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# PARTICULATE PROPERTY TESTING REPORT, GUNNS PULP MILL

by

A Mariani and W C Glamore

Technical Report 2010/10
August 2010
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THE UNIVERSITY OF NEW SOUTH WALES
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING
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The work reported herein was carried out at the Water Research Laboratory, School of Civil and Environmental Engineering, University of New South Wales, acting on behalf of the client.

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# 1. INTRODUCTION

Gunns Limited (Gunns) proposes to build a bleached kraft pulp mill in Bell Bay, Tasmania. The pulp mill will comprise an ocean outfall to discharge effluent 2.7 km offshore from the north coast of Tasmania (see Figure 1). Approval by the regulatory authorities to commence the pulp mill operations requires the undertaking of a comprehensive hydrodynamic modelling and measurement study to characterize the fate of the mill effluent when released into Bass Strait.

The study program includes several modelling related tasks that can be summarised as:

(i) Far-field hydrodynamic modelling

(ii) Near-field modelling

(iii) Sediment transport modelling

(iv) Wave modelling

(v) Field measurement program.

This report solely focuses on the sediment transport modelling tasks. Other tasks are being undertaken separately by other organisations. This component is Task (iii), which aims to simulate the processes of sedimentation and re-suspension by ambient hydrodynamic forcing of the fine organic particulate suspended within the effluent upon discharge. A major requirement of this task is measuring the physical properties of the fine particulate (or flocs) in the effluent, including particle size distribution, settling rates and re-suspension rates. These properties must be determined by physical modelling processes using representative samples of effluent from a similar (overseas) operating mill.

## 1.1 Study Components

To satisfy Task (iii), the Water Research Laboratory (WRL) of the University of New South Wales (UNSW) was commissioned by Gunns to study the physical properties of flocs within the pulp mill effluent using a series of physical model experiments. Overall, this investigation aimed to track by physical simulation the suspended floc throughout its dynamic transport cycle from the end of the production process, through the discharge pipe, and in the marine receiving environment within the near-field zone, including settling and re-suspension dynamics. Figure 2 and Table 1 illustrate the various phases of the floc transport cycle analysed in this study and related WRL investigations.

**Table 1**
**Floc Hydrodynamics Study Methodologies**

| Sub-task # | Hydrodynamic Condition During Discharge Process | Associated Investigation | Developed Methodology |
|---|---|---|---|
| 1 | Floc undergoes shear within the discharge pipeline | Floc size evolution under different shear rates | Jar test and particle size analysis |
| 2 | Floc is discharged from the diffusers, transported within the plume and subject to settling and aggregation forces | Settling rates of flocculated material | Settling column tests and particle image tracking (PIT) |
| 3 | Floc accumulates on the seabed. Floc network is broken down under ambient shear forces | Critical shear threshold condition for floc mat | Uniform flow over floc mat in a recirculating flume |

## 1.2 Veracel Pulp Mill

As Gunns pulp mill is currently not constructed, the investigation required the use of an “equivalent” effluent sourced from an existing overseas mill. The Veracel pulp mill located near Eunapolis in the state of Bahia, Brazil (Figure 3) was chosen by Gunns due to the similar effluent treatment operations proposed for the Tasmanian pulp mill. Due to quarantine and sample preservation concerns, the study was conducted on-site at Veracel during February-March 2010.

## 1.3 Report Structure

This particulate property testing report is broken down into 5 main sections. Following this introduction, each subsequent section represents one of the major sub-tasks outlined in Table 1. In Section 2 we present the analysis of the floc particle size distribution and behaviour under shear. In Section 3 the floc settling velocities are described, while in Section 4 the critical bed shear stresses are analysed. Finally, in Section 5, the results are summarised and the main conclusions are provided.

## 2. PARTICLE SIZE DISTRIBUTION OF THE FINE PARTICULATE (FLOC)

The particle size distribution (PSD) of the fine particulate (or floc) in the effluent was investigated using a range of instruments and testing protocols. The aim of the investigation was to understand the floc behaviour as it is subject to different levels of turbulence (and shear) during discharge. The consequent cycles of growth, breakage and floc re-growth are of particular interest. Figure 4 shows photos of the effluent samples and instrumentation.

In the proposed pulp mill, the discharge operations will consist of the effluent being discharged from the final treatment stage to the diffusers through the outfall pipeline. Currently it is proposed to use 800 mm diameter HDPE (high density polyethylene) pipe, with a maximum permitted daily flow of 64 ML/d, regulated on an average monthly basis. Therefore, it is expected that within the pipe, the floc will be subject to shear stresses ranging from nearly zero (in the middle of the pipe) to approximately 3.4 Pa, equivalent to a shear rate (or velocity gradient, G) of 3400 $s^{-1}$ (assuming a Newtonian fluid and a dynamic viscosity of 0.001 Pa*s) at the pipe wall. Once discharged through the diffusers, the effluent will undergo mixing with seawater and will be subject to ambient turbulent shear in the ocean.

### 2.1 Sampling Operations

As per the proposed Gunns pulp mill, the Veracel effluent treatment plant comprises pre-treatment, primary clarification, selectors and aeration basins (activated sludge process) and secondary clarification processes. Effluent samples for this study were collected during February and March 2010 from the final basin of the treatment process, from which the treated effluent is discharged through the outfall pipeline. Testing was undertaken using both grab and composite samples collected over different days to ensure that the samples were representative of the effluent during standard pulp mill operations.

Composite samples consisted of effluent samples automatically collected from the final basin sampling location every hour. Characterisation of the composite samples was undertaken during the study period and included determination of pH, conductivity, settleable solids and total suspended solids. Effluent quality records from Veracel during 2010, including the period of sampling, are provided in Figure 5.

## 2.2 Methods and Instrumentation

A variable speed jar test apparatus (Milan JT102) was used to apply shear to the effluent (see Figure 4). The samples were sheared using a 2-blade flat radial impeller in 2 L square jars. Average shear rates within the stirred vessels were estimated from established empirical equations (Selomulya 2001, Kusters 1991) and power consumption measurements provided by the jar test apparatus suppliers.

A series of laser diffraction instruments were used to analyse the floc particle distribution as shear was applied. While a Malvern Mastersizer 2000 was used for the majority of the testing, tests were replicated using both a Pola Particle Counter 2000 and a Sequoia Lisst-25X (see Figure 4). Measurements using calibrated glass beads of various size were undertaken prior to testing for all three instruments. In-line sampling was performed via in and out-flow tubes positioned in the sample jar just above the impeller paddles. The particle size was reported in terms of volumetric weighted mean (commonly referred to as D[4,3]). This assumes a gaussian size distribution, with approximately 85% of the particle volume being within approximately 30% of the reported diameter.

After performing a series of preliminary tests on the effluent, a testing protocol was adopted in relation to the time taken for flocculation processes to occur. The undiluted effluent was initially slow stirred (achieving a shear rate, G, of 15 to 40 $s^{-1}$) until the floc size reached a steady state. While the suspension was monitored in-line with the particle size analyser, the shear rate (G) was then increased by discrete steps (of approximately 10 $s^{-1}$) and maintained until the floc size reached a new steady state. The shear rate was increased until total breakage of the floc was observed.

The effluent was then diluted 200 times with seawater and re-growth processes were monitored by repeating the same testing protocol as for the above undiluted samples.

## 2.3 Results

As described previously, several grab and composite samples were collected over the 3 week testing and analysis period and are therefore representative of the variability in effluent quality over that period. The above tests were undertaken and repeated on all samples. In this section a (i) typical floc size distribution and behaviour under shear and a (ii) worst (conservative) case scenario are presented.

### *2.3.1 Typical Case*

The initial particle size distribution (PSD) of the effluent was typically unimodal with floc median sizes varying from 10 to 30 µm (microns).

Figure 6a shows the typical floc dynamics under various shear. Figures 6a and 6b show that the floc initially had a unimodal PSD with a median (50th percentile) diameter, d(50), of 29 µm. By the end of the growth cycle, the d(50) had increased to 78 µm which is more than double its original size with a PSD more markedly bimodal and a peak around 110 µm forming (Figure 6b). At higher shears, the breaking phase took place, with the median size d(50) rapidly reduced to 25 µm. With the bigger flocs (of around 100 µm) broken into smaller flocs (of around 20 µm), the PSD then showed a bimodal trend with a reduced peak at 110 µm and an increased peak at 20 µm.

After mixing the effluent with seawater, the floc regrew at low shear rates. Figures 6a and 6c show that the floc median size reached 62 µm with a unimodal PSD and increased peakiness (higher Kurtosis). At higher shear rates, the floc underwent breakage with the d(50) rapidly reducing to 18 µm and the unimodality and kurtosis maintained.

Table 2 presents the d(50), d(10) and d(90), being the 50th, 10th and 90th percentile diameters respectively, corresponding to the initial, maximum growth and final PSD.

**Table 2**
**Floc Size Evolution Under Shear**

| | **d(50)** | **d(10)** | **d(90)** |
|---|---|---|---|
| **Stage** | µm | µm | µm |
| Initial | 29 | 12 | 69 |
| Growth | 78 | 12 | 184 |
| Breakage | 25 | 8 | 143 |
| Regrowth (sw) | 62 | 17 | 174 |
| Breakage | 18 | 6 | 33 |

Floc aggregation, and consequently floc growth, was observed for shear rates in the range of G = 60 to 300 $s^{-1}$. For G above 300 $s^{-1}$, breakage of floc occurred and floc size rapidly decreased.

### *2.3.2 Conservative Case*

This case represents the conservative (worst) case where the flocs achieved larger sizes over the growth cycle. Figure 7 depicts floc cycles of growth, breakage, regrowth in seawater and breakage for this effluent sample.

The floc dynamics were similar to those illustrated in Figure 6. Nevertheless the absolute values of floc size were different due to the daily variability in effluent quality. The floc median size grew from an initial 8 µm to a maximum of 135 µm after 30 minutes of slow stirring (low shear rates). As the shear rates were increased to induce breakage, the median floc size rapidly decreased to 6 µm in less than 10 minutes. Seawater was then added (1 in 200 effluent dilution) and, at low shear rates, floc size increased to a d(50) of 55 µm. After the breakage cycle, the floc median size was reduced to 25 µm. Table 3 depicts the floc size evolution.

**Table 3**
**Floc Size Evolution Under Shear - Conservative Case**

| **Stage** | **d(50)** | **d(10)** | **d(90)** |
|---|---|---|---|
| | µm | µm | µm |
| Initial | 8 | 3 | 16 |
| Growth | 135 | 109 | 176 |
| Breakage | 6 | 2 | 13 |
| Regrowth (sw) | 55 | 15 | 118 |
| Breakage | 25 | 5 | 72 |

## 2.4 Discussion

The median size of the flocs in the effluent samples analysed varied from 10 to 30 µm. When the floc was subject to increasing shear rates, aggregation of flocs occurred, which caused the median floc size to increase up to an order of magnitude greater than its original size (i.e. up to ~100 µm). Floc aggregation and growth typically occurred at shear rates ranging from G = 60 to 100 $s^{-1}$ but growth was observed at shear rates up to 300 $s^{-1}$. At higher shear rates, breakage mechanisms and possibly compaction were dominant and floc size decreased to or below the original size. While the aggregation mechanisms and associated floc growth took longer (10 to 30 minutes) to occur, floc break-up occurred more suddenly and smaller floc sizes (or a return to the original floc size) were achieved more rapidly (1 to 5 minutes) in the breakage cycle.

When diluted with seawater, the effluent behaved similarly to when undiluted and went through cycles of aggregation at low shear rates and breakage at higher shear rates. The regrowth was less pronounced and breakage occurred at lower shear, possibly due to the weaker bonds created after being subject to total breakage.

In conclusion, the test results indicated that the floc is likely to undergo growth and breakage cycles in the outfall pipe as it is displaced from zones of low shear to zones of higher shear within the flow. Considering the growth/breakage cycle timeframes and the range of shear rates at which breakage was observed to occur (mainly above 100 $s^{-1}$), it is expected that breakage mechanisms will be dominant within the pipe, where shear rates are estimated to be up to 3400 $s^{-1}$ near the pipe walls. Upon discharge from the diffusers, the ocean ambient shear rates are expected to be significantly lower than in the diffuser pipeline and aggregation/growth of floc size within the effluent plume may occur. However, the test results indicate that floc aggregates have an increased susceptibility to decompose back to a primary floc component if breakage has already occurred.

The samples analysed are only representative of the effluent quality during the period of analysis (February/March 2010). However, from the analysis of the effluent characteristics during the study period presented in Figure 5, it appears that the effluent samples were representative of long term averages during 2010. Therefore, the samples tested can be used to represent typical particle size distribution and typical behaviour under shear.

## 3. FLOC SETTLING VELOCITIES

As the effluent is discharged into the ocean through the diffusers, floc particles within the near-field zone may settle to the bed. Floc size and density are the main factors influencing the settling process in the absence of external perturbations.

A series of free-settling tests were undertaken to obtain information on floc size and relative terminal velocity. These variables are necessary to correctly model the fate of the floc once discharged into the ocean. Floc density was also inferred from the terminal velocity measurements using the force balance equation and assuming an equivalence to spherical particles (i.e. Stokes Law). Lee (1996) suggests that the free-settling testing methods used in this study are considered a valid approach for approximating floc density.

### 3.1 Methodology

The settling tests were undertaken using a 0.5 m high transparent (polymethylmethacrylate PMMA, “clear acrylic”) water column. Figure 8 shows photos of the experimental setup. The column was made of an inner column (8.5 cm by 8.5 cm) immersed in a temperature controlled water bath. The water column was filled with seawater and left undisturbed for at least 3 hours prior to each test to achieve quiescent conditions (characterised by Reynolds number <<< 1).

The flocs were introduced on the water column surface and sufficient vertical distance was allowed to achieve terminal velocity. Particle image tracking (PIT) techniques were then applied to determine the floc’s size and settling rate.

The PIT techniques consisted of a light source that illuminates settling flocs and a digital camera (with a range of magnification lenses) which captures and records the light scattered by the flocs. Subsequent analysis of the recorded digital images allowed particle sizes and settling velocities (from multiple images taken over a set time period) to be calculated. PIT is a well established technique to measure velocities and related properties of flocs (Adrian 2005, Anderson 2004).

The experimental setup was calibrated on-site using standard latex particles of 80 μm diameter and glass bead particles of 100 μm diameter. This established a reference for particle size magnification and validated settling velocity measurements using PIT.

Effluent samples were tested using both undiluted and diluted (200 times) samples in seawater. Sample were subject to low shear before testing in order to enhance floc aggregation.

### 3.2 Results and Discussion

The settling rates and the corresponding floc sizes are presented in Figure 9. Floc sizes up to 200 µm were analysed and the flocs settled at velocities ranging from approximately 1 to 3 mm/s.

Settling rates increased with the floc size for floc less than 100 µm, while settling velocities reached a plateau at around 3 mm/s for flocs bigger than 100 µm. This is likely due to larger floc being characterised by a more porous structure (i.e. less dense) which would have decreased the settling velocity of the larger floc. As a consequence, the settling rates of the larger flocs did not increase with size following a power law relationship.

Under a series of assumptions for which the Stokes law is applicable (floc sphericity, impermeability), the density of the flocs was estimated to range from 1400 and 1600 kg/m$^3$. This is in line with previous estimates of porous material (Lee 1996).

# 4. CRITICAL BED-SHEAR STRESSES FOR CONSOLIDATED FLOCS

Depending on the settling rate, the floc could potentially accumulate on the seabed and form a cohesive floc network (or floc mat). The floc would then be exposed to ambient hydrodynamic conditions and whether the porous network of floc will persist on the seabed or be resuspended would depend on the floc's ability to withstand shearing forces.

A recirculating flume was constructed at the Veracel plant in Brazil to determine the threshold conditions for motion of the floc mat under unidirectional current flows. The experiment included detailed measurements of the velocity and turbulence fields using a Sontek Micro-ADV (Acoustic Doppler Velocimeter). The study, coupled with the knowledge of the ambient currents at the outfall site, permits the estimation of whether the floc will likely remain in the near-field zone or whether it will be resuspended by the local ambient currents.

## 4.1 Methodology

### *4.1.1 Recirculating Flume*

With the collaboration of the Veracel staff, a recirculating flume measuring 3 m in length, 0.2 m in width and 0.3 m in depth was built on site. The flume was built using plywood (painted and sanded to ensure smoothness of the internal walls), with one side of the flume made of glass to allow visual observations of the test. Pump and pipework connected the downstream tail tank to the upstream head tank. The head tank was built 0.4 m deep and equipped with internal geo-textiles screens and gravel to provide buffering of the incoming flow. The flow was controlled through a valve and a downstream weir. Based on this experimental setup and various measurements, a uniform steady flow could be achieved in the test section for flows ranging from 0 - 15 cm/s. Figures 10 and 11 depict photos of the flume construction and experimental setup.

### *4.1.2 Velocity Measurements*

Velocity measurements were undertaken using a Sontek/YSI 16-MHz MicroADV (Acoustic Doppler Velocimeter) sampling at a rate of 25 Hz with a down-looking probe. The ADV is considered to be a relatively non-intrusive device (Gratiot 2000, Schaaf 2006) and therefore the effect of secondary turbulence generated by the sensor was assumed to be negligible.

Velocity profiles were undertaken above the floc mat in the test section. By measuring the instantaneous three-dimensional components of the flow, the turbulence of the flow could be described through the root-mean-square (RMS) values of the turbulent velocity fluctuations.

### *4.1.3 Experimental Protocol*

Approximately 0.5 $m^3$ of water was used to fill the flume's recirculating system. Water depths in the flume varied depending on the flow from 90 to 120 mm. Floc (consolidated for more than 72 hours) was introduced in the flume test section using a 100 ml pipette while making sure that the floc internal bonds remained undisturbed during the transfer. The floc formed a dense elastic mat on the flume floor.

Once the floc mat was established, the flow velocity was gradually increased in discrete steps until incipient motion of the floc was observed. The flow velocity was then further increased until general motion of the floc occurred. This flow was maintained until all the floc was removed from the test section. Velocity profiles and near-bed measurements were recorded at each step, which allowed the estimation of critical bed shear stresses. High resolution video images were obtained for each test.

### *4.1.4 Threshold of Incipient Motion*

The threshold condition of incipient motion is the transition period from the condition of "no motion" to initial sediment motion. In practice, it is defined through qualitative visual assessment of the first particle movement. Subjectivity in the visual observations has led to significant scattering of experimental data in previous studies related to sediment motion (Paphitis 2001).

For this investigation, the threshold of incipient motion was defined as occasional particle movement at some location within the floc mat. A threshold condition corresponding to general particle motion in all parts of the floc mat was also defined. Tests were repeated several times, recorded with two video cameras (plan and side view), and witnessed by at least three persons to avoid subjectivity and ensure consistency in judgement.

### *4.1.5 Calculation of Bed Shear Stresses*

Threshold conditions for sediment movement are expressed as a critical bed shear stress ($\tau_c$) which was derived from velocity measurements. Several well established methods exist to estimate bed shear stresses from velocity measurements (Andersen 2007). A description of these methods is presented in Appendix A. For this investigation, bed shear stresses were calculated using the three primary methods namely: the Law of the Wall, Reynold stresses and the Turbulent Kinetic Energy (TKE) methods. After comparing the results of the three methods and various reference material, it was decided for data consistency to use the shear stresses calculated from the TKE method. It is worth noting that for all flows tested, the three methods gave consistent results.

### *4.1.6 Estimation of Erosion Rates*

Two cameras were set up for the flume testing. One was mounted vertically above the test section, while the other recorded sideways to the test section. Calibration grids were marked on the floor and wall of the flume to quantify volumetric changes occurring to the floc mat during the shear tests. Photos and video streams were taken prior, during and after testing for each sample. Figure 12 shows prior and post testing images of the floc mat.

Image analysis allowed a qualitative estimation of the volumetric loss of the floc mat during erosion events. The volumetric loss could then be related to a mass loss, having an estimation of the floc density from the column free-settling tests (see Section 3.2).

## 4.2 Results

### *4.2.1 Incipient Sediment Motion*

Incipient motion was characterised by flocs being occasionally displaced at some location along the mat network. Displaced flocs were usually transported away within the flow but occasionally were re-captured by the floc mat.

Incipient motion of the floc under unidirectional current was observed for a flow velocity (averaged over the flow depth) of 2.9 cm/s. That corresponds to a critical bed shear stress of 0.006 N/m$^2$. The critical bed shear stress was calculated from velocity measurements using the TKE method (see Appendix A for a description of the method). Volumetric erosion of the floc mat was inferred by the analysis of the images and the video records. Assuming a floc density of 1400 kg/m$^3$ (estimated from the settling column tests), the erosion rate was calculated to be 0.0007 kg/m$^2$s.

Figure 13 shows the measured velocity profile (in the direction of the flow) in the middle of the channel, above the test section. The data exhibits a typical logarithmic profile within the turbulent boundary layer. Figure 13 also shows plots of the three velocity components

($V_x$, $V_y$ and $V_z$) as measured by the ADV sampling at 25 HZ (every 0.04 sec) at various distances above the flume floor. $V_x$ is the velocity component in the direction of flow, $V_z$ is along the vertical z-axis and $V_y$ is across the flume (with the positive y-axis defined by a right-handed coordinate system). As the distance from the boundary increased, mean flow velocity and consequently turbulence increased as shown by the amplitude of the turbulent velocity fluctuations around a mean.

### *4.2.2 General Sediment Motion*

General sediment motion was characterized by frequent displacement of flocs in several locations of the sample section. Displaced flocs were rarely re-captured by the floc mat network and usually were rapidly transported away with the current. Once flocs were set in motion through shear with the flow, they showed a tendency to entrain surrounding flocs due to the bonding properties of the mat. When a large portion of the mat was moved, the erosion processes were accelerated by the lift and drag of the floc mat. Figure 14 shows photos of floc displacement and erosion.

General motion of the floc was observed for an average (over the depth) flow velocity of 8.4 cm/s, at which the flow in the channel was fully turbulent (Re >2000). The corresponding critical bed shear stress was 0.048 N/m$^2$ and the erosion rate was estimated at 0.113 kg/m$^2$s.

Figure 15 shows the velocity profile above the test section and plots of the measured velocity at different distances from the boundary. The velocity fluctuations are, as expected, greater than the incipient motion flow conditions and increase with distance from the boundary.

## 4.3 Discussion

Consolidated (minimum of 72 hours) floc was subjected to a unidirectional, uniform and steady flow in a recirculating flume. Critical bed shear stresses were inferred using the TKE method from velocity measurements for thresholds of:

- Sediment incipient motion
- Sediment general motion.

Testing results showed that floc particles consolidated into a mat network on the seabed would be displaced at a critical bed shear stress of 0.006 N/m$^2$ and an erosion rate of

0.0007 kg/m$^2$s. While the threshold of general motion was reached for a critical bed shear stress of 0.048 N/m$^2$, the erosion rate was estimated at 0.113 kg/m$^2$s.

For perspective, a quartz ( of 2650 kg/m$^3$) particle of 1 mm diameter in water temperature of around 20° C is characterized by critical bed shear stresses for incipient motion ranging from 0.3 to 0.8 N/m$^2$, while a quartz grain of 3.9 µm diameter has critical bed shear stress of 0.09 to 0.016 N/m$^2$ (Shields 1936, Paphitis 2001).

Current velocity measurements at the Gunns proposed outfall location undertaken by RPS MetOcean from September to December 2009, showed 5th, 50th and 95th exceedence percentiles of 0.17, 0.1 and 0.03 m/s (values measured at 3.4 m above seabed). The floc critical bed shear stress of incipient motion was reached for a flow velocity (averaged over the flume depth) of approximately 0.03 m/s, which is equivalent to the 95th %-ile of measured ambient current speed. Therefore, it is unlikely that a floc mat will persist on the seabed in the near-field as it is likely to be re-suspended by the ambient currents most of the time (95% of the time over the measured field campaign for instance).

## 5. SUMMARY AND CONCLUSIONS

A series of physical modelling experiments was undertaken to investigate the physical properties of the suspended fine organic particulate in a pulp mill effluent and to model the processes affecting its transport and settling. The experiments were carried out using an effluent equivalent to that expected to be produced by the proposed Gunns pulp mill in Tasmania. The testing took place on site at the Veracel pulp mill near Eunapolis, Bahia, Brazil.

The main outputs of the study were:

- Particle size distribution of the suspended floc particulate in the treated effluent
- Floc dynamics when subject to shear
- Settling velocity of the floc within a seawater medium
- Critical bed shear stress and erosion rates for a consolidated floc mat.

The floc size in the effluent ranged from 10 to 30 µm (equivalent diameter) with a primarily unimodal particle size distribution around the median. When subject to low shear, the floc underwent cycles of aggregation up to a median size of approximately 100 µm. High shear caused the floc to break and the original (or smaller) median sizes were rapidly attained. When diluted in seawater, floc underwent aggregation and breakage cycles similar to that which occurred in the effluent.

Based on these results, it is expected that upon discharge in the ocean, when subject to the shear in the outfall pipeline and in the diffusers, the floc dynamics will be dominated by breakage mechanisms. Once discharged into the ocean, in the absence of highly turbulent hydrodynamic conditions, the floc may aggregate and form slightly larger flocs. Settling column experiments provided estimate of the floc settling velocity. Flocs of 20 to 200 µm settled at velocities ranging from approximately 1 to 3 mm/s. Based on these rates and current measurements taken by MetOcean, it is unlikely the floc will settle on the seabed.

Settled floc tended to form a dense, elastic mat network. After consolidation (longer than 72 hours), the floc mat was subject to shear generated by a unidirectional flow in a recirculating flume. Critical bed shear stress for floc incipient motion was calculated from velocity measurements. It was determined that the floc was set in motion with a critical bed shear stress of 0.006 N/m$^2$, corresponding to a flow velocity of approximately 0.03 m/s in the flume.

Considering that measurements of the ambient currents at the outfall location yielded a 95th exceedance percentile of 0.03 m/s (i.e. current velocities higher than 0.03 m/s occurred 95% of the time during the field measurements), it is likely that any floc mat formed in the near-field will be re-suspended and transported from the near-field zone.

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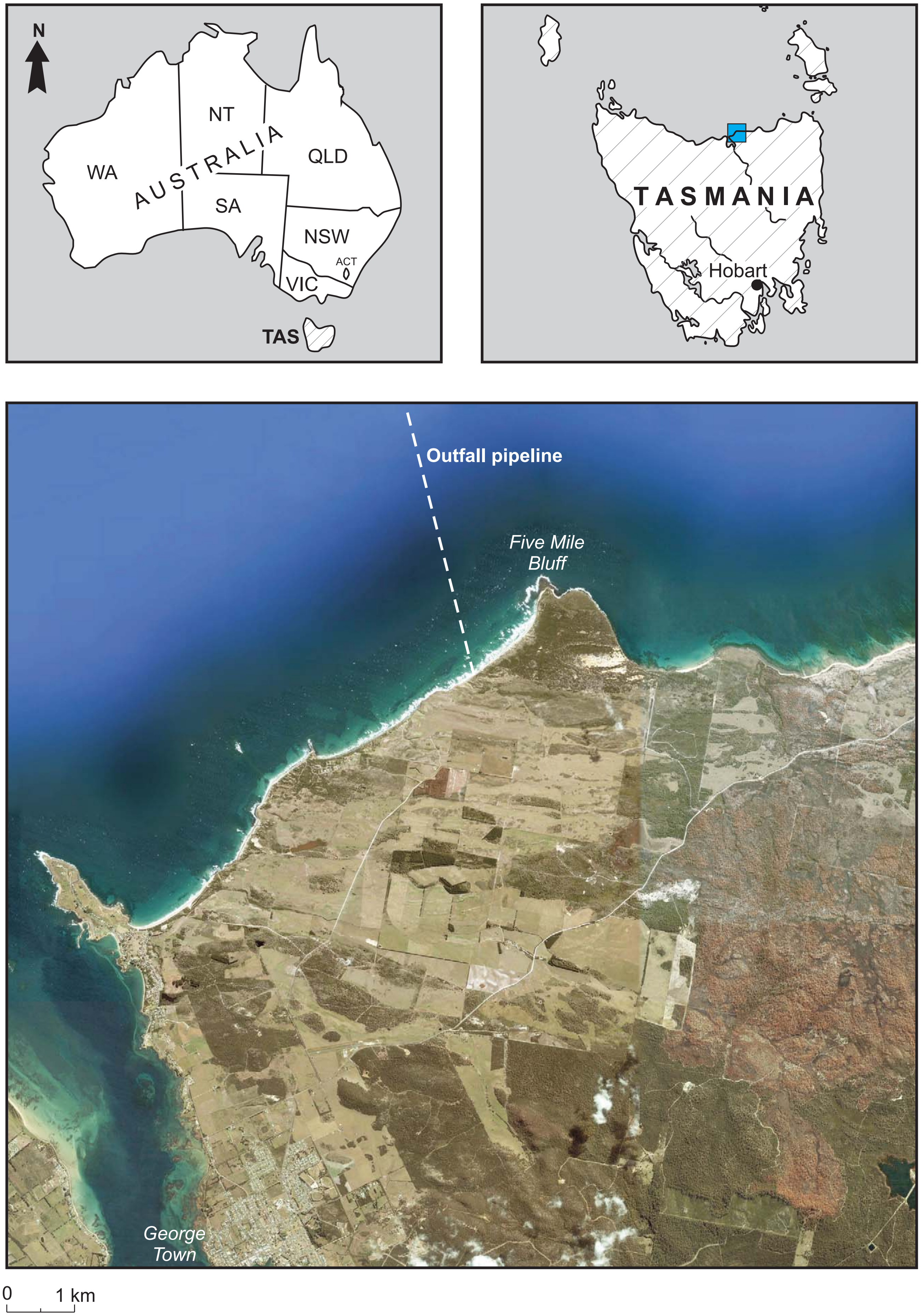

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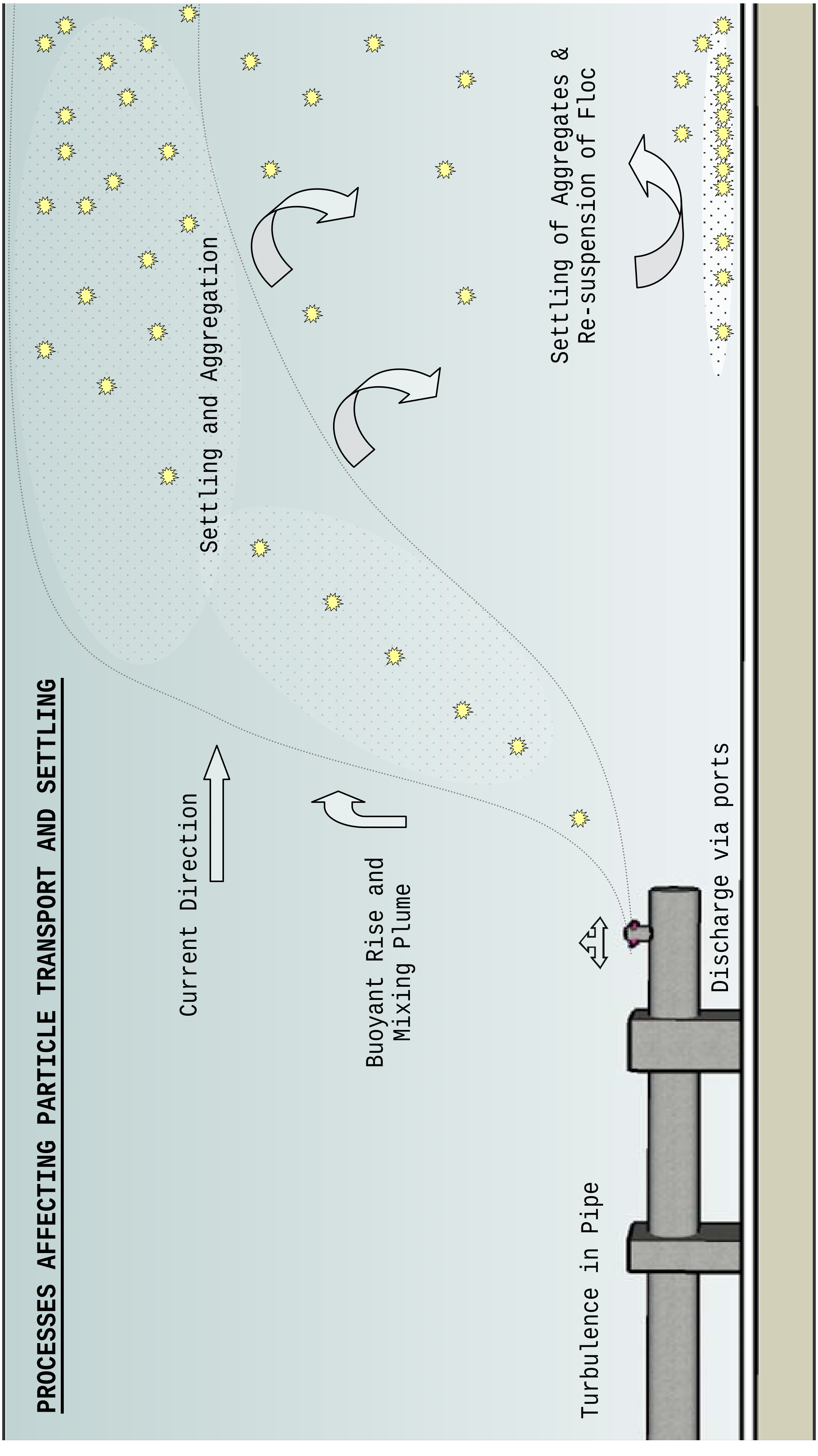
LOCATION MAP OF PROPOSED
GUNNS PULP MILL AND OUTFALL

Figure

1

08068-01.cdr



WRL

Report No. 2010/10

FLOC TRANSPORT AND SETTLING PROCESSES

Figure 2

Veracel Pulp Mill

Veracel Pulp Mill, near Eunapolis, Bahia, Brazil

VERACEL PULP MILL

Figure
3

Jar Test and Pola Particle Size Analyser

Effluent Samples

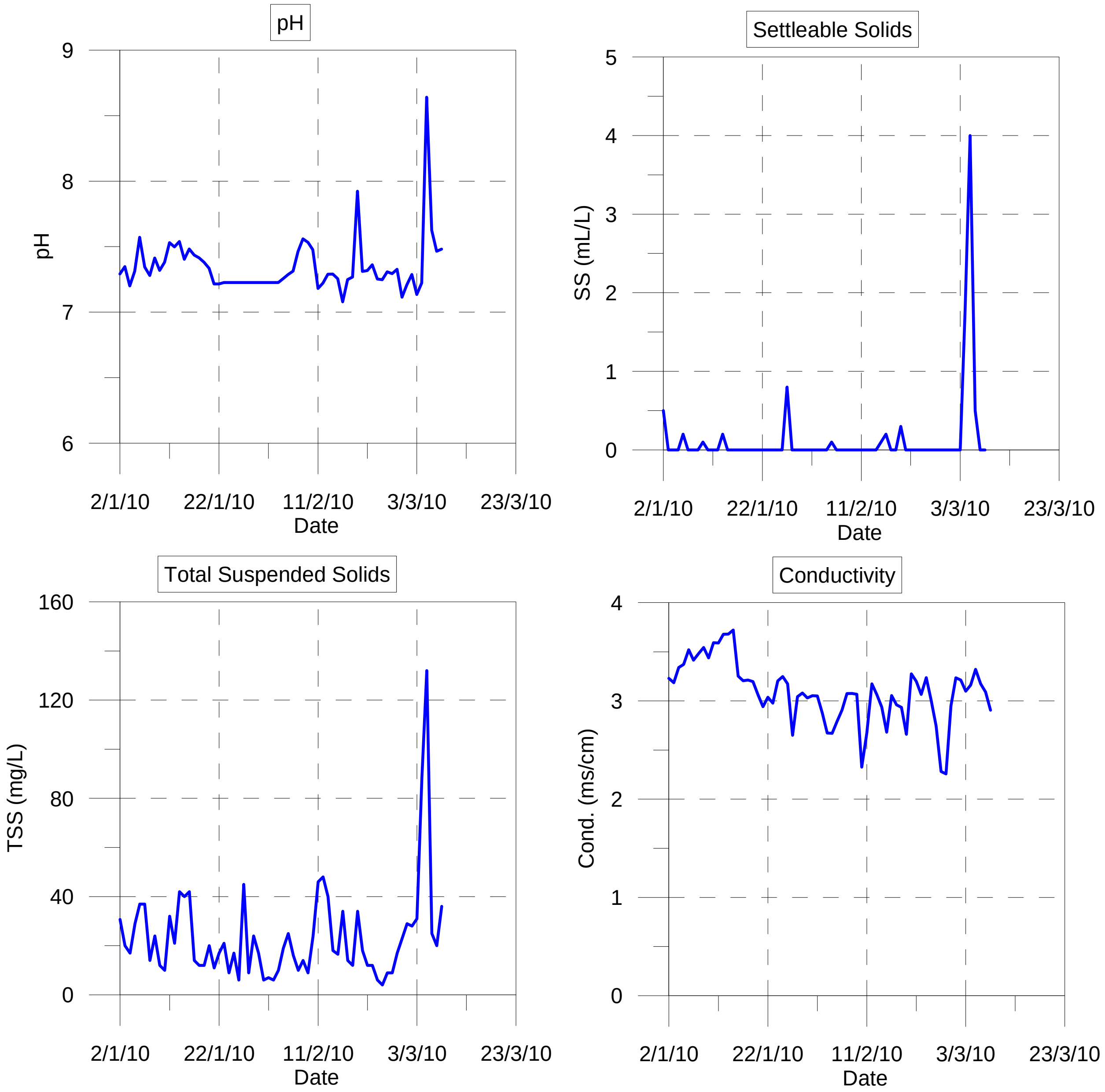
Malvern Mastersizer 2000

Malvern Dispersion Unit Hydro2000

LISST 25

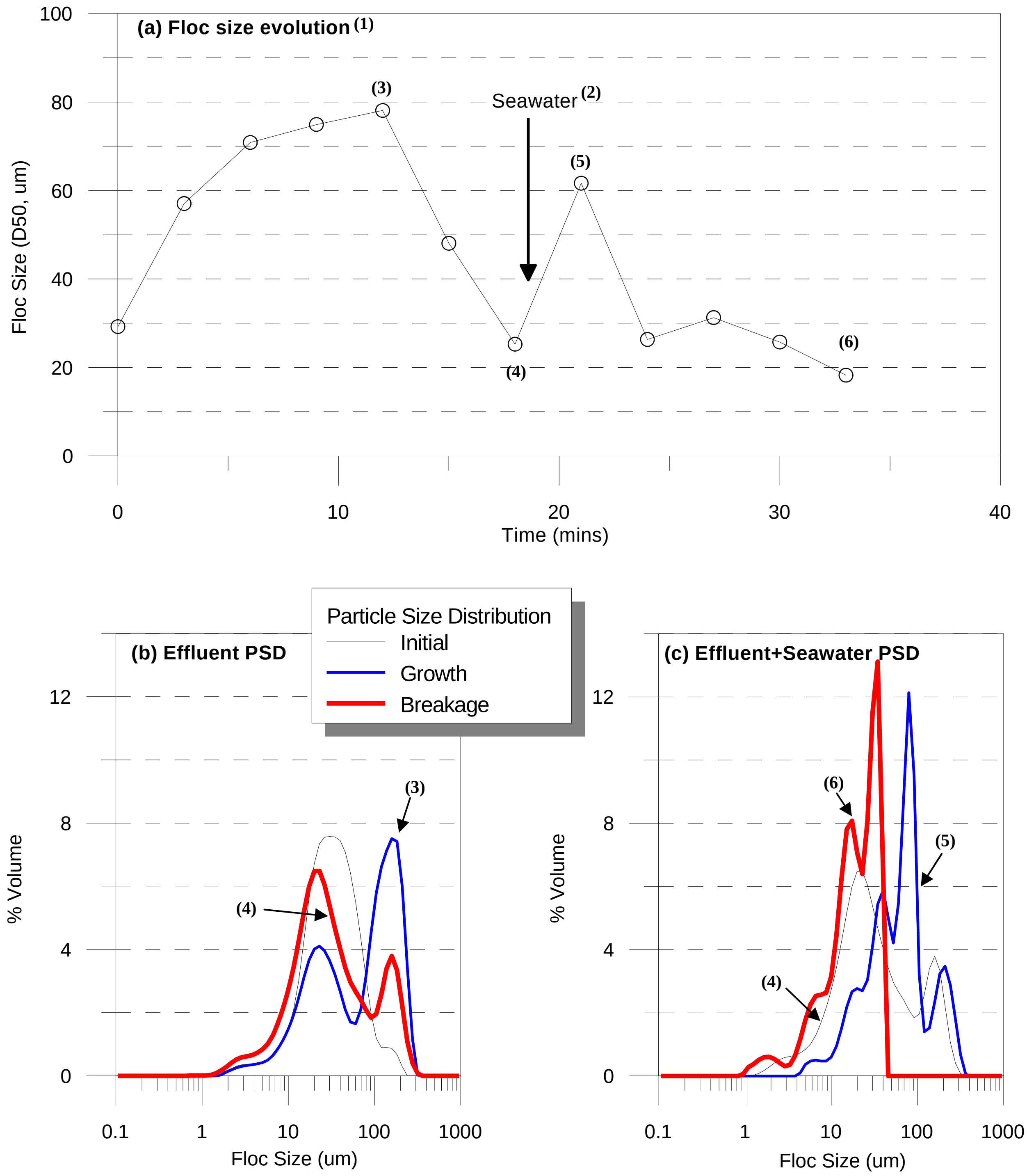
LISST 25 Effluent Testing Apparatus

PARTICLE SIZE ANALYSERS AND SHEAR TESTING EQUIPMENT



Note: field samples for this study were collected between 20th February 2010 to 1st March 2010 and are representative of long term average conditions. The spikes in pH, Sett. Solids and TSS plots observed around the 3/3/2010 occurred after this study was completed and are not included in the analysis. Veracel staff explained the presence of these peaks as a result of maintenance operations (dredging) in the final effluent basin.

| WRL<br>Report No. 2010/10 | LONG TERM EFFLUENT CHARACTERISATION AT VERACEL PULP MILL | Figure<br>5 |
|---|---|---|

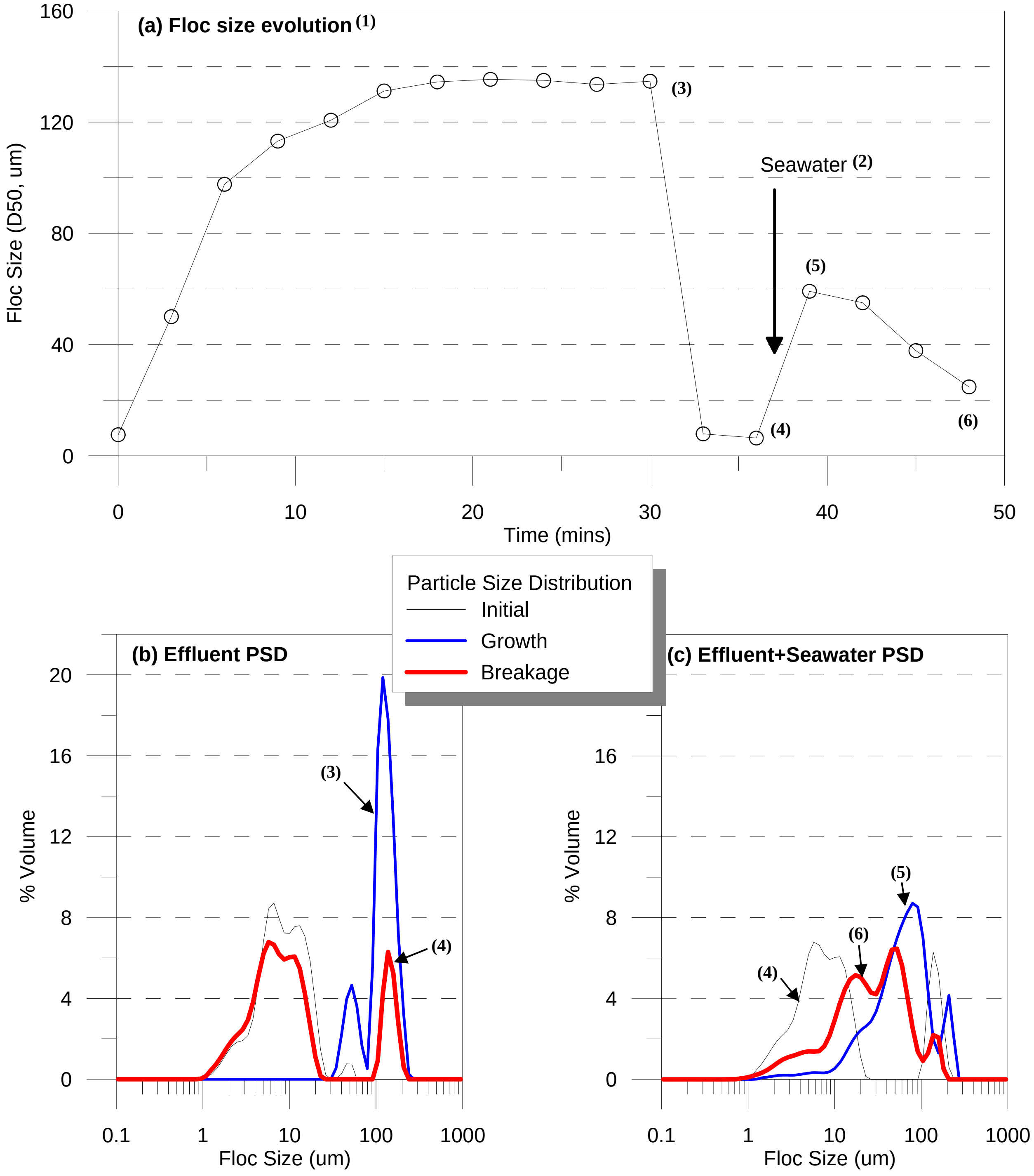


Notes:

1. The sampling time of the particle size analysers was set to 1 minute. Only average values over each sampling period are shown in plot (a).
2. Shear rates (G) were increased in discrete steps till breakage. Particle size distribution was analysed in-line. When effluent was mixed with seawater, shear rates were reset to low G forces and slowly increased again. During this period re-growth and breakage cycles were noted.
3. Point 3 in floc size evolution (plot a) is represented by growth PSD in plot b.
4. Point 4 in floc size evolution (plot a) is represented by breakage PSD in plot b and initial PSD in plot c.
5. Point 5 in floc size evolution (plot a) is represented by growth PSD in plot b.
6. Point 6 in floc size evolution (plot a) is represented by breakage PSD in plot b.

TYPICAL FLOC SIZE EVOLUTION AND PARTICLE SIZE DISTRIBUTION

Figure
6

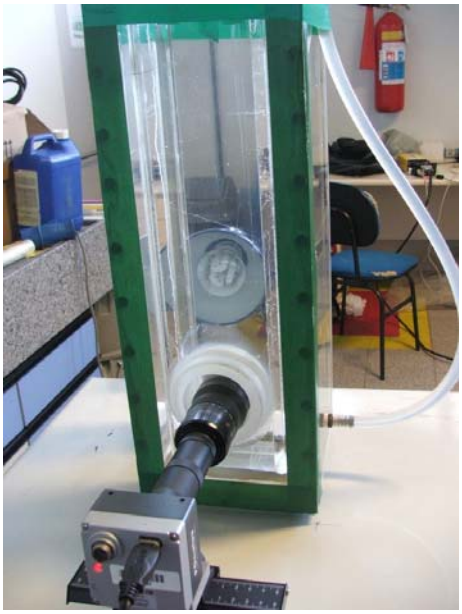


Notes:

1. The sampling time of the particle size analysers was set to 1 minute. Only average values over each sampling period are shown in plot (a).
2. Shear rates (G) were increased in discrete steps till breakage. Particle size distribution was analysed in-line. When effluent was mixed with seawater, shear rates were reset to low G forces and slowly increased again. During this period re-growth and breakage cycles were noted.
3. Point 3 in floc size evolution (plot a) is represented by growth PSD in plot b.
4. Point 4 in floc size evolution (plot a) is represented by breakage PSD in plot b and initial PSD in plot c.
5. Point 5 in floc size evolution (plot a) is represented by growth PSD in plot b.
6. Point 6 in floc size evolution (plot a) is represented by breakage PSD in plot b.

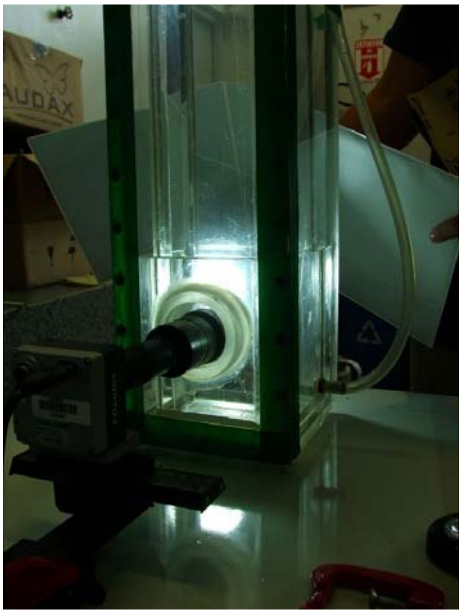
FLOC SIZE EVOLUTION AND PARTICLE SIZE DISTRIBUTION (CONSERVATIVE CASE)

Figure
7

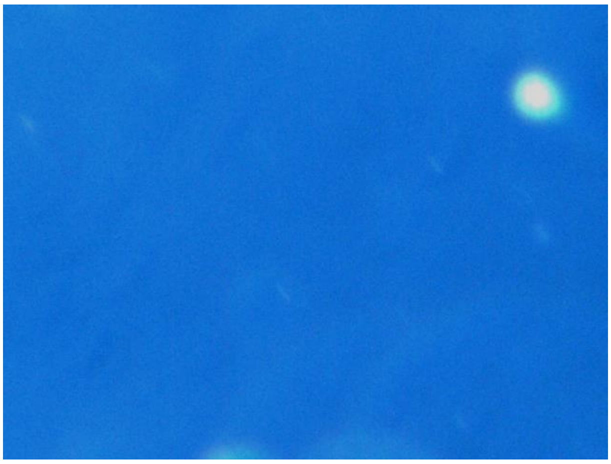


**Settling Column**

**PIT camera**

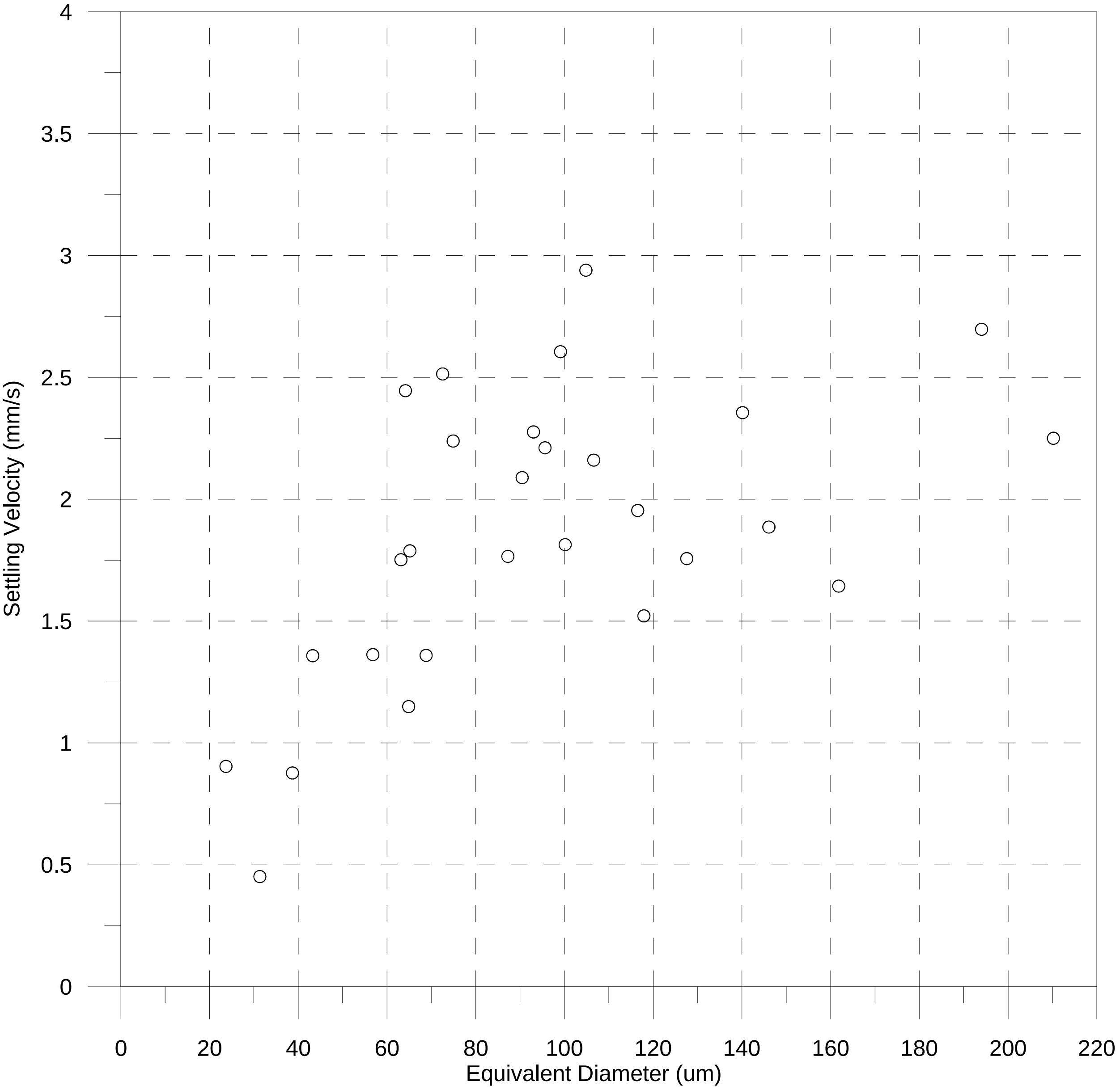


**Settling Column Testing**



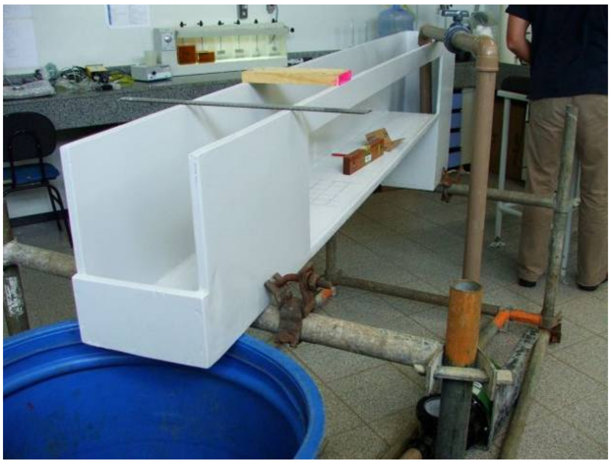
**PIT: image of 80 um latex particle**

SETTLING VELOCITY EXPERIMENT SETUP

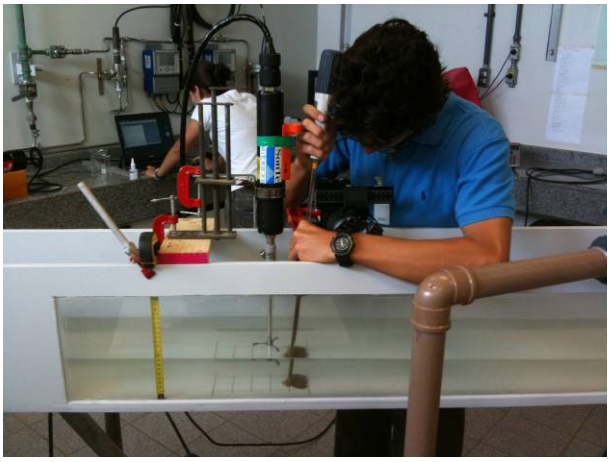


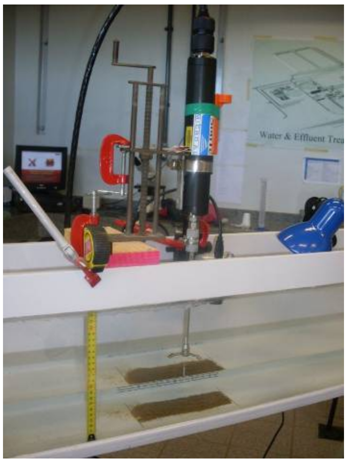
| | | |
|---|---|---|
| WRL<br>Report No. 2010/10 | FLOC SETTLING VELOCITY RESULTS | Figure<br>9 |


Flume construction


Flume setup in laboratory


Flow in flume

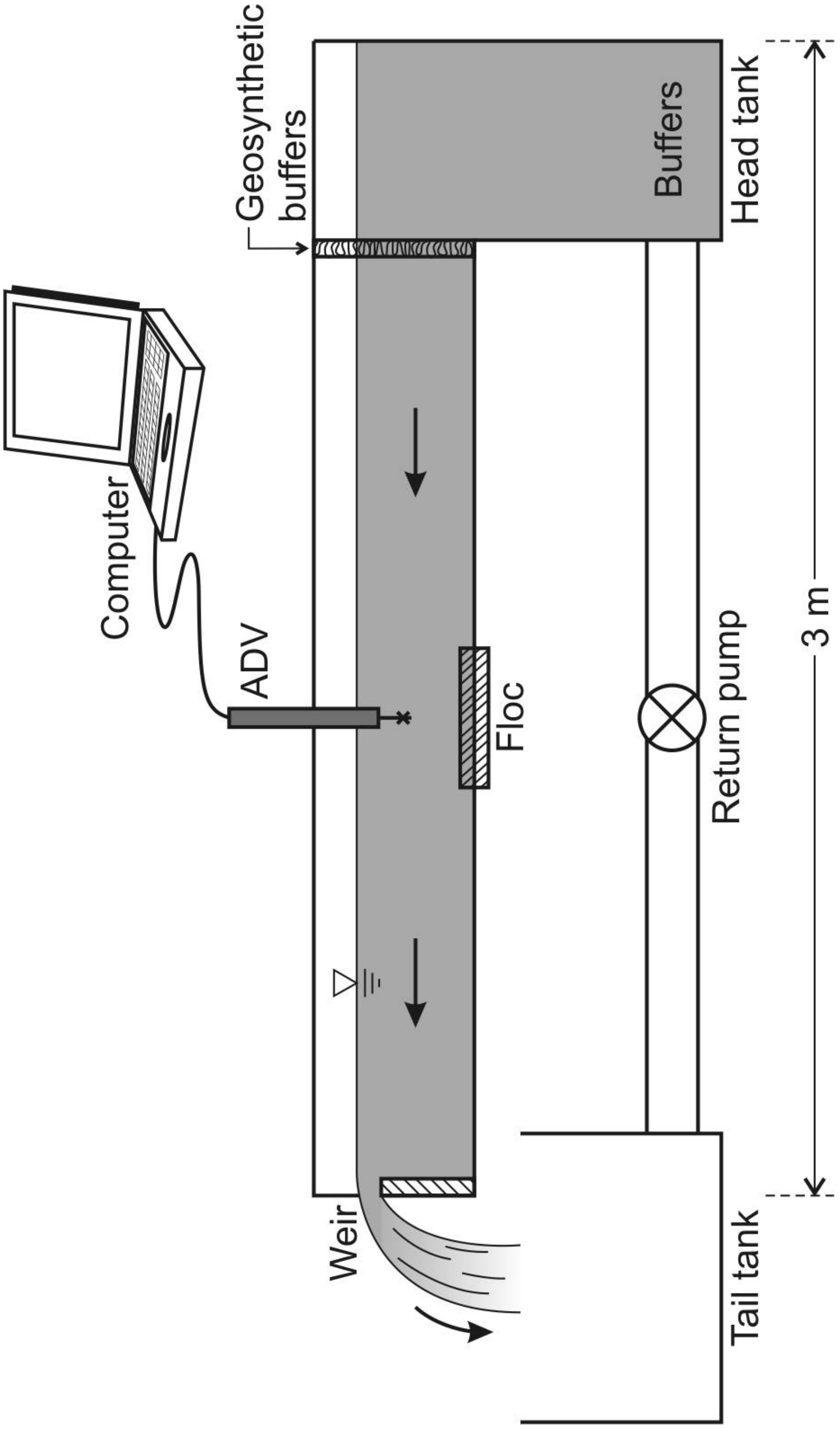

Test section


ADV setup

Camera setup

RECIRCULATING FLUME AND INSTRUMENTATION

Figure
10



RECIRCULATING FLUME SETUP

Figure 11

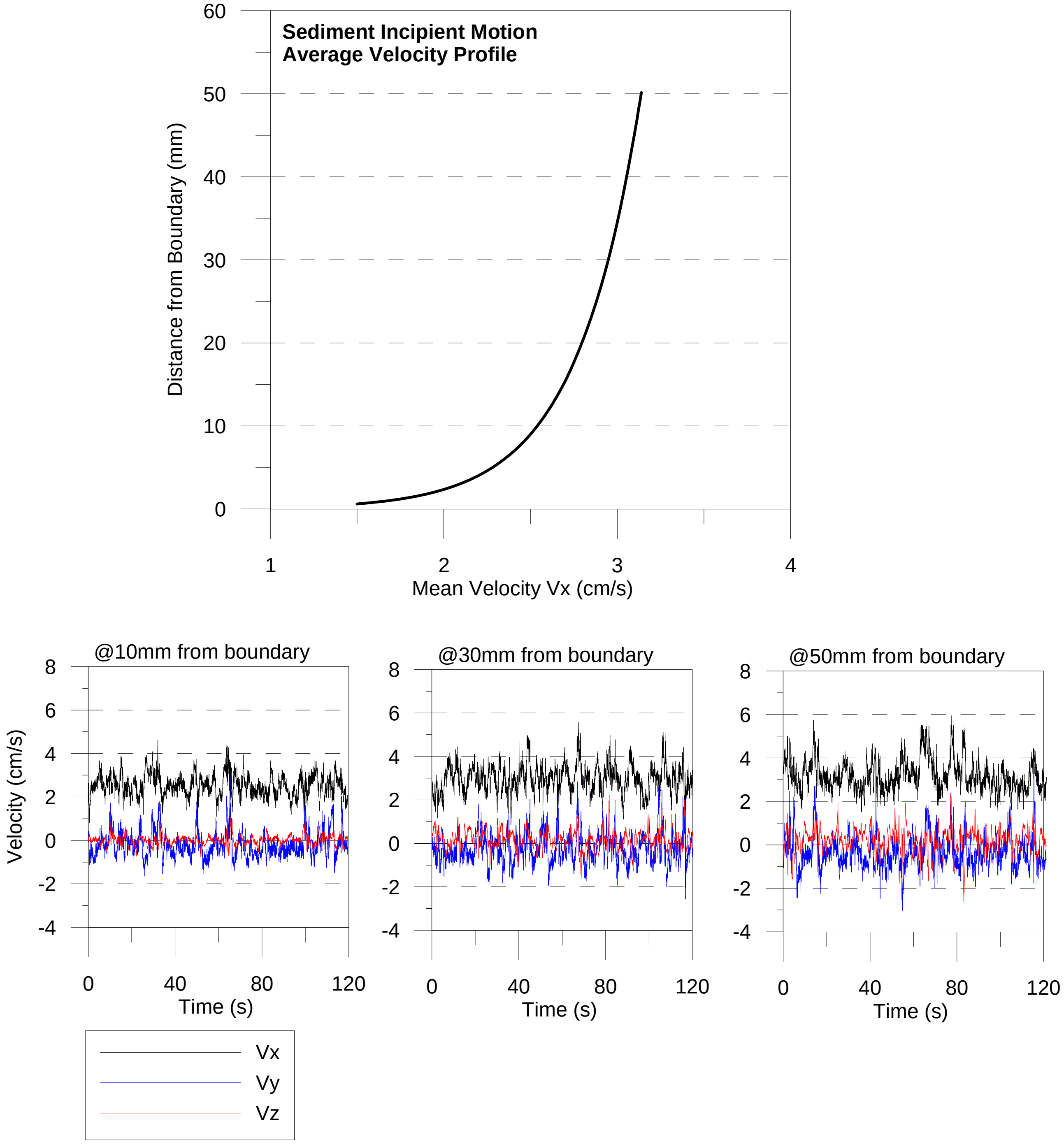
**Floc mat at start of test**

**Floc mat eroding**

**Floc mat near complete erosion**

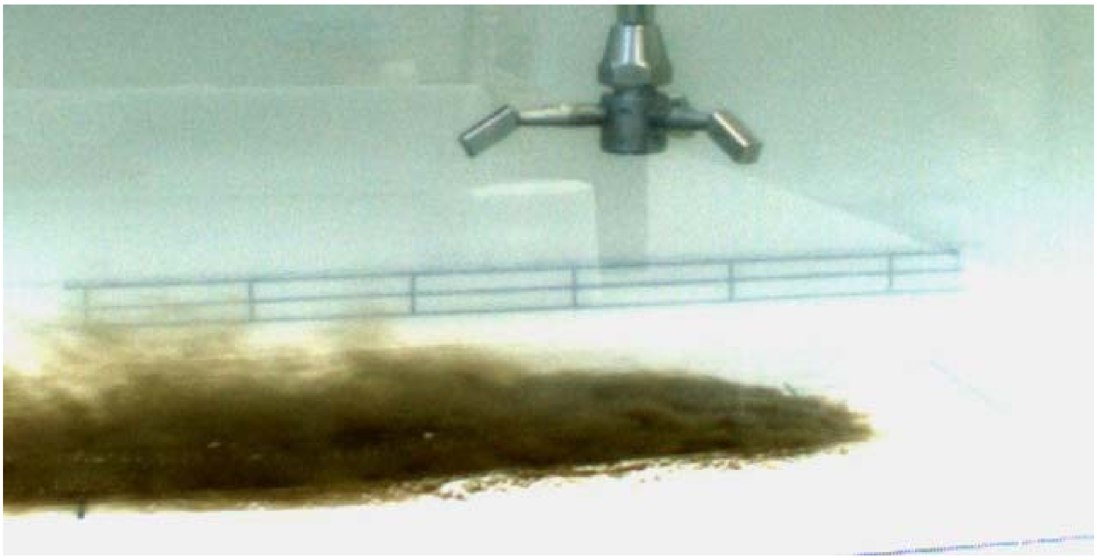
Note that velocity and turbulence profiles for these images are provided in Figure 13.

| WRL<br>Report No. 2010/10 | FLOC MAT EROSION IMAGES | Figure<br>12 |
|---|---|---|



| WRL<br>Report No. 2010/10 | THRESHOLD OF INCIPIENT SEDIMENT MOTION | Figure<br>13 |
|---|---|---|

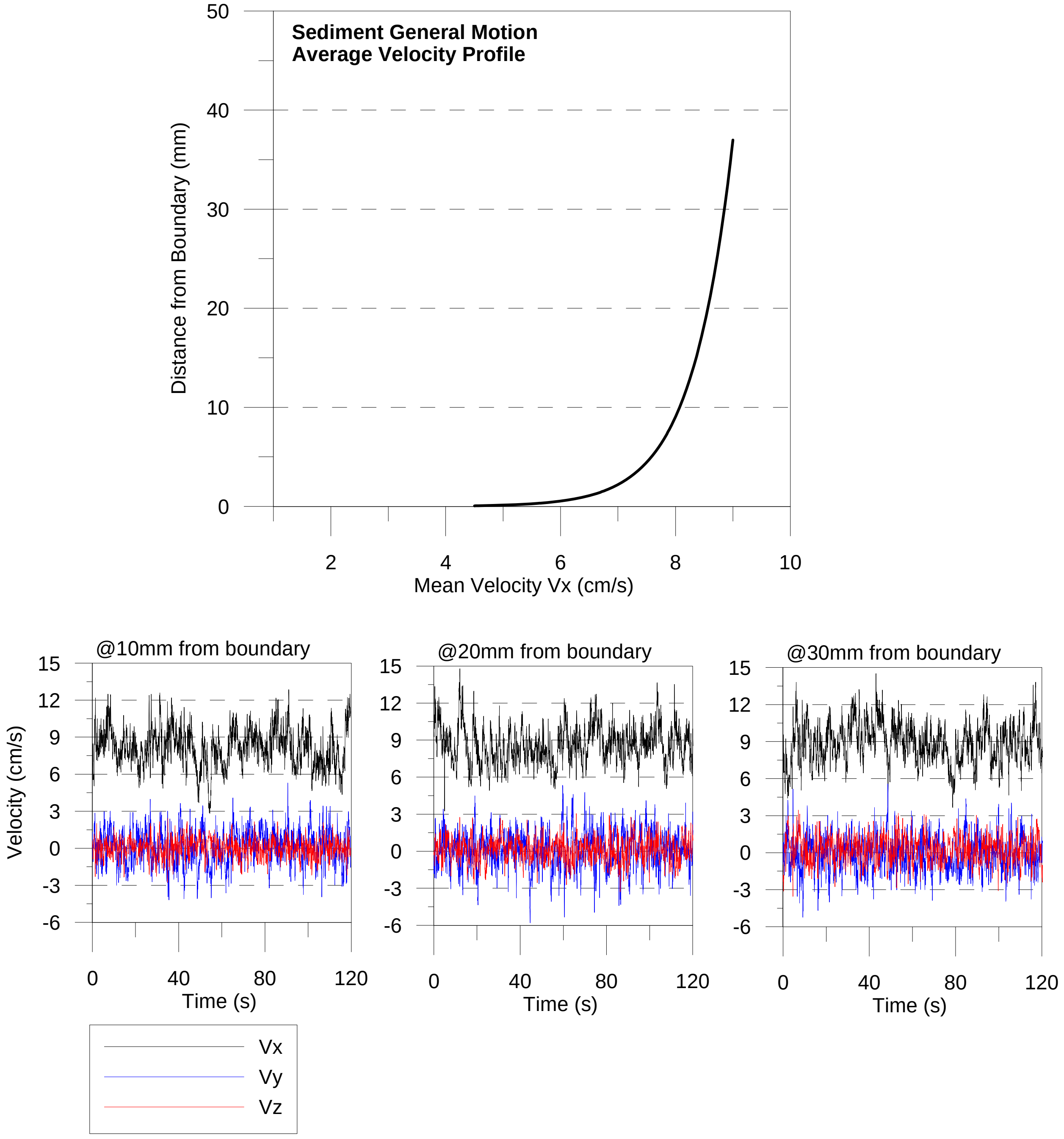
**Floc mat at start of test**



**Floc mat during erosion**

**Floc mat near complete erosion**

Note that velocity and turbulence profiles for these images are provided in Figure 15.



THRESHOLD OF GENERAL SEDIMENT MOTION

Figure
15

# APPENDIX A

## A.1 CALCULATING BED SHEAR STRESS

Threshold condition for sediment movement is commonly expressed as a critical bed shear stress ($\tau_c$). Bed shear stresses are indirectly derived from velocity measurements.

The measured velocity ($U$) is characterized by a mean ($\bar{U}$), and a fluctuating component ($u'$):

$$U = \overline{U} + u'$$

Bed shear stress can be estimated from the first moment (mean) statistics or the second moment (turbulence) statistics (Andersen, 2007).

Assuming logarithmic velocity distribution (Law of the Wall, or Log Profile technique), the von Karmen-Prandtl equation relates the friction or shear velocity, $u*$, to the mean velocity measurement, $\bar{u}$, at height, $z$, above the bed:

$$\frac{\overline{u}}{u*} = \frac{1}{\kappa}\ln(\frac{z}{z_0})$$

Where $\kappa$ is the von Karmen constant (taken as 0.407) and $z_0$ is the bed roughness length (Pope *et al.* 2006).

The relationship between shear velocity, $u*$, and bed shear stress, $\tau_0$, is given by:

$$\tau_0 = \rho u*^2$$

Where $\rho$ is the density of the fluid.

For fully turbulent flows, bed shear stresses can also be estimated via the Reynolds stress measurements (i.e. from the turbulent fluctuations from the mean current near the bed):

$$\tau_0 = \rho(-\overline{u'w'})$$

Where $u'$ and $w'$ represent the turbulent deviations from the mean flow in the horizontal (flow direction) and vertical direction respectively.

Finally, TKE (Turbulent Kinetic Energy) is defined as:

$$TKE = \frac{1}{2}\rho(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$$

And the shear stress can be derived using the following empirical relation:

$$\tau_0 = C_1 TKE$$

Where $C_1$ was found to be 0.19 through laboratory studies (Pope *et al.* 2006).