24 Pinewood sample: particles concentration in the PSTL for the suspension and transport phases and the first two cycles of the settling phase. The pump speed was reduced at time=31 minutes to allow settling to begin.

Figure 1.25 Particle concentrations during the settling phase up to 300 minutes.

After approximately 150 minutes, the peaks disappeared, and the larger size fractions reduced substantially, as would be expected because the larger size fractions would settle more quickly than the smaller. Figure 1.26 also shows that the particle size distribution changes as the large particles fall out of suspension during the settling phase. Note that Figure 1.25 shows that the concentration of particles in the 3-5 and 5-7 micron ranges also reduce with time, so settling is occurs for all sizes.
For the Particle Sediment Model, it is important to know how fast the sediment settles. Using the Stokes settling model, the times for spherical particles of specific gravity=1.62 to settle across the 0.1m diameter pipe are given in Table 1.9.

If the Pinewood sediment particles were spherical and of SG approximately 1.62, then these figures would apply to the settling phase of the experiment (Test 49). However, it is clear from Figure 1.24 that the 20 micron particles do not all settle in 12 minutes because the second peak associated with the “puff” of particles still exists at time=72 minutes. Similarly, this Figure 1.24 reveals that the 8.5, 12 and 16 micron particles also settle more slowly than would be expected from Table 1.9.

**Table 1.9** Time for spherical particles of SG=1.62 to settle across a 100 mm diameter pipe in quiescent flow as a function of particle diameter.

<table>
<thead>
<tr>
<th>Particle Size (micron)</th>
<th>Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 micron</td>
<td>309</td>
</tr>
<tr>
<td>6 micron</td>
<td>137</td>
</tr>
<tr>
<td>8.5 micron</td>
<td>68</td>
</tr>
<tr>
<td>12 micron</td>
<td>34</td>
</tr>
<tr>
<td>16 micron</td>
<td>19</td>
</tr>
<tr>
<td>20 micron</td>
<td>12</td>
</tr>
</tbody>
</table>

**Conclusion: Stoke’s theory cannot be applied for particle settling.**

Figure 1.27 shows the particle concentrations for various size fractions over an extended period of settling. The concentration of the largest particle sizes reduces quickest, and the concentration of all fractions reduces, but again settling times are much greater than expected from Table 1.9. Figure 1.28 shows the settling behaviour of the fine fraction of the Pinewood sample settling out over 1200 minutes in Test 49.
Figure 1.27 Pinewood sample settling for an extended time in the PSTL.

Figure 1.28 Setting of fine particle fraction in the PSTL (Test 49).

After 1200 minutes, the particle size distribution measured in the PSTL was as shown in Figure 1.29. This shows that the remaining particles are mostly below 6 microns in size.
Figure 1.29 Particle size distribution after an extended settling phase of Test 49.

After the above-mentioned initial tests, further investigations were made of the settling behaviour of the sediments. For example, in Test 60, particles from sample 1D were suspended at 0.55 m.s⁻¹, then allowed to settle at zero pipe velocity. Figure C.8 and Figure C.9 in Appendix C show typical settling curves, in which it can also be seen again that larger particles settle quicker than small ones.

A series of tests was carried out to determine the effect of pipe velocity on the settling phase. Settling tests were carried out at 0.013 m.s⁻¹, 0.036, 0.102, 0.23, and 0.34 m.s⁻¹. The results are shown in Figure C.11, Figure C.13, Figure C.14, Figure C.17 and Figure C.19 in Appendix C. A typical result is shown in Figure 1.30 below.

However, it is notable that the particle concentration falls as time increases at this velocity of 0.23 m.s⁻¹, which is above the velocity initially required to suspend the sediment (0.16 – 0.21 m.s⁻¹, Table 1.8).

Figure 1.30 Particle concentration as a function of time for settling of sample 1D at 0.23 m/s.
Further experiments investigated the form of the decay of particle concentration with time. Results are summarised in Figure C.20, Figure C.23, Figure C.24, Figure C.25 and Figure C.26 where exponential decay curves are shown as best fitted to the experimental data. The form of the exponential curves is

\[ C = C_\infty + (C_o - C_\infty) e^{(-\beta T)} \]

where \( C \) = concentration at time \( T \),
\( C_\infty \) = concentration after a large time,
\( \beta \) = decay constant.

Larger values of \( \beta \) represent quicker settling. Representative values of \( \beta \) are given in Table 1.10, where it can be seen that zero pipe velocity gives slowest settling, and 10 – 18 micron particles settle quickest.

<table>
<thead>
<tr>
<th>Test number</th>
<th>Figure</th>
<th>Pipe velocity m/s</th>
<th>( \beta ) for 3 – 10 micron particles</th>
<th>( \beta ) for 10 – 18 micron particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>68</td>
<td>Figure C.23</td>
<td>0</td>
<td>0.0011</td>
<td>-</td>
</tr>
<tr>
<td>67</td>
<td>Figure C.20</td>
<td>0.37</td>
<td>0.0035</td>
<td>-</td>
</tr>
<tr>
<td>70</td>
<td>Figure C.25</td>
<td>0.36</td>
<td>0.0035</td>
<td>-</td>
</tr>
<tr>
<td>70</td>
<td>Figure C.26</td>
<td>0.36</td>
<td>-</td>
<td>0.0060</td>
</tr>
</tbody>
</table>

The initial suspension of a dense sample, and its transport and settling phases have been described for test 49. Next, the re-suspension phase was studied in test 50. Following test 49, the PSTL was left recirculating the fluid over-night at a velocity of 0.018 m.s\(^{-1}\) (Reynolds number 1800) during which it was expected that settling would continue.

Next day, a re-suspension test (test 50) was carried out, which involved switching on the PSTL at a pipe velocity of 0.215 m.s\(^{-1}\) (wall shear stress 0.14 Pa) and logging the particle counts as usual for a period of 350 minutes. The results of this test are shown as a time log of particle concentrations in Figure 1.31.

![Test 50 Re-suspension test at 0.21 m/s](image)

**Figure 1.31** Time log of particle concentrations during re-suspension test 50 for Pinewood sediment sample

It is evident from a comparison of this figure with Figure 1.24 that particle concentrations after re-suspension for the larger particles (less than 80 ppb) are much lower than the original concentrations (1000 ppb) in the suspension and transport phases – and even the settling phase.
That is, the wall shear stress (0.14 Pa) at a pipe velocity of 0.215 m.s\(^{-1}\) is adequate to suspend loose sediment poured into the pipe, but is not adequate to re-suspend it after transport, dispersion around the pipe loop and a period of settling.

This requirement of a higher stress to re-suspend is in accord with the experience of some water authorities who find that flushing velocities of approximately 0.7 – 1.2 m.s\(^{-1}\) are required to clean pipes, depending on specific gravity and diameter.

During further tests, there were many opportunities to measure the re-suspension performance of various sediment samples, and the results are presented graphically in the Appendix C. A typical test result is shown below for sample 1D re-suspending at 0.62 m.s\(^{-1}\). The features of this test result are typical of all the findings:

- all the particles re-suspend within approximately 20 minutes, and
- larger particles suspend immediately, whereas finer particles suspend slower.

![Figure 1.32 Particle concentration as a function of time for the re-suspension of sample 1D at a pipe velocity of 0.62 m.s\(^{-1}\)](image)

### 1.3.9.5 Concentration as a function of height across the pipe

In a few tests, the concentration of particles was measured at various heights in the pipe. There was only a small gradient of particle concentration over the height of the pipe. Results are given in Figure C.4, Figure C.7, Figure C.31 and Figure C.34.

### 1.3.9.6 Concentration as a function of velocity

To find the “equilibrium” concentration corresponding to each velocity, sample 3A (which was a heavy sediment load) was inserted into the PSTL for a series of tests. First, the velocity was increased in steps, with each step extending over approximately 10 hours, and the concentration of suspended sediment in the pipe was measured after each step. Figure 1.33 shows the concentration for slowly increasing velocity.
Tests 78,79 Sample 3A. Slowly increasing velocity.

Figure 1.33 Particle concentration as a function of velocity for sample 3A

Test 82 Sample 3A Slowly decreasing velocity

Figure 1.34 Particle concentration as a function of velocity for slowly decreasing velocity

Secondly, Figure 1.34 shows the corresponding results for slowly decreasing velocity. There is some hysteresis evident in comparing these two graphs.

Settling appears to occur for velocity decreasing at approximately 0.07 m.s⁻¹, whereas suspension occurs in the velocity-increasing case between 0.07 and 0.15 m.s⁻¹.

However, the concept that there may be a simple equilibrium between suspended sediment concentration and pipe velocity, is discussed in section 1.3.9.8 below, where evidence based on this series of tests is presented to show that there is no true equilibrium between concentration and velocity for lower concentrations of particles.
1.3.9.7 Combination tests

Test 91 - 94 Settling of all particle > 3 micron at various speeds for sample 4A

![Graph showing particle concentration as a function of time for settling of sample 4A at various velocities. Fluid velocity was increased in steps, with no delay between steps.](image)

Figure 1.35 Particle concentration as a function of time for settling of sample 4A at various velocities. Fluid velocity was increased in steps, with no delay between steps.

Figure 1.35 shows that particle concentration falls with time for velocities at and below 0.2 m.s\(^{-1}\) for the moderate concentration sample 4A.

This effect was further investigated in Test 109. Figure 1.36 shows the results of this combination test in which the pipe velocity was slowly increased in small steps, with a delay between steps to allow equilibrium to be established between particles attached to the walls and particles in suspension.

However, at 0.25 m.s\(^{-1}\), the velocity was held constant for 66.7 hours, and it can be seen from the graph that the concentration of particles in suspension dropped by a factor of ten. These particles attached to the walls of the pipe. After the delay, the velocity was increased again in the same way, but the particles were not stripped back off the walls until a pipe velocity of 0.4 m.s\(^{-1}\) was reached because of some kind of “conditioning” of the wall layer.

This shows that there is no fixed relationship between sediment concentration in the fluid and fluid velocity for a given amount of particles in the system. Rather, there is a process of “conditioning” the wall layer with more particles attaching to the wall as time progresses.
Test 109 Sample 5: Re-suspension with slowly increasing speed

Figure 1.36 Particle concentration as a function of velocity for slowly increasing velocity for sample 5A

Test 97 - 101 Settling for speed decreasing, all particles, sample 4A.

Figure 1.37 Particle concentration as a function of time for settling of sample 4A at various speeds, beginning at 0.5 m.s\(^{-1}\), and reducing in steps

Figure 1.37 shows the reducing concentration of suspended particles in a series of speed reducing tests for sample 4A.

Figure 1.38 shows a similar “conditioning” of the wall layer of particles. In this case, the test comprised an initial re-suspension of particles at 0.25 m.s\(^{-1}\), followed by “settling” at 0.25 m.s\(^{-1}\), then a period of settling with the pump off. Next, a re-suspension was initiated at 0.25 m.s\(^{-1}\), but only a very reduced re-suspension concentration was achieved because of the conditioning of the wall during the 1500 minute “settling” process at 0.25 m.s\(^{-1}\).
Figure 1.38  Particle concentration as a function of time for sample 5A. Note that the re-suspension at time 3000 minutes does not recover the particles initially suspended at time zero.

1.3.9.8 Special effects

In summary, there were two notable effects discovered during the tests.

1. Particle concentration would decrease with time at pipe velocities of 0.2 m.s\(^{-1}\) – 0.35 m.s\(^{-1}\) for low concentrations of particles in suspension (but in the range existing in reticulation systems) as shown in Figure 1.30 and Figure C.25, whereas for high concentrations of particles in suspension, Figure 1.33 and Figure 1.34 showed that suspension should be maintained at these velocities. That is, some sort of particle “settling / conditioning” process operates at low particle concentrations to trap particles at the wall over a long time scale of order of 600 – 1000 minutes. Research into possible mechanisms indicate that this is most likely caused by Van de Waals forces acting on the small particles, which are often clay, with a probable flat, flaky form, which gives a height dimension in the range of 1 micron where Van de Waals forces are active.

2. After this “conditioning” process, the particles required considerably greater velocity to re-suspend. (see Figure 1.36 above).
1.4 Summary and Conclusions

The objective of the test-work is to develop data for use in the Particle Sediment Model (PSM). The PSM originally proposed was of simple form, requiring

- a velocity at which sediment would suspend,
- a velocity at which sediment would settle, and
- a settling velocity.

1. Tests carried out thus far indicate that the velocity (0.21 m.s\(^{-1}\)) and corresponding shear stress (0.14 Pa) to suspend samples injected into the PSTL to form a thick layer (e.g. 1-2 mm thick) is much less than the velocity (and shear stress) to re-suspend those samples after transport, dispersion and settling around the pipe loop for a period of approximately 16 hours. There appears to be a form of “conditioning” of the wall layer whereby particles attach to the wall at quite high velocities (e.g. in excess of 0.3 m.s\(^{-1}\)) and stay attached, so that gradually particles are removed from the fluid, although a velocity of 0.65 m.s\(^{-1}\) removed them.

2. The effect of consolidation for a week or more is to increase the shear stress to re-suspend particles in the Water Tunnel, although 3 month and 6 month results show little further increase.

3. The SG of the particles from YVW and SEWL is in the range of 1.3 - 2, with a mean value of 1.64. The Brisbane sample, however, had an SG of 1.97.

4. Tests carried out in the PSTL show that the sediment settles much slower than expected from Stokes settling of spherical particles of the same SG as the sediment samples. The larger particles settle quicker. Settling can be described by an exponential form for the decay of particle concentration with time. Thus, the settling velocity in pipe flow is not well predicted by Stokesian methods, but is rather more like fouling of pipes.

5. Thick sediment samples settled for a day or more exhibit a gel-like cohesion which probably arises from Van de Waals forces of attraction between the particles, but is very unlikely to arise from biological effects.

1.5 Recommendations

- Repeat these tests with Cast Iron Cement Lined pipes and establish the suspension, re-suspension, transport and settling performance of sediments for that type of pipe.
- Examine the sediment samples under a microscope to investigate the shape of the particles.
- Develop a model for the PSM computer program.
- Repeat the suspension, transport, settling and re-suspension tests for other sediment samples.
PART 2: PARTICLE SEDIMENT MODELLING

This part of the report documents the basic theory and the key equations used in the Particle Sediment Modelling (PSM) software. Two mechanisms responsible for accumulation of particles in a water distribution system are introduced. The gravitational settling mechanism has been implemented. The wall deposition mechanism is yet to be implemented in PSM. A CD containing PSM trial version accompanies this report. A case study was conducted in collaboration with Yarra Valley Water to validate PSM. PSM was found to predict particle concentration within ±50% of field measurements. A detailed account of the measurement and theory on particle wall deposition is presented.

PSM software needs to be further improved before it can be used as a working tool at water authorities. In particular, it is recommended to improve the accuracy and the user interface.

2.1.1 Introduction

The objectives of the Particle Sediment Modelling (PSM):

- Predict sediment mass distribution in water distribution systems;
- Predict particle mass into customer’s taps.

PSM requires input flow data from the hydraulic modelling as schematically shown in Figure 2.1. PSM also requires input of particle concentration loading at the inlet of the water reticulation zone. As PSM is independently developed, there is no restriction on the type of the hydraulic modelling software used. Detailed input data format and output data are illustrated in Appendix F.

![Figure 2.1 PSM modelling, input data: hydraulic modelling data, particle concentration loading at the inlet of the water zone.](image-url)
2.1.2 Particle Sediment Model

Two mechanisms (Figure 2.2) are responsible for particle mass build up in a water distribution system:
- Mechanism 1: settling of particles under gravity.
- Mechanism 2: deposition of particles onto pipe wall due to particle/pipe surface attractive forces, e.g. Von der War force.

**Figure 2.2** Mechanisms for particles build up in a pipe

### 2.1.2.1 Mechanism 1: gravitational settling model

A simple model has been developed for Mechanism 1 as shown in Figure 2.3:

**Figure 2.3** Gravitational settling model.
As can be seen from Figure 2.3, the dynamics of particles in a water pipe is characterised by the three statuses, depending on the velocity $u$:

1. $u > u_{rs}$, re-suspension of all sediments; $u_{rs}$ is the critical velocity beyond which particles are resuspended. $u_{rs}$ increases with the pipe diameter and is a function of particle diameter, density and packing of the sediment.

2. $u_d \leq u \leq u_{rs}$, particle mass transported through the pipe with no settling/re-suspension.

3. $u < u_d$, particles settling out at a downward velocity of $u_s$.

To characterise the settling statues of particles, a vertical particle cloud height $H_s$ is defined in Figure 2.4.

![Figure 2.4 Particle cloud height, defined by Hs](image)

A non-dimensional particles cloud height $s$ is defined below:

$$s = \frac{H_s}{d},$$

where $d$ is the pipe diameter. The settling statues of particles can be characterised by tracking $s$ using the following equation until $s$ become zero (i.e. complete settling out):

$$s(t + \Delta t) = s(t) - \frac{u_s \Delta t}{d}, \text{ for } u < u_d$$

It is obvious that:

- Particles fully suspended: $s=1$;
- Particles fully settled: $s=0$;
- Particles cloud partially settled out (i.e. a stratification as in Figure 2.4): $0 < s < 1$.

The parameters $u_{rs}, u_d, u_s$ were measured using the pipe test loop described in the 5th progress report (Grainge et al. 2003). A typical set of these parameters is listed in Table 2.1, obtained from testing particle samples from Yarra Valley Water.

**Table 2.1** A typical set of gravitational model parameters, based on Y. V. Water particle samples.

<table>
<thead>
<tr>
<th>$u_{rs}$ (m/s), for pipe diameter of 0.1m</th>
<th>$u_d$ (m/s)</th>
<th>$u_s$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>0.07</td>
<td>1.6×10^{-6}</td>
</tr>
</tbody>
</table>
2.1.2.2 Mechanism 2: particle wall deposition model

It was found from tests carried out using the pipe test loop, particles disappeared from the suspension in a wide range of velocities up to 0.3 m/s or more, whilst it was observed that particles re-suspended from the pipe bottom in the range of 0.15-0.25 m/s. An example of loss of particle mass to the pipe wall is shown in Figure 2.5. The pipe test loop was initially injected with a small quantity of particles, and the test loop was kept running at a fixed speed (0.337 m/s in this example) while the particle count reading was recorded over time. The decrease with time of the particle count indicates loss of particle mass to the pipe wall surface.

It is hypothesised that particles deposit onto the wall surface under Von-Der War force, which is different from settling under the gravity force (Mechanism 1). It can be shown from the Fick’s law (Appendix E) that:

\[
\frac{\partial C}{\partial t} = -\alpha (C - C_\infty)
\]

\[
C_w = \beta C_\infty
\]

where

- \(C\) - concentration of particles in suspension (mg/L, ppm)
- \(C_0\) - initial concentration of particles (mg/L, ppm)
- \(C_w\) - mass of particles on the wall, per unit volume of water (mg/L, ppm)
- \(C_\infty\) - final steady state concentration of particles (mg/L, ppm)
- \(\alpha\) - decay coefficient (-)
- \(\beta\) - wall mass coefficient (-)

It can be seen from Figure 2.5 that the wall deposition model based on eq(1) compares well with the experimental data, where an appropriate decay coefficient was used in eq(1).

It can be seen from eqs(1), (2) that:

- Particle concentration \(C\) increases with time, if \(C < C_\infty = C_w/\beta\), implying stripping of particles from the wall into suspension.
- Particle concentration \(C\) decreases with time, if \(C > C_\infty = C_w/\beta\), implying deposition of particles onto the wall from water.
- A steady state condition reaches when \(C = C_\infty = C_w/\beta\), and \(C\) stays constant with time.

An extensive laboratory test program was conducted to quantify \(\beta\), and the results are presented in section 2.4.

Once \(\beta\) is known, it is straightforward to calculate the particle mass at the wall using eq(2), in the steady state. The steady state mass of particles deposited on the wall per unit pipe length can be found:

\[
\frac{M_w}{L} = C_w \frac{1}{4} \pi d^2 = \beta C_\infty \frac{1}{4} \pi d^2
\]

where \(M_w/L\) is the particle mass per unit pipe length, \(d\) is the pipe diameter.

Table 2.2 shows a list of particle wall deposition parameters obtained from measuring particle samples supplied by the 4 water companies (YVW, UW, WC, SW). As illustration, particle mass per unit pipe length (100 mm diameter pipe) is included in the table, all with given input particle mass concentration of 0.5 ppm.
Figure 2.5 Particle concentration decays with time, a typical result from the pipe test loop.

Table 2.2 A comparison of the wall deposition data obtained in the CICL loop for four water authorities. The particles mass deposited on the pipe wall were calculated for three typical flow speeds based on $\beta$.

<table>
<thead>
<tr>
<th>Particles origin</th>
<th>Flow speed [m/s]</th>
<th>Parameter $\beta$ [-]</th>
<th>$C_\infty$ [ppm]</th>
<th>Mass (Mw/L) [g/m] for 100 mm pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yarra Valley Water (YVW)</td>
<td>0.07</td>
<td>6.14</td>
<td>0.5</td>
<td>0.024</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>2.57</td>
<td>0.5</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>1.08</td>
<td>0.5</td>
<td>0.004</td>
</tr>
<tr>
<td>United Water (UW)</td>
<td>0.07</td>
<td>10.11</td>
<td>0.5</td>
<td>0.039</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>3.34</td>
<td>0.5</td>
<td>0.013</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>2.57</td>
<td>0.5</td>
<td>0.010</td>
</tr>
<tr>
<td>Water Corporation (WC)</td>
<td>0.07</td>
<td>13.28</td>
<td>0.5</td>
<td>0.052</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>3.20</td>
<td>0.5</td>
<td>0.012</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>0.72</td>
<td>0.5</td>
<td>0.003</td>
</tr>
<tr>
<td>Sydney Water (SW)</td>
<td>0.07</td>
<td>3.00</td>
<td>0.5</td>
<td>0.012</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>1.70</td>
<td>0.5</td>
<td>0.006</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>0.98</td>
<td>0.5</td>
<td>0.004</td>
</tr>
</tbody>
</table>

2.1.3 PSM software

2.1.3.1 Software window platform

A window visual C++ platform was developed by NewPara Engineering Software, under a contract from CSIRO CMIT. The window platform provides user interface to run the PSM code, with the following features:

- Graphics to visually present the particle mass distribution through the water pipe network with time;
• User dialog boxes to interact individual pipes, enabling “adding” particles, inspecting particle mass data at any location, setting up parameters for the PSM engine;

• Export particle mass distribution via files.

2.1.3.2 PSM engine

“PSMSedimentCalculator.cpp”, the program behind the PSM engine, written in C++ is the main program containing all the key algorithms for calculating transport of the particle mass in the water distribution system.

Particle mass parameters described in Figure 2.6 are calculated at each time step for all the pipes:

- \( dM_{in} \), particle mass transport into the pipe, during time step \( \Delta t \);
- \( dM_o \), particle mass transport out of the pipe, during time step \( \Delta t \);
- \( M_x \), particle mass per unit length distribution along the pipe at time \( t \);
- \( M_s \), particle mass settled at time \( t \);
- \( M_w \), particle mass deposited at the wall at time \( t \) (not implemented yet).

Detailed mathematical equations to calculate the particle mass parameters are listed in Appendix D, based on Mechanism 1. Mechanism 2 is yet to be implemented in the future.

Figure 2.6 Particle mass in a pipe, calculated by PSM at each time step.

The followings are the main steps used in the PSM engine:

1. The particle mass output \( dM_o \) from each pipes at time \( t \) are used to calculate the mass input into the current pipe at the next time step \( t+\Delta t \):

\[
dM_{in}(t + \Delta t) = \frac{Q}{\sum Q_k} \sum dM_o(t)
\]

where \( Q \) is the flow rate in the pipe, \( Q_k \) is the \( k^{th} \) pipe connected to (and with flow into) the current pipe, and \( \sum \) is to all the pipes with flow into the current pipe. A function was developed to identify those pipes connected at the inlet of any given pipe.

2. Calculate particle mass parameters as described in Figure 2.6, given input mass \( dM_{in} \), using codes developed based on equations listed in Appendix A.

3. Calculate particle settling status parameter \( s \).

4. Repeat calculations for all the pipes.

5. Calculate the next time step from (1).
2.2 User Manual, PSM Trial Version 2003
This section has been included in the PSM trial version CD.

PSM Trial Version, 30 July 2003-07-30
CRC WQT 4.3.6
For CRC WQT member only

Data Preparation Steps
- Prepare hydraulic modelling data into the data format in “PSMInputDataTemplate.xls”, in the CD;
- Convert the data in the spread sheet into the 3 txt files (ascii format)
  H2Odata.txt,
  NodeData.txt
  MassDistribution.txt
  in the same form of the demonstration files in CD;
- Double click PSM.exe to run.

A Demonstration Run
- Run PSM.exe;
- Select Data Processing manual to clean the pipes;
- Choose a pipe, double click, you will see a pipe dialog box;
  enter 100 kg in suspension;
- Right click mouse, you can select to show Suspension Weight;
- Run from PSM engine from Data Processing/PSM manual, a dialog box pop up;
- Enter No. of time steps to 2000 (say, your choice);
- Click OK will start the run.
2.3 Case Study using PSM

2.3.1 Input/output

Hydraulic modelling was carried out for the Doncaster East water zone (Melbourne) using H2ONet at Yarra Valley Water. The flow vs time data at each pipe were used as input for particle sediment modelling (PSM). PSM runs were conducted for each day from 30 Sept to 10 Oct 2002, with the following parameter settings:

<table>
<thead>
<tr>
<th>PSM Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u_s )</td>
<td>4E-6 m/s</td>
</tr>
<tr>
<td>( u_d )</td>
<td>0.07 m/s</td>
</tr>
<tr>
<td>( u_{rs} ) for 100 mm pipe</td>
<td>0.20 m/s</td>
</tr>
<tr>
<td>Time step</td>
<td>36 sec</td>
</tr>
<tr>
<td>No. of steps per run</td>
<td>2400 (duration=24hrs)</td>
</tr>
<tr>
<td>Operating mode</td>
<td>Constant input loading</td>
</tr>
<tr>
<td>Pipe element resolution</td>
<td>1000 points</td>
</tr>
<tr>
<td>Pipe start condition</td>
<td>Clean</td>
</tr>
</tbody>
</table>

Particle concentration at the tank outlets was assumed to be 0.65 ppm, based on the field measurements (Nguyen et al. 2002). This determined the particle loading into the Doncaster East water zone.

An extraction of the input data is listed in Appendix F, containing the flow vs. time data, and pipe ID, node junction coordinates.

The simulation results were displayed on the screen during the runs and also saved in the output file “MassDistribution.txt”, as illustrated in Appendix F, where the particle mass distribution on 10 Oct 2002 is listed.

2.3.2 Validation of PSM

The accuracy of PSM was validated by comparing particle concentrations predicted by PSM and measured by filters in the field (refer to Nguyen et al. 2002 for the filter measurement technique). Approximately 20 particle concentration measurement filters were installed in the Doncaster East water zone to monitor the concentrations of particles suspended in water between Sept 2002 to Sept 2003. Predictions by PSM and measurements by filters are plotted in Figure 2.7 for comparison. The predictions are on average within approximately \pm 50\% of measurements. There are a few reasons for the discrepancy:

1. Some filters installed in dead-end courts were not modelled in the hydraulic modelling. Guess had to be made to use PSM data in locations close to the filter locations.
2. PSM started the simulation assuming pipes all clean, which were not true in reality.
3. It is not known the exact accuracy of the hydraulic modelling (performed with H2ONet). PSM relies on hydraulic modelling for the flow information.
4. PSM only accounts for settling due to gravity. Particle loss at pipe wall due to Mechanism 2 is not accounted for at the moment.
5. Concentration of particles suspended in water flow is a small figure, at an order approximately of 0.1-0.7 ppm. It was difficult to measure it accurately. The measurement accuracy of the filters is estimated within \pm 10-15\%.
2.3.3 Sedimentation Rate

2.3.3.1 Total Sedimentation rate

The average sedimentation rate in the Doncaster East water zone was found to be approximately 8 mg/day/m, estimated for the period between 30 Sep to 10 Oct 02, refer to Table 2.4.

Table 2.4 Total sedimentation rate: Doncaster East zone, 30 Sept to 10 Oct 02.

<table>
<thead>
<tr>
<th>Doncaster East Water Zone from 30 Sept to 10 Oct 02</th>
</tr>
</thead>
<tbody>
<tr>
<td>tank outlet concentration: 0.65 ppm</td>
</tr>
<tr>
<td>total mass settled: 17.6 kg</td>
</tr>
<tr>
<td>total particles in suspension: 2.5 kg</td>
</tr>
<tr>
<td>no. of days of simulation: 11 days</td>
</tr>
<tr>
<td>sedimentation rate (total zone): 66.66667 g/hr</td>
</tr>
<tr>
<td>total pipe length: 190 km</td>
</tr>
<tr>
<td>sedimentation rate per meter: 0.350877 mg/hr/m</td>
</tr>
<tr>
<td>8.421053 mg/day/m</td>
</tr>
</tbody>
</table>

2.3.3.2 Sedimentation Rate Distribution

The unit pipe length sedimentation rates expressed in mg/m per day across all the pipes are listed in Appendix F. Accumulative fraction of pipes vs. sedimentation rate is plotted in Figure 2.8. The vertical axis shows the accumulative percentage of pipes, at a sediment rate less than the corresponding reading at the horizontal axis.
Figure 2.8 Accumulative distribution of sedimentation rate over pipes. The y-axis shows the percentage of pipes with sedimentation rate less than the x-axis.

It is shown that approximately 23% pipes are clean; 65% of pipes have sedimentation rates less than 10 mg/m/day. Approximately 4% of pipes with sedimentation rates exceeding 30 mg/m/day. These are the “hot spots” dirty pipes need to be cleaned.

2.3.4 Case study conclusions

- PSM is validated and found to predict particle concentration within ±50% of field measurements.

- The accuracy of sedimentation prediction is expected to be in the same order, but with no available field sedimentation data for PSM validation at this stage.

- Total unit pipe length sedimentation rate in Doncaster East zone was found to be 8.4 mg/m/day during 30 Sept and 10 Oct 2002.

- It is possible to determine pipes with sedimentation rate above a given value. For example, it was found that 4% of pipes with sedimentation rates exceeding 30 mg/m/day, while there are approximately 23% pipes are free of sediment.
2.4 Pipe test loop data

Extensive laboratory test work was carried in the pipe test loop as reported in the 5th progress report (Grainger et al. 2003). The acrylic pipe loop was later changed to the cement pipe loop (CICL) as shown in Figure 2.9. The CICL pipes used in the pipe loop were standard resin-coated 100 mm diameter pipes supplied by South East Water.

Figure 2.9 Pipe test loop cement pipe with resin lining.

As stated previously in section 2.1.2.1, the second “particle mechanism” is related to the deposition of particles to the pipe wall surface. The deposition of particles on the pipe walls occurs over a wide range of velocities. The aim of the tests performed in the CICL pipe loop was to model the mechanism of wall deposition by analysing different effects such as pipe material, type of particle sediments and particle concentration.

The basics of wall deposition can be approached by a mass transfer formulation. The equations describing this phenomenon are introduced in section 2.1.2.2 and are given in detail in Appendix E.

2.4.1 Effect of the pipe material

The results collected in the cement (CICL) pipe loop were compared to those obtained in the acrylic pipe test loop reported in the 5th progress report (Grainger et al. 2003). The same experimental procedure was followed in both test loops (acrylic and cement).

The procedure was to inject a sediment sample in the test loop and run the test loop at a speed of 0.6 m/s for a period of two hours to ensure that all particles were suspended. Then the speed was switched over to a chosen value and particle count was monitored with time for typically overnight.
Figure 2.10 A comparison of particle/wall deposition process in PVC pipes and CICL pipes. The sediments were supplied by Yarra Valley Water.

Figure 2.10 shows an example of decay of the normalised particle concentration with time for both types of pipe. Where the particle concentration is normalised by the initial concentration $C_0$. The reduction in the particle concentration indicates a loss of particles to the pipe wall rather than settling out the bottom, since the velocity is still above the critical velocity for gravitational settling (i.e. $u>u_d \approx 0.06 \text{ m/s}$). This loss of particles to the wall is evident for all the velocities tested, from $u=0.07 \text{ m/s}$ up to $0.30 \text{ m/s}$.

It can be seen that there was a substantially more reduction in the particle concentration with the PVC pipes, indicating that there were more particles deposited on the walls for the acrylic pipe walls than the CICL pipes. All the tests performed at different speeds confirmed this trend, i.e. the amount of particles deposited on the wall of the acrylic pipes was larger than the amount deposited on the wall of the CICL pipes, for the same working condition (velocity, initial concentration).

The amount of particles deposited on the pipe wall is best characterised by the $\beta$ coefficient defined in section 2.1.2.1. This coefficient can be determined from the particle concentration vs. time reduction curves (e.g. Figure 2.10), using the following equation:

$$\beta = \frac{C_0 - C_\infty}{C_0}$$

where $C_0$ is the initial particle concentration at the start of the test, and $C_\infty$ is the final particle concentration when the reduction of the concentration reading reaches the steady state. Refer to Appendix B for detailed formulations.

Variation of the $\beta$ parameter with flow speed is plotted in Figure 2.11. It is observed that the $\beta$ parameter is more sensitive to the flow speed in the case of using the PVC pipe loop.
Figure 2.11 Comparison of the $\beta$ coefficient for the PVC pipe loop and the CICL pipe loop.

Figure 2.12 Estimation of the particles mass deposited on the wall for both PVC and CICL pipes of 100 mm diameters (sediment samples from YVW). The mass on the wall per unit length (in g/m) is plotted vs. the concentration in the water stream.

With parameter $\beta$ defined in Figure 2.12, it is now possible to quantify the steady state particle mass deposited on the surface of a pipe, using the equation described in section 2.1.2.2:

$$\frac{M_w}{L} = \beta C_\infty \frac{1}{4} \pi d^2$$

Such result is plotted in Figure 2.12, for pipe diameter of 100 mm, using $C_\infty$, the incoming flow particle concentration at the steady state, and the velocity as variables.
2.4.2 Effect of the particles concentration

To study the effect of the initial concentration of particles on the wall deposition process, two samples of different initial concentrations \(C_0 = 1.86, 24.78\) ppm were used. The particle samples were collected from the YV Water. Variation of \(\beta\) with the pipe flow velocity for these 2 samples is shown in Figure 2.13. It appears that \(\beta\) is not sensitive to the initial concentration, at least in the range tested. More work is required to check the sensitivity of \(\beta\) outside this range. The upper limit of particle concentration tested was limited by the dynamical range of the particle counter.

![Figure 2.13](image-url) Effect of the particles concentration on the wall deposition process. The initial concentration is defined as the mass of the particles divided by the pipe loop water mass.

2.4.3 Test of samples from 4 water companies

Four sediments samples collected from four water authorities were studied in the pipe test loop. The experimental procedure followed for each of the investigated samples was the same as before, i.e. the test samples were firstly injected into the pipe loop, and a high velocity of 0.6 m/s was set for 2 hours to homogenise the particles throughout the test loop, and then the test loop was switched to the test velocity, and the reduction of particle concentration with time was recorded over typically a period of 18 hours. The pipe flow velocities used for study are 0.07, 0.15 and 0.3 m/s.

2.4.3.1 Gravitational mechanism

For each sample the settling at zero velocity was measured. The flow in the test loop was set to run at 0.6 m/s for about two hours then the pump was turned off and the particle concentration was recorded with time.
The settling results presented in Figure 2.14 show that the settling due to gravity occurred within 1000 min or approximately 17 hours. This gives an approximate settling velocity of $u_s = 1.66 \times 10^{-6}$ m/s. This is the velocity below which gravitational settling kicks in, as described in detail in section 2.1.2.1, for Mechanism 1. This value is estimated to be $u_d = 0.06$ m/s for all the 4 sediment samples tested.

Re-suspension tests showed that $u_r = 0.15-0.25$ m/s, for 100 mm diameter pipe. Detailed data are presented in the 5th progress report.
2.4.3.2 Wall deposition mechanism

The effect of location on particle deposition is illustrated in Figure 2.15 (a) and (b), based on the particle samples supplied by the 4 water companies. More detailed data are included in Appendix G. The horizontal axis $C_\infty$ is the steady state particle concentration, which is a variable affecting the amount of deposited particle mass.

Figure 2.15 A comparison of the wall deposition for the different water authorities, YVW=Yarra Valley Water, UW=United Water, WC=Water Corporation, SW=Sydney Water. (a) 0.07m/s, (b) 0.15m/s.
In general, it can be seen from Figure 2.15 (a) and (b) that $Mw/L$, particle mass deposited per unit length, increases with $C_\infty$, but decreases with velocity. For all the velocities tested, the particles from UW (United Water) or WC (Water Corporation) showed the largest $Mw/L$ values at a given velocity and particle concentration. This suggests that the amount mass of particles deposited on the pipe wall follows a descending order of mass of UW/WC>mass of YVW>mass of SW, in terms of the influence of the location. Thus the tendency for particles to deposit on the wall is the strongest for particles collected from UW and WC.

It is known from our particle characterisation research work that the particles collected from UW are rich in Manganese (Mathe et al. 2003). It appears that this contributes to an increased tendency of deposition of particles to the pipe wall surface.

2.4.4 Steps to calculate particle mass deposited on the pipe wall

- Determine a typical mean pipe velocity, and water particle concentration (varies typically from 0.1-1.0 ppm);
- Select $\beta$ value, refer to Figure 2.13, typically $\beta=1-5$, depending on the velocity, and also on particle physical/chemical property;
- Obtain pipe diameter data $d$;
- Calculate mass per unit length using: \[ \frac{M_w}{L} = \beta C_\infty \frac{1}{4} \pi d^2. \]

It should be pointed that the present data is still of preliminary nature. It is prudent to validate the theory and data presented, using whatever means available.

2.5 Concluding Comments

- The concept of modelling transport of particles in the water distribution system is described and implemented by developing a particle sediment modelling (PSM) software, using the input data from the hydraulic modelling, but de-coupled from the hydraulic modelling software.
- Two mechanisms are responsible for particle mass build up in a water distribution system. Mechanism 1: gravitational settling. Mechanism 2: particle/wall deposition.
- Basic equations for Mechanism 1 & 2 are presented, with detailed formulations outlined in Appendix D & E.
- A trial version of PSM has been released to the sponsors, with Mechanism 1 implemented.
- Parameters used in Mechanism 1 & 2 are presented, based on particle samples supplied by 4 water companies.
- A case study was carried out using PSM to predict particle mass distribution in a water zone in YV Water. PSM was found to predict particle concentration within $\pm 50\%$ of field measurements.
- The mass of particle deposited on the pipe wall can be characterised using the $\beta$ coefficient. The steady state mass of particles deposited on the wall surface is found to increase with particle concentration, decreases with velocity, and varies with the type of particles. A simple calculation procedure is presented in section 2.4.4.
2.6 Recommendations

- The accuracy of PSM should be improved via refined modelling, and more laboratory and field measurements. A detailed technical program has been outlined in the preliminary stage-2 proposal. Most importantly, it is anticipated that if multiple particle size effect is considered, and Mechanism 2 is included, an improved accuracy could be achieved.

- The software data input module needs to be improved to make it easy to use for water companies. This requires additional software programming service.

References


APPENDIX A PARTICLE SIZE DISTRIBUTIONS

Figure A.1 Particle size distribution for Whittlesea tank sediment.

Figure A.2 Particle size distribution for Birts Hill storage tank sediment.
**Figure A.3** Particle size distribution for Wantirna Tank No.2 sediment.

**Figure A.4** Particle size distribution for Growler Hill storage tank sediment.
Figure A.5 Particle size distribution for sediment from a hydrant in Watts Court.

Figure A.6 Particle size distribution for sediment from Pinewood Drive hydrant.
### APPENDIX B RE-SUSPENSION RESULTS

<table>
<thead>
<tr>
<th>No.</th>
<th>Locations:</th>
<th>Consolidation Period</th>
<th>Shear stress $\text{Pa}$</th>
<th>Equivalent velocity in 100mm dia. Pipe $\text{m/s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Birts Hill wrs36</td>
<td>1day</td>
<td>0.18 - 0.26</td>
<td>0.23 - 0.28</td>
</tr>
<tr>
<td>2</td>
<td>Growler Hill wrs 59</td>
<td>1day</td>
<td>0.15 - 0.3</td>
<td>0.21 - 0.3</td>
</tr>
<tr>
<td>3</td>
<td>Warbuton wrs60</td>
<td>1day</td>
<td>0.22 - 0.31</td>
<td>0.26 - 0.31</td>
</tr>
<tr>
<td>4</td>
<td>Mt Cuelyn Wrs140</td>
<td>1day</td>
<td>0.13 - 0.19</td>
<td>0.2 - 0.24</td>
</tr>
<tr>
<td>5</td>
<td>Montrose HL</td>
<td>1day</td>
<td>0.13 -0.19</td>
<td>0.2 - 0.25</td>
</tr>
<tr>
<td>6</td>
<td>Nth emerald</td>
<td>1day</td>
<td>0.16 - 0.19</td>
<td>0.22 - 0.24</td>
</tr>
<tr>
<td>7</td>
<td>Sherbrooke</td>
<td>1day</td>
<td>0.18 - 0.26</td>
<td>0.23 - 0.28</td>
</tr>
<tr>
<td>8</td>
<td>YVW</td>
<td>1day</td>
<td>0.19 - 0.25</td>
<td>0.24 - 0.27</td>
</tr>
<tr>
<td>9</td>
<td>Panton hill wrs93</td>
<td>1day</td>
<td>0.15 -0.18</td>
<td>0.21 - 0.23</td>
</tr>
<tr>
<td>10</td>
<td>Memorial P wrs97</td>
<td>1day</td>
<td>0.15</td>
<td>0.21</td>
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<td>11</td>
<td>Whittlesea tank wrs129</td>
<td>1day</td>
<td>0.18 - 0.28</td>
<td>0.23 - 0.29</td>
</tr>
<tr>
<td>12</td>
<td>Olinda Wrs50</td>
<td>1day</td>
<td>0.11 - 0.23</td>
<td>0.17 - 0.26</td>
</tr>
<tr>
<td>13</td>
<td>Wantirna Storage =2</td>
<td>1day</td>
<td>0.37 - 0.43</td>
<td>0.34 - 0.37</td>
</tr>
<tr>
<td>14</td>
<td>Wantirna Storage =3</td>
<td>1day</td>
<td>0.2 -0.43</td>
<td>0.24 - 0.37</td>
</tr>
<tr>
<td>15</td>
<td>Whittlesea tank wrs129</td>
<td>1day</td>
<td>0.18 - 0.28</td>
<td>0.23 - 0.29</td>
</tr>
<tr>
<td>16</td>
<td>Whittlesea wrs130 Autoclave</td>
<td>1day</td>
<td>0.1 - 0.15</td>
<td>0.17 -0.21</td>
</tr>
<tr>
<td>17</td>
<td>Whittlesea wrs130 Gamma rays</td>
<td>1day</td>
<td>0.16 - 0.24</td>
<td>0.215 - 0.27</td>
</tr>
<tr>
<td>18</td>
<td>Whittlesea wrs130 Chlorine</td>
<td>1day</td>
<td>0.16 - 0.23</td>
<td>0.215 - 0.26</td>
</tr>
<tr>
<td>19</td>
<td>Olinda Wrs50</td>
<td>1day</td>
<td>0.11 - 0.23</td>
<td>0.17 - 0.26</td>
</tr>
<tr>
<td>20</td>
<td>Olinda Wrs51 Autoclave</td>
<td>1day</td>
<td>0.12 - 0.16</td>
<td>0.18 - 0.21</td>
</tr>
<tr>
<td>21</td>
<td>Olinda Wrs51 gramma rays</td>
<td>1day</td>
<td>0.15 - 0.19</td>
<td>0.21 -0.235</td>
</tr>
<tr>
<td>22</td>
<td>Olinda Wrs51 Chlorine</td>
<td>1 day</td>
<td>0.15 - 0.23</td>
<td>0.21 - 0.26</td>
</tr>
<tr>
<td>23</td>
<td>Pinewood drive Temp 48hrs</td>
<td>48hrs</td>
<td>0.18 - 0.26</td>
<td>0.23 - 0.28</td>
</tr>
<tr>
<td>24</td>
<td>Watts Court Temp 48hrs</td>
<td>48hrs</td>
<td>0.18 -0.26</td>
<td>0.23 - 0.28</td>
</tr>
<tr>
<td>25</td>
<td>Pinewood driveTemp</td>
<td>1day</td>
<td>0.16 - 0.25</td>
<td>0.215 - 0.27</td>
</tr>
<tr>
<td>26</td>
<td>Watts Court Temp</td>
<td>1 day</td>
<td>0.16 - 0.27</td>
<td>0.215 - 0.285</td>
</tr>
<tr>
<td>27</td>
<td>SEW Site 4</td>
<td>1 day</td>
<td>0.16 - 0.22</td>
<td>0.22 - 0.26</td>
</tr>
<tr>
<td>28</td>
<td>Templemore Drve draining line</td>
<td>1 day</td>
<td>0.15 - 0.16</td>
<td>0.21 - 0.215</td>
</tr>
<tr>
<td>29</td>
<td>Owen st. Doncaster</td>
<td>1 day</td>
<td>0.1 - 0.15</td>
<td>0.17 - 0.21</td>
</tr>
<tr>
<td>30</td>
<td>Templemore drve. During scouring</td>
<td>1 day</td>
<td>0.1 - 0.15</td>
<td>0.17 - 0.21</td>
</tr>
<tr>
<td>31</td>
<td>Beresford Court Doncaster</td>
<td>1 day</td>
<td>0.15 - 0.16</td>
<td>0.21 -0.215</td>
</tr>
<tr>
<td>32</td>
<td>Tucker rd Doncaster</td>
<td>1 day</td>
<td>0.1 - 0.15</td>
<td>0.17 -0.21</td>
</tr>
<tr>
<td>33</td>
<td>Loxley Court Doncaster</td>
<td>1 day</td>
<td>0.1 - 0.15</td>
<td>0.17 -0.21</td>
</tr>
<tr>
<td>34</td>
<td>Woodlea St. Doncaster</td>
<td>1 day</td>
<td>0.1 - 0.15</td>
<td>0.17 -0.21</td>
</tr>
<tr>
<td>35</td>
<td>Unknown 1</td>
<td>1 day</td>
<td>0.1 - 0.15</td>
<td>0.17 -0.21</td>
</tr>
<tr>
<td>36</td>
<td>Unknown 2</td>
<td>1 day</td>
<td>0.1 - 0.15</td>
<td>0.17 -0.21</td>
</tr>
<tr>
<td>37</td>
<td>SEW</td>
<td>2 day</td>
<td>0.18 - 0.21</td>
<td>0.23 - 0.25</td>
</tr>
<tr>
<td>38</td>
<td>YVW panorama tank</td>
<td>1 day</td>
<td>0.17 - 0.26</td>
<td>0.22 - 0.28</td>
</tr>
<tr>
<td>39</td>
<td>SEW( Wantirna + Cranbourne)</td>
<td>2 day</td>
<td>0.1 - 0.15</td>
<td>0.17 - 0.21</td>
</tr>
<tr>
<td>40</td>
<td>United Water</td>
<td>1 day</td>
<td>0.1 - 0.14</td>
<td>0.17 - 0.20</td>
</tr>
<tr>
<td>41</td>
<td>Brisbane Water</td>
<td>1 day</td>
<td>0.15 - 0.18</td>
<td>0.21 - 0.23</td>
</tr>
<tr>
<td>41a</td>
<td>Brisbane Water Repeat</td>
<td>2 day</td>
<td>0.15 - 0.23</td>
<td>0.21 - 0.26</td>
</tr>
<tr>
<td>42</td>
<td>Sydney Water</td>
<td>1 day</td>
<td>0.15 - 0.18</td>
<td>0.21 - 0.23</td>
</tr>
</tbody>
</table>
APPENDIX C  PSTL RESULTS OCT 2002 – APRIL 2003

Test 55  Re-suspension at 0.42 m/s after weekend settling

Figure C.1  Re-suspension at 0.42 m.s\(^{-1}\) after a weekend of settling for sample 1C.

Test 56  Re-suspension of sample 1C at 0.42 m/s after 4 days settling

Figure C.2  Re-suspension of sample 1C at 0.42 m.s\(^{-1}\) after 4 days of settling.
Figure C.3 Particle concentration in PSTL as a function of time for the fresh sample 1D after 4 days settling. The peaks of concentration correspond to the increased concentration at the site of injection of the sample moving around the pipe loop past the HACH particle counter.

Test 58 Vertical traverse of total particle count for sample 1D immediately after pump was switched off

Figure C.4 Particle concentration as a function of height from the bottom of the pipe for sample 1D at time = 37 minutes. This shows substantially uniform concentration across the pipe.
Figure C.5 Particle concentration as a function of height across the pipe after 90 minutes of settling for sample 1D, and for various particle sizes.

Figure C.6 Particle concentration as a function of distance across the pipe for sample 1D, after 184 minutes of settling at zero velocity.
**Figure C.7** Concentration of 20 micron particles as a function of distance across the pipe and as a function of time. Sample 1D. Zero velocity.

**Figure C.8** Particle concentration as a function of settling time for sample 1D after initial suspension at 0.55 m/s$^{-1}$. Particles 3 – 10 micron settle in approximately 500 minutes, but particles larger than 18 micron settle within 100 minutes. Sampling probe at the pipe centreline.
Figure C.9 Concentration of particles at the bottom of the pipe as a function of time for sample 1D settling at zero pipe velocity.

Figure C.10 Particle volume concentration as a function of particle size for sample 1D at time=36.5 minutes after beginning to settle. Particles assumed to be spherical for this calculation.
Test 63 Sample 1D. Settling at 0.013 m/s after suspension at 0.62 m/s.

Figure C.11 Particle concentration as a function of settling time for sample 1D. Initial suspension was obtained with a pipe velocity of 0.62 m.s⁻¹, which was followed by a “settling” of particles at a pipe velocity of 0.013 m.s⁻¹.

Test 64. Suspension of sample 1D at 0.62 m/s.

Figure C.12 Particle concentration as a function of time for a re-suspension process for sample 1D. Sediment was re-suspended as 0.62 m.s⁻¹. Note that the larger particles suspended immediately, whereas the finer particles took longer.
**Figure C.13** Particle concentration as a function of time for sample 1D "settling" at 0.036 m.s$^{-1}$ after initial re-suspension at 0.62 m.s$^{-1}$.

**Figure C.14** Particle concentration as a function of time for sample 1D "settling" at a pipe velocity of 0.102 m.s$^{-1}$ after initial re-suspension at 0.62 m.s$^{-1}$ (see figure below).
Figure C.15 Particle concentration as a function of time for sample 1D re-suspending at 0.62 m.s$^{-1}$. Finer particles take longer to re-suspend.

Figure C.16 Particle concentration as a function of time for re-suspension of sample 1D by a fast pump start. Larger particles suspend immediately, but fine particles do not.
Figure C.17 Particle concentration as a function of time for sample 1D. Initial re-suspension at 0.62 m.s^{-1} was followed by “settling” at 0.23 m.s^{-1} for 5000 minutes. A slow reduction of suspended particles was observed, even at this substantial velocity which would suspend the initial sediment load.

Figure C.18 Particle concentration as a function of time for the initial re-suspension of sample 1D for test 66 (see figure above).
Figure C.19 Particle concentration as a function of time for sample 1D suspended as 0.62 m.s\(^{-1}\), then “settling” at a pipe velocity of 0.34 m.s\(^{-1}\).

Figure C.20 Particle concentration during a “settling” process at 0.37 m.s\(^{-1}\) as a function of time for sample 1D particles in the size range 3 – 10 microns.
**Figure C.21** Particle concentration as a function of time for the initial re-suspension of sample 1D at 0.62 m.s\(^{-1}\) for test 67.

**Figure C.22** Particle concentration as a function of time for settling of sample 1D at zero velocity after the completion of test 67 settling at 0.34 m.s\(^{-1}\) pipe velocity.
Test 68 Sample 1D Exponential decay of particle count at zero velocity

Exponential curve:

\[ \text{Particle count / mL} = N_b + (N_s - N_b) \cdot \exp(- (\text{Beta} \times \text{Time})^k) \]

where \( N_b = 600, \ N_s = 2120, \ \text{Beta} = 0.0011, \ k = 1 \)

Figure C.23 Particle concentration as a function of time for settling of sample 1D at zero velocity after the completion of test 67 settling at 0.34 m.s\(^{-1}\). The exponential form of the decay of concentration is shown.

Test 70 Sample 1E (Salted) Re-suspension at 0.62 m/s

Figure C.24 Particle concentration during re-suspension as a function of time for sample 1E with salt added to change the conductivity of the fluid in the PSTL. Particle concentrations rose slightly compared with test 67 which had the same particles.
**Figure C.25** Concentration of 3 - 10 micron particles as a function of time for "settling" of sample 1E (salted) at a pipe velocity of 0.355 m.s⁻¹. Comparison with Figure C.20 shows the same decay constant, Beta=0.0035.

**Figure C.26** Concentration of 10-18 micron particles as a function of time for "settling" of sample 1E particles at a pipe velocity of 0.355 m.s⁻¹.
Figure C.27 Particle concentration as a function of time for sample 2A. Initial suspension velocity was 0.57 m.s\(^{-1}\), then at time = 110 minutes the pipe velocity was reduced to 0.21 m.s\(^{-1}\). Final concentrations after approximately 1000 minutes were similar to the initial background concentrations.

Figure C.28 Particle concentration as a function of pipe velocity for sample 3A (very heavy sediment load). Pipe velocity was increased slowly, with time for substantial equilibrium to establish between settled and suspended load.
Figure C.29 Particle concentration as a function of velocity for sample 3A. Velocity was slowly decreased to allow substantial equilibrium to establish between settled and suspended sediment.

Figure C.30 Particle concentration as a function of time for settling of sample 3A. Initial re-suspension was at 0.39 m.s\(^{-1}\). “Settling” was at 0.05 m.s\(^{-1}\) pipe velocity.
Figure C.31 Particle concentration as a function of height across the pipe for sample 3A. Pipe velocity 0.4 m.s\(^{-1}\).

Figure C.32 Particle concentration as a function of height across the pipe for sample 3A after 12 hours "settling" at 0.1 m.s\(^{-1}\) pipe velocity. Initial suspension was at 0.47 m.s\(^{-1}\).
Test 88  Vertical traverse after 8 hours settling at 0.05 m/s

Figure C.33 Particle concentration as a function of height across the pipe for sample 3A after 8 hours "settling" at a pipe velocity of 0.05 m.s⁻¹. Initial re-suspension was at 0.47 m.s⁻¹.

Test 89 Vertical traverse after 40 hours settling at 0.05 m/s

Figure C.34 Particle concentration as a function of height across the pipe for sample 3A "settling" at a pipe velocity of 0.05 m.s⁻¹ for 40 hours. Initial re-suspension was at 0.47 m.s⁻¹.
Tests 85-89 Average particle counts at various conditions

0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5

Particle count / mL.

0 100 1,000 10,000 100,000 1,000,000

Full suspension then 12 hours settling at 0.1 m/s
Full suspension, then 8 hours settling, then 40 hours settling at 0.05 m/s

Figure C.35 Particle concentration of sample 3A as a function of pipe velocity at various times in tests 85 to 89.

Test 91 - 94 Settling of all particle > 3 micron at various speeds for sample 4A

0 500 1000 1500 2000 2500 3000 3500 4000 4500

Time (min)

0 100 1000 10,000 100,000 1,000,000

0.5 m/s
0.2 m/s
0.1 m/s
0.05 m/s
0.03 m/s

Figure C.36 Particle concentration as a function of time for settling of sample 4A at various velocities. The tests were run in succession, with the speed increasing, and the 0.03 m.s\(^{-1}\) test followed a suspension / settling episode which left approximately 8,000 particles / mL. After the 0.03 m.s\(^{-1}\) test, the particle concentration was approximately 2000, which was the starting concentration for the 0.05 m.s\(^{-1}\) test, and so on.
Figure C.37 Particle concentration as a function of time for sample 4A "settling" at 0.2 m.s⁻¹.

Figure C.38 Particle concentration as a function of time for sample 4A "settling" at 0.05 m.s⁻¹.
Figure C.39 Particle concentration as a function of time for "settling" of sample 4A at various speeds. Initially the speed was set at 0.5 m.s\(^{-1}\), then it was reduced in steps and the concentration measured with time at each step. No time delay was permitted at the beginning of each step reducing the velocity, so the initial concentration at each velocity is the final concentration at the next higher speed.

Figure C.40 Particle concentration as a function of time for initial operations with sample 5A.
Figure C.41 Total particle concentration as a function of time for the initial suspension of sample 5A at 0.16 m.s\(^{-1}\).

Figure C.42 Total particle concentration as a function of time over an extended period for sample 5A after suspension and “settling” at 0.16 m.s\(^{-1}\). See Figure C.41 for the initial suspension.
Figure C.43 Particle concentration as a function of time for re-suspension of sample 5A.

Figure C.44 Particle concentration as a function of time for re-suspension of sample 5A corresponding to a speed increase from 0.25 m.s\(^{-1}\) to 0.315 m.s\(^{-1}\).
Test 109 Sample 5: Re-suspension with slowly increasing speed

![Graph showing particle count as a function of velocity for slowly increasing pipe velocity for sample 5A.](image)

**Figure C.45** Particle concentration as a function of velocity for slowly increasing pipe velocity for sample 5A. Note that the concentration decreased with time for the period where the velocity was held constant at 0.25 m.s\(^{-1}\).

Test 111,112 Sample 5: Operations at 0.25 m/s

![Graph showing particle concentration as a function of time for sample 5A.](image)

**Figure C.46** Particle concentration as a function of time for sample 5A for a sequence of suspension, “settling” at 0.25 m.s\(^{-1}\), settling at zero velocity, then re-suspension at 0.25 m.s\(^{-1}\). Note that the final re-suspension does not recover the particles initially suspended at time just greater than zero.
PARTICLES IN WATER DISTRIBUTION SYSTEMS

APPENDIX D  PSM

d pipe diameter (m)
L pipe length (m)
dMi particle mass transport into the pipe, during time step Δt; (kg)
dMo particle mass transport out of the pipe, during time step Δt; (kg)
M(x) particle mass per unit length distribution along the pipe at time t; (kg/m)
Ms particle settled at time t; (kg)
s the ratio of particle cloud height over pipe diameter (-)
t time (s)
u average velocity in pipe (m/s)
Δt time step (s)

The key particle mass transport equations are listed in the following sections; these formulations are implemented in the following C++ function:

\[\text{PSMSedimentCalculator::PipeMassTransport (double } u, \text{ double } u_s, \text{ double } u_d, \text{ double } u_r, \text{ double } dt, \text{ double } L, \text{ double } D)\]

1. Case \( u > u_r \)

In this case, particles are assumed to be re-suspended instantly.

1.1 \( u \Delta t \leq L \)

\[M(x) = M(x) + \frac{Ms}{L}, x \in 0, L\]
\[Ms = 0\]
\[\Delta Mo = \int_{L-u \Delta t}^{L} M(x) \, dx\]
\[M(x) = M(x - u \Delta t), x \in u \Delta t, L\]
\[M(x) = \frac{\Delta Mi}{u \Delta t}, x \in 0, u \Delta t\]
\[s = 1\]

1.2 \( u \Delta t > L \)

\[\Delta Mo = \Delta Mi \ast \frac{\Delta t - L/u}{\Delta t}\]
\[M(x) = M(x) + \frac{Ms}{L}, x \in 0, L\]
\[Ms = 0\]
\[s = 1\]
\[\Delta Mo = \Delta Mo + \int_{0}^{L} M(x) \, dx\]
\[M(x) = \frac{\Delta Mi}{u \Delta t}, x \in 0, L\]
2. $u_d < u \leq u_{rs}$
Particles move through the pipe with no change in mass.

2.1 $u \Delta t \leq L$

$$\Delta M_o = \int_{L-u\Delta t}^L M(x)dx$$

$$M(x) = M(x-u\Delta t), x \in u\Delta t, L$$

$$M(x) = \frac{dM_i}{u\Delta t}, x \in 0, u\Delta t$$

2.2 $u \Delta t > L$

$$\Delta M_o = \Delta M_i \cdot \frac{\Delta t - L/u}{\Delta t}$$

$$\Delta M_o = \Delta M_o + \int_0^L M(x)dx$$

$$M(x) = \frac{\Delta M_i}{u\Delta t}, x \in 0, L$$

3. $0< u \leq u_d$
Particles settle out with a settling velocity of $u_s$, the settling position is described by $s$.

3.1 $u \Delta t \leq L$

if $\frac{ud\Delta t}{d} \geq s$:

$$M_s = M_s + \Delta M_i$$

$$t_s = \frac{sd}{u_s}$$

$$\Delta x = ut_s$$

$$M_s = M_s + \int_0^{L-\Delta x} M(x)dx + 0.5 \int_{L-\Delta x}^L M(x)dx$$

$$\Delta M_o = 0.5 \int_{L-\Delta x}^L M(x)dx$$

$$M(x) = 0, x \in 0, L$$

$s = 0$

if $\frac{ud\Delta t}{d} < s$:...
\[ M_s1 = 0.5 \frac{u_s \Delta t}{s d} \int_{L-u\Delta t}^{L} M(x) \, dx \]

\[ \Delta M_o = \int_{L-u\Delta t}^{L} M(x) \, dx - \Delta M_s1 \]

\[ M(x) = M(x-u\Delta t), \, x \in u\Delta t, L \]

\[ M(x) = \frac{\Delta M_i}{u\Delta t}, \, x \in 0, u\Delta t \]

\[ \Delta M_s = \frac{u_s \Delta t}{s d} \int_{0}^{L} M(x) \, dx + \Delta M_s1 \]

\[ Ms = Ms + \Delta Ms \]

\[ M(x) = M(x) - M(x) \frac{u_s \Delta t}{s d}, \, x \in 0, L \]

\[ s = s - \frac{u_s \Delta t}{d} \]

### 3.2 \( u\Delta t > L \)

if \( \frac{L u_s}{d u} \geq s \):

\[ Ms = Ms + \Delta M_i \]

\[ \Delta x = \frac{sd}{u_s}, \quad L - \Delta x/2 \]

\[ \Delta M_s = \int_{0}^{L-\Delta x/2} M(x) \, dx \]

\[ Ms = Ms + \Delta Ms \]

\[ \Delta M_o = \int_{L-\Delta x/2}^{L} M(x) \, dx \]

\[ M(x) = 0, \, x \in 0, L \]

if \( \frac{L u_s}{d u} < s \)

\[ \Delta y = \frac{u_s L}{u} \]

\[ \Delta M_s = \frac{\Delta y}{2sd} \int_{0}^{L} M(x) \, dx \]

\[ Ms = Ms + \Delta Ms \]

\[ \Delta M_o = \int_{0}^{L} M(x) \, dx - \Delta Ms \]

\[ \Delta M_s1 = \frac{L u_s}{usd} \Delta M_i \]

\[ Ms = Ms + \Delta Ms1 \]

\[ \Delta M_o = \Delta M_o + \Delta M_i \left(1 - \frac{L u_s}{usd}\right) \left(1 - \frac{L}{u\Delta t}\right) \]

\[ M(x) = \frac{\Delta M_i}{u\Delta t} \left(1 - \frac{L u_s}{usd}\right), \, x \in 0, L \]
4. *u=0*

Particles settling out, zero mass in and out of the pipe.

if \( \frac{u_i \Delta t}{d} \geq s \):

\[
M_s = M_s + \int_0^L M(x)dx
\]

\( M(x) = 0, x \in [0, L] \)

\( \Delta M_0 = 0 \)

\( s = 0 \)

if \( \frac{u_i \Delta t}{d} < s \) and \( s > 0 \):

\[
M_s = M_s + \frac{u_i \Delta t}{sd} \int_0^L M(x)dx
\]

\( s = s - \frac{u_i \Delta t}{d} \)

\( M(x) = M(x) - M(x) \frac{u_i \Delta t}{sd}, x \in [0, L] \)

\( \Delta M_0 = 0 \)

5. *\( u_{rs} \) correction equation: pipe diameter effect*

\[
u_{rs} = \frac{f_{100}}{f} \sqrt{\frac{f_{100}}{f}}
\]

\[
f = (1.14 - 2 \log_{10}(\frac{\epsilon}{d} + \frac{21.25}{Re^{0.7}}))^{-2}
\]

where \( f \) is the pipe friction coefficient (refer to Blevins 1984), \( \epsilon \) is the pipe roughness, the subscript of 100 denotes the pipe diameter of \( d=100 \) mm.

The equations are used to calculate \( u_{rs} \) for any pipe diameter, based on the \( u_{rs} \) data at \( d=100 \) mm. The conversion is based on the fact that it is the shear stress which controls the critical condition at which sediment re-suspends.

An example of \( u_{rs} \) conversion is listed in Table D.1

**Table D.1 \( u_{rs} \) variation with pipe diameter \( d \).**

<table>
<thead>
<tr>
<th>( d ) (mm)</th>
<th>100</th>
<th>87</th>
<th>151</th>
<th>387</th>
<th>626</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u_{rs} ) (m/s)</td>
<td>0.20</td>
<td>0.196</td>
<td>0.211</td>
<td>0.237</td>
<td>0.256</td>
</tr>
</tbody>
</table>

Note: at the moment, the conversion only accounts the effect of pipe diameter variation (with fixed roughness). It is not the intention of these equations to account for the effect of roughness on the critical shear stress, even though it is used in the friction coefficient calculation.

Re-suspension occurs if the flow shear stress at the sediment bed > a critical shear stress. The flow shear stress increases with roughness as suggested by the friction equation. It is also known from laboratory experience that the critical shear stress increases with surface roughness (Nguygen and Mehid 2003). More work is needed to fully quantify these data.
1. Introduction

The process of deposition of particles on the pipe walls in a reticulation system can be described as a mass transfer process in which fine particles diffuse from suspended in the water onto the pipe wall.

2. Mathematical formulation:

The particle mass transfer rate can be quantified in terms of mass flux, which is the amount of particle material flowing through the unit cross-sectional area per unit of time. According to the Fick's 1st law, the transfer of a solute per unit of area:

\[ J = -D \frac{\partial C}{\partial t} \]  

where \( J \) is the particle mass flux, \( C \) is the concentration of the solute, \( D \) is the diffusion coefficient and \( r \) the distance.

Rewrite eq(1) in terms of particle mass:

\[ \frac{\partial m}{\partial t} = -D \frac{\partial C}{\partial r} \]  

where \( m = \frac{\partial m}{\partial t} \), \( t \) is the diffusion time and \( A \) is the lateral area of the pipe wall given by:

\[ A = \pi d L \]  

where \( d \) is the pipe diameter and \( L \) the pipe length.

The concentration of the particles in a fixed volume is given by:

\[ C = \frac{m}{V} = \frac{m}{\pi d^2 L / 4} \]  

\( V \) is the volume of the pipe section under consideration.

The previous equations lead to:

\[ \frac{d}{4} \frac{\partial C}{\partial t} = -D \frac{\partial C}{\partial r} \]  

\[ \text{(5)} \]
Assuming that all the mass transfer occurs in the vicinity of the pipe wall, the distance \(\Delta r\) in which the transfer predominates, is represented by the boundary layer thickness \(\delta\), thus the Equation (5) can be re-written as:

\[
\frac{\partial C}{\partial t} = -\frac{4D}{d} \frac{\Delta C}{\delta}
\]  

(6)

Introducing \(\alpha\) coefficient:

\[
\frac{\partial C}{\partial t} = -\alpha (C - C_\infty)
\]

(7)

Where \(\alpha = \frac{4D}{d} \frac{d}{\delta}\) and \(C_\infty\) is the final steady state concentration of the particles remaining in the water after the particle mass transfer to the pipe wall ceases.

The solution of Equation (7) has a solution of the following form:

\[
C(t) = (C_0 - C_\infty) \exp(-\alpha t) + C_\infty
\]

(8)

This equation satisfies the conditions:

- \(C(0) = C_0\), which is the initial concentration of particles injected in the system starting from the condition of clean wall.
- \(C(\infty) = C_\infty\).

These conditions lead to the following equation:

\[
C_0 = C_\infty + C_W
\]

(9)

Where \(C_W\) is the concentration of particles deposited on the pipe wall.

Let’s define the non-dimensional concentration \(C^*\) by:

\[
C^* = \frac{C}{C_0}
\]

(10)

Then the Equation (8) reduces to:

\[
C^*(t) = (1 - \gamma) \exp(-\alpha t) + \gamma
\]

(11)

where:

\[
\gamma = \frac{C_\infty}{C_0}
\]

(12)
Figure E.1 represents a typical evolution of the concentration governed by equation (11).

3. Evaluation of the mass of particles on the wall:

Let’s assume that the amount of particles remaining in the fluid is a fraction of the particles on the pipe’s wall, and let’s define a coefficient $\beta$:

$$C_W = \beta C_\infty$$

(13)

Dividing Equation (9) by $C_\infty$, and using Equations (12) and (13), we can re-write:

$$\frac{1}{\gamma} = 1 + \beta$$

(14)

Thus:

$$\beta = \frac{1 - \gamma}{\gamma} = \frac{C_0 - C_\infty}{C_0}$$

(15)

The coefficient $\beta$ can be deduced from the curve fit giving the coefficient $\gamma$. In order to express the mass on the wall in terms of $\beta$, let’s write:
\[ C_w = \frac{M_w}{V} = \beta C_\infty \]  

(16)

where \( m_w \) is the mass of particles on the wall, Equation (16) can be re-written as:

\[ M_w = V \beta C_\infty = S L \beta C_\infty \]  

(17)

where \( S \) is the cross-sectional area of the considered pipe and \( L \) the length of the pipe. Expressing the mass per unit pipe length, Equation (17) becomes:

\[ \frac{M_w}{L} = \beta C_\infty \frac{\pi d^2}{4} \]  

(18)

The practical use of Equation (18) to estimate the mass of particles deposited on the wall is as follows:

- Measure the concentration of particles in the water flow;
- Estimate the \( \beta \) parameter from the experimental data;
- Use equation eq(18) to calculate the mass on the wall.

**Figure E.2** Typical concentration decay vs. time.

A typical such test result is presented in Figure E.2, where particles were released into a clean pipe \((C^*(0)=1)\) then the concentration was monitored with time until reaching a steady state value of \( C_\infty \).
APPENDIX F  PSM CASE STUDY

**Input data to PSM**


<table>
<thead>
<tr>
<th>PIPE ID</th>
<th>From Node To Node</th>
<th>Length (m)</th>
<th>Diameter (mm)</th>
<th>Material</th>
<th>Roughness</th>
<th>Flow (L/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2050 M184_161</td>
<td>7000</td>
<td>0.1</td>
<td>626 DICL</td>
<td>0.8</td>
<td>744.09 744.97 743.85 743.74 743.61</td>
<td></td>
</tr>
<tr>
<td>2052</td>
<td>7000 STR_179</td>
<td>0.1</td>
<td>750 DICL</td>
<td>0.8</td>
<td>92.93 89.49 89.16 85.6 81.15</td>
<td></td>
</tr>
<tr>
<td>2054</td>
<td>7004 M184_163</td>
<td>20.11</td>
<td>626 DICL</td>
<td>0.8</td>
<td>744.09 744.97 743.85 743.74 743.61</td>
<td></td>
</tr>
<tr>
<td>2056 DON3979</td>
<td>FE5168</td>
<td>54.57</td>
<td>626 DICL</td>
<td>0.17</td>
<td>-21.06 -21.13 -21.11 -21.68 -20.6</td>
<td></td>
</tr>
<tr>
<td>2060 DON3971</td>
<td>FE5170</td>
<td>201.03</td>
<td>626 DICL</td>
<td>0.6</td>
<td>12.62 12.67 12.65 13 12.37</td>
<td></td>
</tr>
<tr>
<td>2064 DON4718</td>
<td>PE5387</td>
<td>5.24</td>
<td>87 DICL</td>
<td>0.6</td>
<td>-0.12 -0.12 -0.12 -0.13 -0.12</td>
<td></td>
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**Output data from PSM**

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APPENDIX G  PIPE TEST LOOP DATA

Figure G.1 A comparison of the concentration decay for PVC and CICL loops for a flow speed of 0.07 m/s.

Figure G.2 A comparison of the concentration decay for PVC and CICL loops for a flow speed of 0.11 m/s.
**Figure G.3** A comparison of the concentration decay for different water authorities sample for a flow speed of 0.07 m/s.

**Figure G.4** A comparison of the concentration decay for different water authorities sample for a flow speed of 0.15 m/s.
Figure G.5 A comparison of the concentration decay for different water authorities sample for a flow speed of 0.3 m/s.
Research Report

Water Quality and Health Risks from Urban Rainwater Tanks

The Cooperative Research Centre for Water Quality and Treatment is Australia's national drinking water research centre. An unincorporated joint venture between 29 different organisations from the Australian water industry, major universities, CSIRO, and local and state governments, the CRC combines expertise in water quality and public health.

The CRC for Water Quality and Treatment is an unincorporated joint venture between:

- ACTEW Corporation
- Australian Water Quality Centre
- Australian Water Services Pty Ltd
- Brisbane City Council
- Centre for Appropriate Technology Inc
- City West Water Limited
- CSIRO
- Curtin University of Technology
- Department of Human Services Victoria
- Griffith University
- Melbourne Water Corporation
- Monash University
- Orica Australia Pty Ltd
- Power and Water Corporation
- Queensland Health Pathology & Scientific Services
- RMIT University
- South Australian Water Corporation
- South East Water Ltd
- Sydney Catchment Authority
- Sydney Water Corporation
- The University of Adelaide
- The University of Queensland
- The University of Western Sydney
- The University of Technology, Sydney
- University of South Australia
- University of Technology Sydney
- Water Services Association of Australia
- Yarra Valley Water Ltd

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Water Quality and Health Risks from Urban Rainwater Tanks

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