Lower Duwamish Waterway: Tracing Short-Term Movements of Suspended Sediment

Summary Report

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Cover photo: Partrac Ltd. and Washington State Department of Ecology staff releasing silt sediment tracers into the Lower Duwamish Waterway.

Lower Duwamish Waterway: Tracing Short-Term Movements of Suspended Sediment

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Summary Report

by
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Glossary and Acronyms

Glossary

Contaminant load: Mass of harmful substances associated with sediment particles over a given time.

Grab sample: A discrete sample from a single point in the water column or sediment surface.

Net deposition: Amount of sediment that settles on the bottom of a lake or stream minus the sediment that is re-suspended in a given timeframe.

Plume: Describes the three-dimensional concentration of particles in the water column (example, a cloud of sediment).

Reach: A specific portion or segment of a stream.

Scour: Erosion of bottom sediments due to high current velocity or local turbulence.

Sediment: Solid fragmented material (soil and organic matter) that is transported and deposited by water and covered with water (example, river or lake bottom).

Sediment cap: A remediation technique that covers contaminated sediments with clean sands or sediments, thereby decreasing the potential exposure to the contaminants.

Tracer: Particles manufactured to behave like native sediment particles when suspended in the water column.

Suspended sediment: Solid fragmented material (soil and organic matter) in the water column.

Total suspended solids: Portion of solids in the water column retained by a filter.

Acronyms

Following are acronyms used frequently in this report:

LDW	Lower Duwamish Waterway
STM	Sediment transport model
RM	River mile

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Abstract

During 2009, the Washington State Department of Ecology (Ecology) conducted a field study at the Lower Duwamish Waterway (LDW) sediment cleanup site in Seattle. The study involved the release and recovery of sediment tracer particles having both fluorescent and magnetic properties. The main goal of this short-term study was to assess the movement and fate of incoming suspended sediments from the Green River. Ecology contracted with Partrac Ltd. to manufacture and analyze these tracer particles.

This summary report describes the study methods, major findings, and recommendations presented in two attached Partrac Ltd. reports produced as a result of the field study:

1. *Assessment of the Hydraulic Characteristics of Native Sediments (Lower Duwamish Waterway) and Tracer Design and Testing.*
2. *Tracking Short-Term Movements of Suspended Sediment in the Lower Duwamish Waterway*.

In February 2009, Ecology released sand-sized and silt-sized tracers upstream of the cleanup site. During the two months following release, tracer particles were recovered from the water column and surface sediments. Samples were analyzed to determine mass of tracer particles present.

Overall, the manufactured tracers successfully mimicked native suspended sediments. Tracers were released with little difficulty and did not alter concentrations of total suspended solids in the Green River. Tracers were recovered in a variety of samples collected from the LDW over a two- month period.

The distribution of the tracer types and their masses generally confirmed sediment transport model (STM) predictions:

- Sand-size tracers were transported and accumulated in upstream areas of the LDW cleanup site.
- Sand-size tracers underwent sorting (mean size decreased with distance traveled).
- Silt-size tracers released into the LDW from the Green River were easily transported throughout the LDW and beyond.
- Silt-size tracers were diluted with distance traveled, deposited throughout the LDW, resuspended (present in the LDW water column after two months), and transported upstream of the release site during flood tides.

Acknowledgements

The authors of this report would like to thank the following people for their contributions to this study:

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Introduction

The Lower Duwamish Waterway (LDW) is a tidally influenced state and federal cleanup site in Seattle, Washington. The site contains elevated concentrations of polychlorinated biphenyls (PCBs), dioxins and furans, polycyclic aromatic hydrocarbons (PAHs), arsenic, and other chemicals in deposited sediments.

Remedial investigations, including a sediment transport model (STM), conclude that nearly all sediment entering the LDW cleanup site is from the Green River.[1]

In 2008 and 2009, the Washington State Department of Ecology (Ecology) conducted a study that measured contaminant concentrations in suspended Green River sediments. Results were used to estimate contaminant loads to the LDW (Gries and Sloan, 2009).

The fate of these suspended sediments, and associated contaminants, was predicted by the STM and a streambed composition model.

The STM identifies three main reaches in the LDW (Figure 1) distinguished by the apparent long-term stability of bottom sediments:

- Reach 1 (River Mile (RM) 0.0 - 2.2) is a zone of net deposition, with minimal scour potential.
- Reach 2 (RM 2.2 - 4.0) is a zone of greater net deposition, with moderate scour potential.
- Reach 3 (RM 4.0-4.8) has the highest net sedimentation rates and the greatest potential for scour.

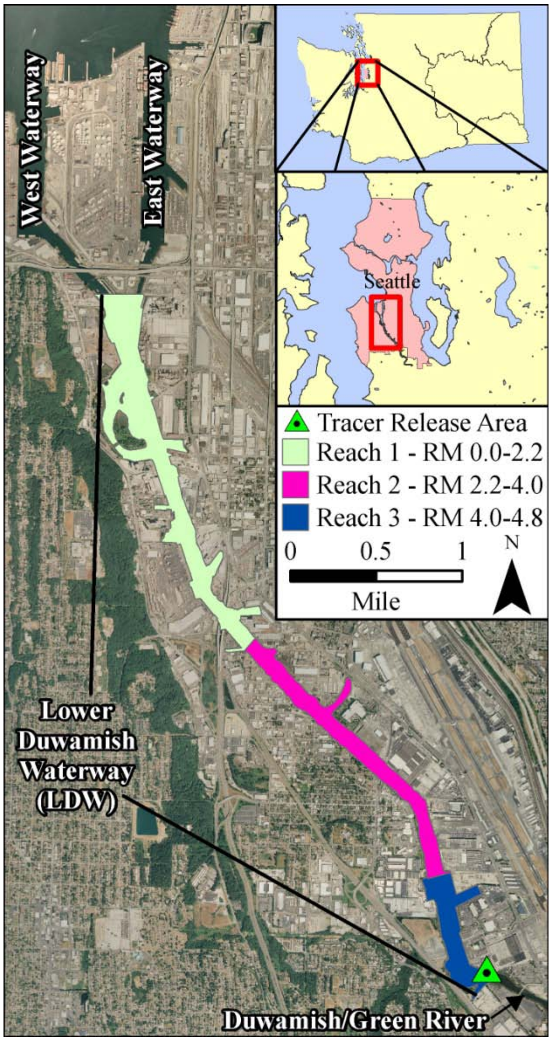

Figure 1. Overview of the Lower Duwamish Waterway (LDW) study site. *Tracers mimicking native sediments were released at River Mile 4.7 (green triangle) and recovered downstream.*

The STM predicts that sand-sized suspended sediments, mostly from the Green River, will accumulate within these three reaches. It predicts approximately one-half of the incoming fine suspended sediments will pass through the LDW into the East and West Waterways or Elliott Bay (LDWG, 2008).

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[1] This study considers the Green River to begin at about the LDW River Mile 4.8, just above the southern turning basin.

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Purpose

Study

The goal of Ecology's 2009 sediment tracer study, summarized here, was to provide field data that could be used to evaluate STM predictions. The study used manufactured sediment tracers (tracers) to demonstrate short-term movement and fate of suspended sediments entering the LDW from the Green River. The *dual signature* tracers had fluorescent and magnetic properties that distinguished them from native sediments (Figure 2).

Specific objectives of the study were to:

- Characterize the physical properties of native sediments, especially settling velocities.
- Use manufactured tracers to mimic the transport of native sediments.
- Release the tracers in a manner not altering concentrations of in-situ suspended solids.
- Recover tracers from the water column and surface sediments of the LDW after their release (and within project time constraints).
- Identify lessons learned from using technology new to the Puget Sound region.

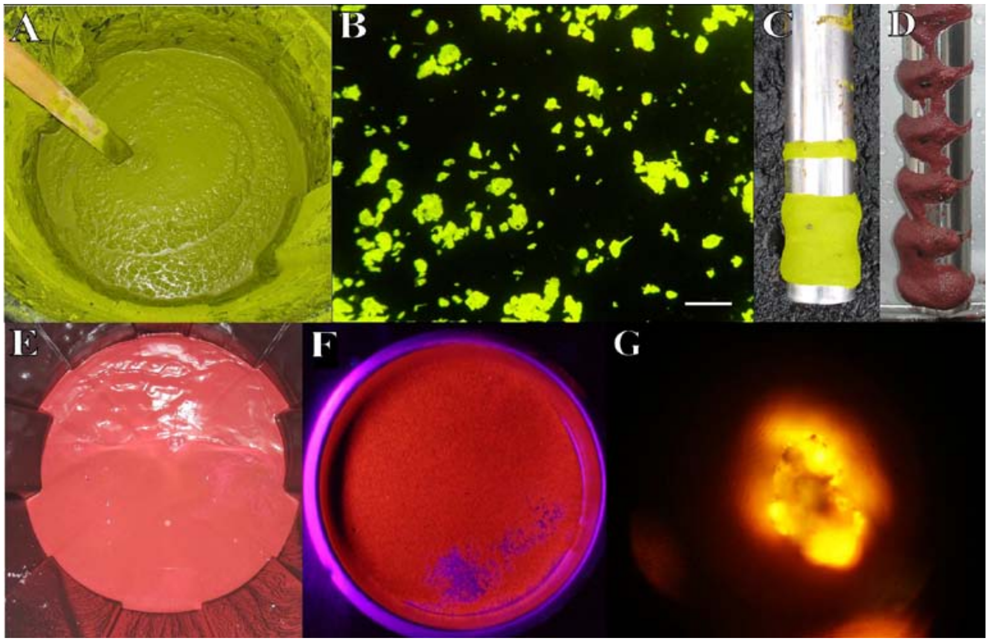

Figure 2. Images of tracers.

Silt-sized tracers: A. Pre-wet; B. Under epifluorescent microscope (bar = 100 µm); C. On bar magnet. Sand-sized tracers: D. On bar magnet; E. Pre-wet; F. Under black light, unmagnified; G. Under epifluorescent microscope. (Photographs B, F, and G courtesy of Kevin Black, Partrac, Ltd.)

Document

This document summarizes the two attached reports prepared by the contractor, Partrac, Ltd.:

1. *Assessment of the Hydraulic Characteristics of Native Sediments (Lower Duwamish Waterway) and Tracer Design and Testing.*
2. *Tracking Short-Term Movements of Suspended Sediment in the Lower Duwamish Waterway.*

Methods

Fluorescent-magnetic sediment tracers were manufactured to specifications that were based on properties of native sediments collected within and upstream of the LDW.[2] Measured properties of the two final batches of tracers were compared to the specifications and judged to be within acceptable limits:

- 99 kg of yellow-green, magnetic tracers had settling velocities equal to 7-27 µm diameter native silt particles (Figures 2A-C).[3]
- 93 kg of reddish, magnetic tracers had a modal settling velocity equivalent to 70-250 um diameter native sand particles with a density of 2.6 g/cm^3 (Figures 2D-G).

On February 13, 2009, Ecology and Partrac Ltd. released the tracers into the portion of the LDW known as the southern-turning basin (~RM 4.7; Figure 1). Silt and sand tracers were washed separately into a pipe mounted on the *RV Skookum* vessel for subsurface discharge. Tracers formed three-dimensional plumes with negligible surface entrainment (Figure 3A-C). Levels of total suspended solids (TSS) near the release point were measured in-situ using a laser particle size analyzer. Presence of tracers in the water column during the initial release was evaluated using a standard filtration setup (Meredith, 2008) and magnets towed in the water column within 100 yards of the release (Figure 3D) and between river miles 0.0 and 2.2 (Figure 4).

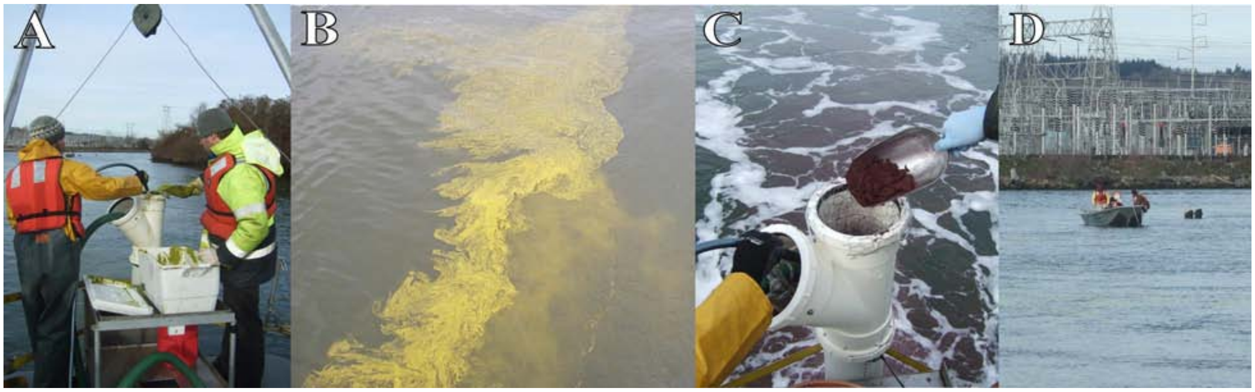

Figure 3. Images of tracer release.

A. Silt tracer being manually scooped into and flushed down PVC delivery pipe using site water.
B. Silt tracer plume passing the boat located approximately 100 meters downstream of the release vessel.
C. Close-up view of sand tracer being scooped into and flushed down the same PVC delivery pipe. Reddish plume and bubbles from residual surfactant trail behind release vessel.
D. Sampling boat located approximately 100 meters downstream from the release boat (picture taken from release boat).

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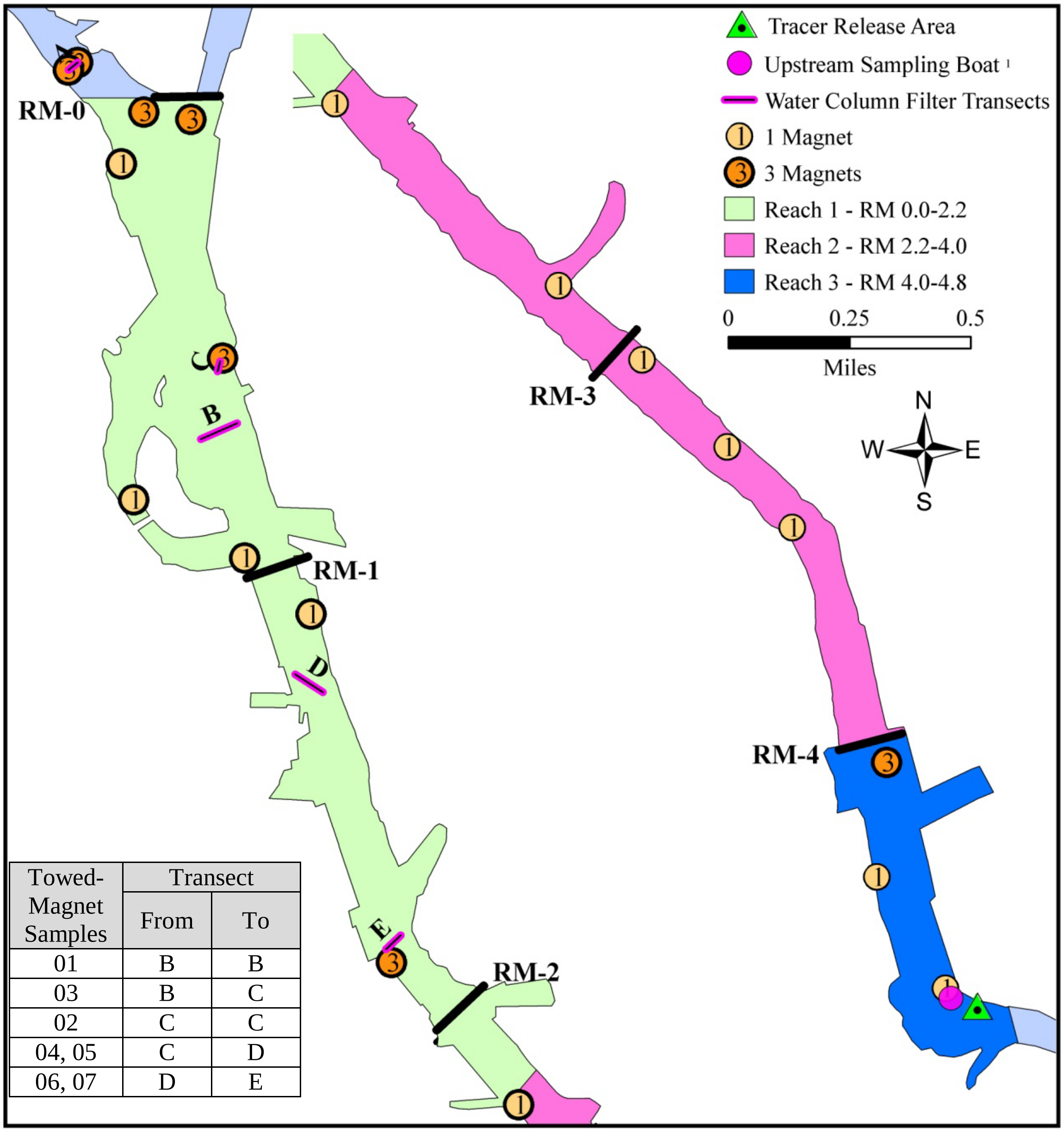
[2] The tracer manufacturing process is proprietary. However, tracers were made using mostly natural materials and have been shown to be non-toxic to aquatic organisms.

[3] 160 kilograms of silt tracers were manufactured and ranged in diameter from 7-162 µm. However, they mimicked the settling velocity of native particles between 3-55 µm. This is due to the tracers reduced density (1.2 g/cm^3) compared to that of native sediments (2.65 g/cm^3).



Towed-Magnet Samples	Transect	
	From	To
01	B	B
03	B	C
02	C	C
04, 05	C	D
06, 07	D	E

Figure 4. Water column sampling locations (18 total).

Filtering of the water column occurred only on the day of tracer release at the upstream sampling boat and the downstream boat transects. The downstream boat also towed a magnet in the water column between the water filter transect (as indicated by the inset table). One or three magnets as indicated were mounted on pilings in the water waterway prior to release. Magnet samples were collected one week, one month, and two months post release

[1] *The upstream sampling boat was located approximately 100 meters downstream of the release boat.*

Recovery of the tracers occurred one week, one month, and two months after release using magnets mounted in the LDW water column and bottom sediment grabs. Tracers were collected from passive magnet samplers by rinsing outer sheaths into containers (Figure 5). Sediment samples were collected using various grab samplers and following established methods (Blakley, 2008). A total of 68 magnet, 60 subjective sediment, and 64 random sediment samples were collected.

Figure 5. Magnet sampling images.

A. Bar magnets mounted to a piling with visible yellow silt tracer.
B. Removing plastic sheath from magnet.
C. Rinsing sheath into a plastic jar.
D. Magnets re-mounted on piling after sample collection.

Magnet and sediment samples were prepared for image analysis. Particles larger than the largest sand tracers were removed using a 350-µm mesh screen. The remaining material was made into a slurry and passed through a magnetic particle separator (MPS). After separation, the MPS collector screen was rinsed into a sample jar. Tracers contained in representative subsamples or aliquots of all samples were analyzed using a Zeiss epifluorescent microscope fit with excitation and emission filters (Figures 2B, 2F, and 2G).

The number and dimensions of each tracer particle were measured. The mass of each particle was calculated by multiplying the estimated volume (computed as a sphere having a mean particle radius) by the manufactured density. Total tracer mass in each sample was equal to the sum of individual particle masses.

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Findings

General

- Manufactured fluorescent sediment tracers served as effective environmental tracers.
    - The tracers successfully mimicked key properties of suspended Green River sediments and bedded LDW sediments.
    - Release of the tracers did not alter concentrations of in-situ suspended sediments.
    - Para-magnetic properties of the tracers facilitated their recovery from the field (using towed and fixed magnets) and concentration for analysis (using a magnetic particle separator).
- Results were often considered qualitative because silt tracers were lost from the overlying water in sediment grab samplers or because too few tracers were counted and measured in samples.
- The mass and spatial distribution of tracers that were recovered by filtering the water column, magnets deployed in the water column, and surface sediment samples generally confirm STM predictions (see below).

Suspended sand tracers

The limited results summarized below generally support STM predictions about the transport and fate of sand-sized particles:

- Remain within the LDW.
- Accumulate in LDW Reach 3 (upstream of RM 4.0) > Reach 1 (RM 0.0-2.2) > Reach 2 (2.2-4.0).
- Accumulate predominantly within the LDW southern-turning basin (approximately RM 4.7).

The distribution of sand tracers in recovered samples indicated mostly near-field transport. During the release of sand tracers, reddish sand-sized particles (64-198 µm) were found in water samples collected approximately 100 meters downstream. One week later, a wide- size range of tracers was found in the sample collected from fixed magnet M1, located approximately 150 meters downstream of the release point. Small amounts of the smallest sand tracers were observed in two towed magnet samples that were collected near the leading edge of the plume. No sand tracers were found in the water column filter samples collected from RM 0.0-2.2. However, a small amount of the finest sand manufactured was recovered from towed magnet samples from RM 0.0-2.2. This indicates that the finest sands may be transported downstream in suspension.

Most sand tracer deposition likely occurred near the point of release.
Samples containing a relatively high mass of sand tracers were most frequently recovered in sediment samples collected from Reaches 2 and 3 (Figures 1 and 6).

Sand tracers were sorted during downstream transport.
Samples collected within approximately 500 meters of the release contained some of the coarsest sand-sized tracers. Sediment and fixed magnet samples collected further downstream (within 1-2 km of the release point) contained finer sand-sized tracers.

Suspended silt tracers

Silt-sized tracers, and larger tracers having settling velocities equivalent to silts, were recovered from water column filter, magnet, and sediment samples. Tracers were present in samples collected throughout the LDW (all reaches), from all depths, and after all sampling intervals (Figure 7). The results summarized below generally support long-term predictions that:

- About 50% of the silt-sized suspended sediments pass through the LDW into the downstream waterways or Elliott Bay.
- The remaining 50% of incoming silt-sized suspended sediments settle to the bottom and accumulate in all LDW reaches (almost all areas are predicted to be net depositional), but perhaps especially within the downstream navigation channel.

Study results showed that the silt tracers were:

- **Transported throughout the entire LDW (and likely beyond) during one ebb tide phase.**
  This was indicated by silt tracers being found in filtered water samples collected near the entrance to the West Waterway (Figure 1) approximately 4.2 hours after being released. The silt tracers (and undersized sand-sized tracers) were also found in water and towed-magnet samples collected at other locations in Reach 1 (RM 0.0-2.2) on the day of release.

- **Diluted, lost to the downstream waterways, and lost to bottom sediments over time.**
  Evidence for this was that the number of silt tracers found accumulated on fixed magnets decreased over the course of the study.

- **Not obviously sorted during transport.**
  There was no substantial difference in the size of silt tracers found in fixed magnet and surface sediment samples (Figure 8).

- **Deposited throughout the LDW cleanup site.**
  Silt tracers recovered from surface sediment samples indicated the potential for at least temporary deposition in all reaches (Figure 7).

- **Resuspended.**
  Silt tracers continued to accumulate on fixed magnets during the second month following release.

- **Transported and temporarily deposited upstream of the release site during flood tides.**
  Sediment samples collected upstream one week after the release contained silt tracers.

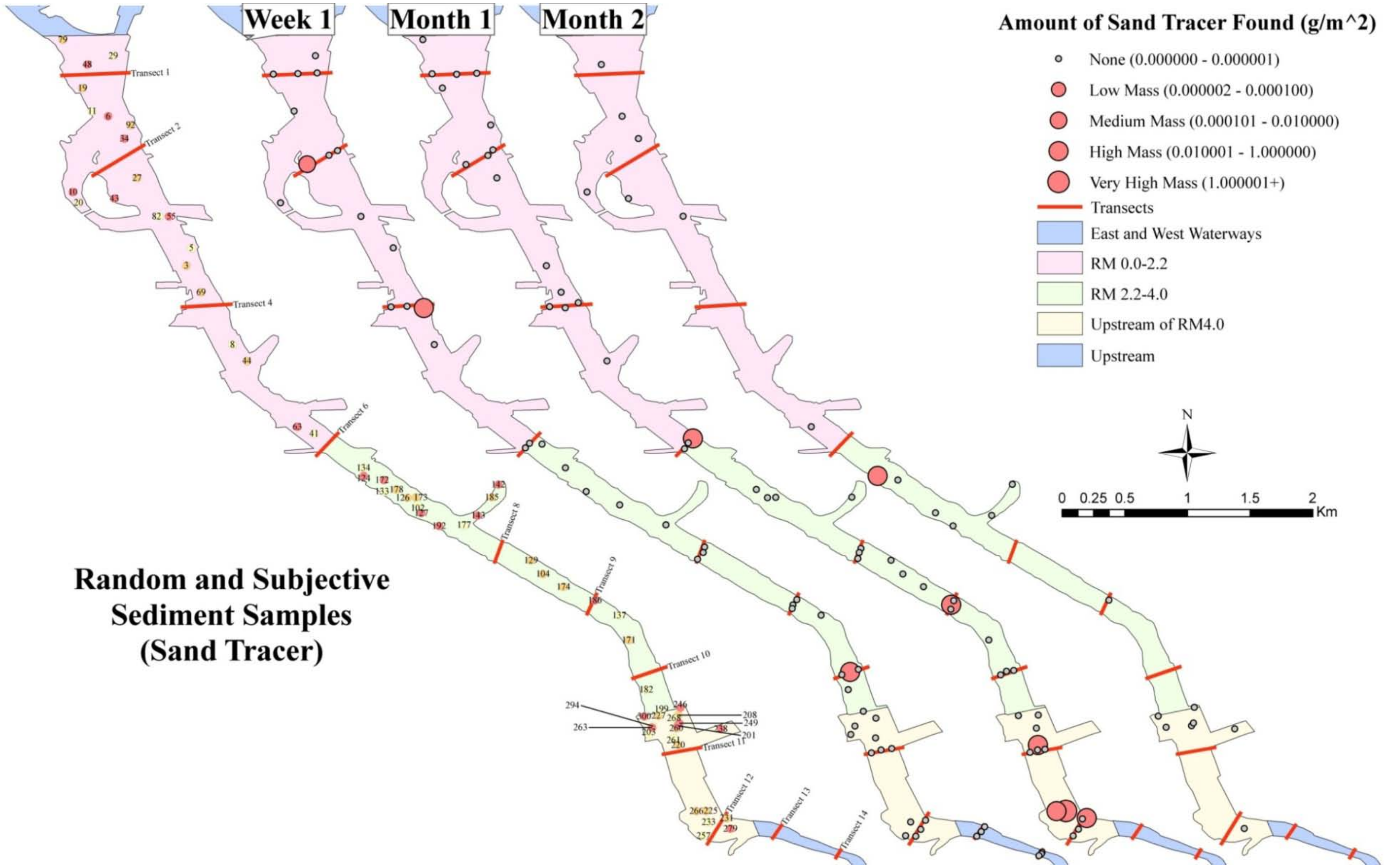

Figure 6. Sand-sized tracers recovered in surface sediments of the LDW.

Locations where surface sediment grabs were collected are identified in the first (left) outline of the waterway. The relative mass of sand tracers recovered during each of the three sampling events is shown in 5 categories (“None” to “Very High”).

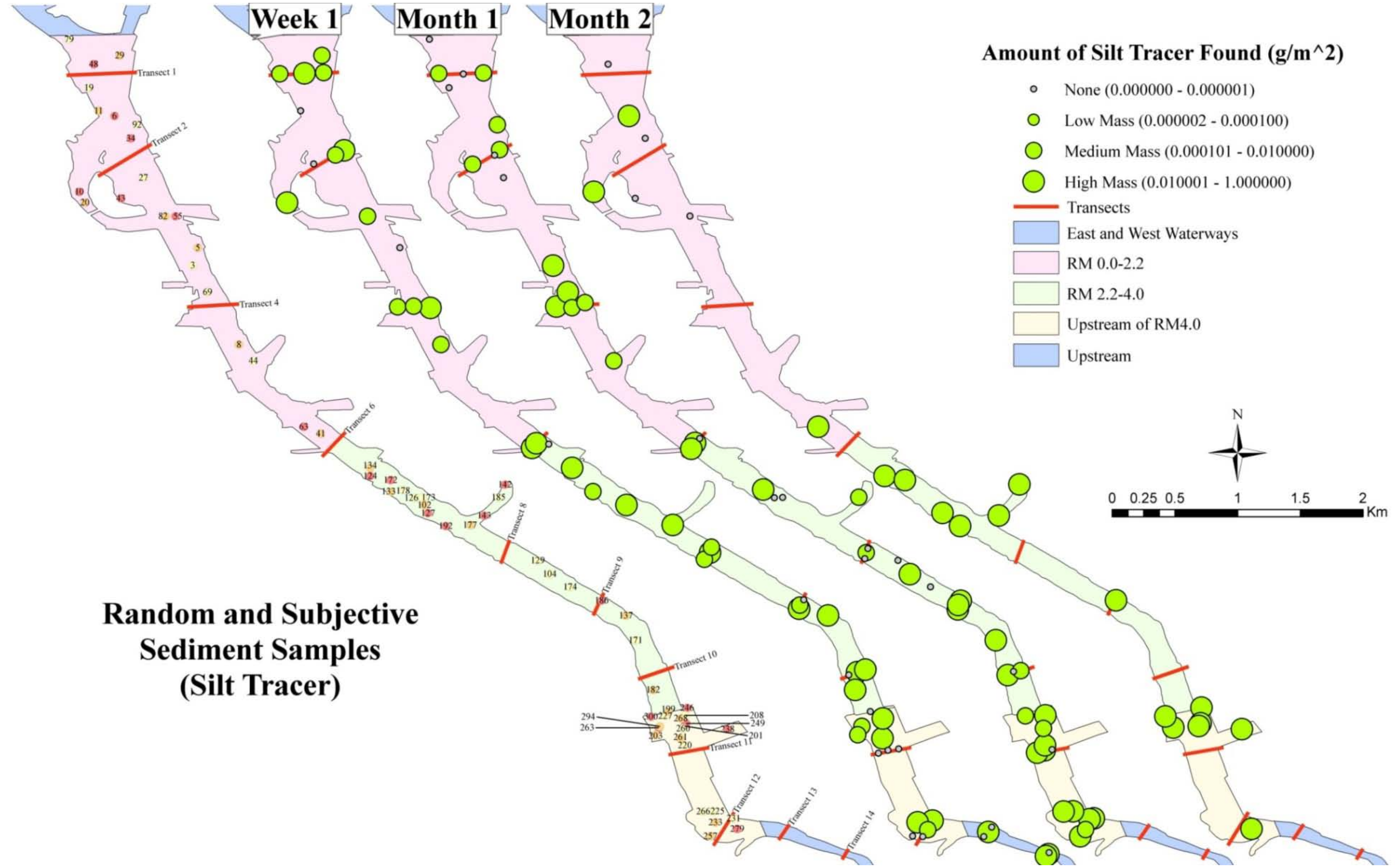

Figure 7. Silt-sized tracers recovered in surface sediments of the LDW.

Locations where surface sediment grabs were collected are identified in the first (left) outline of the waterway. The relative mass of silt tracers recovered during each of the three sampling events is shown in 4 categories ("None" to "High").

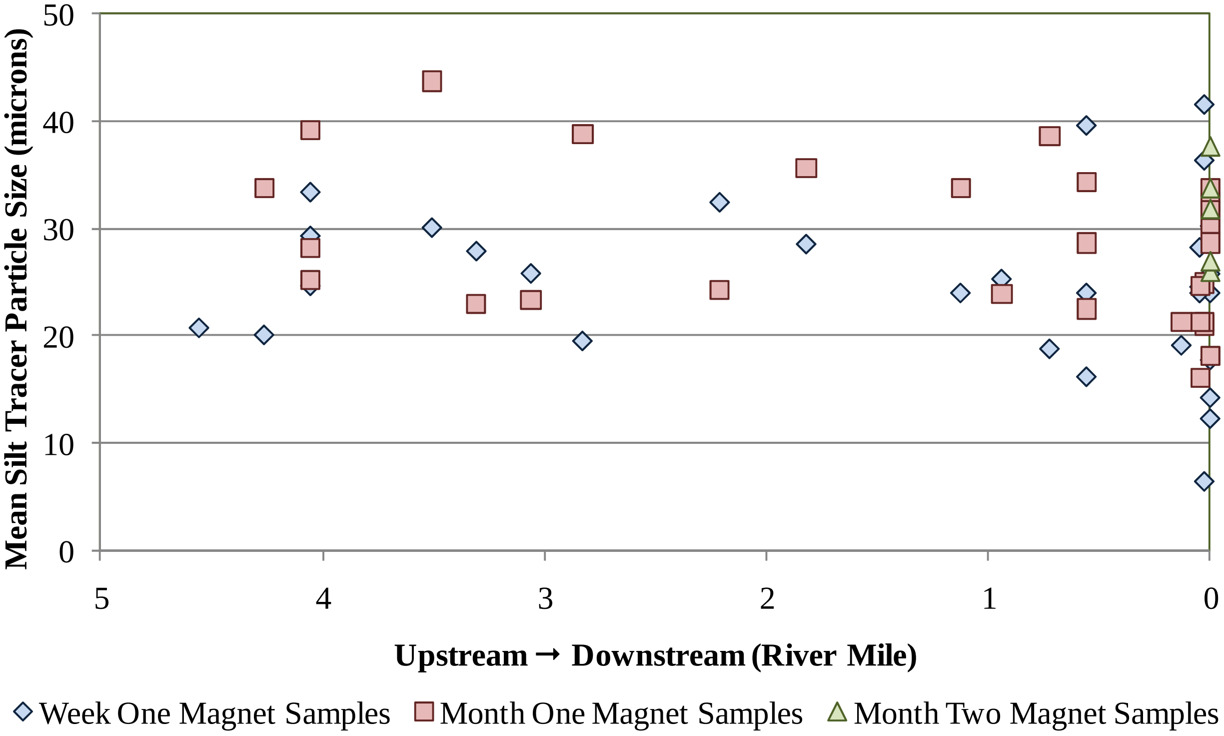

Figure 8. Mean size of silt tracer particles on fixed magnets by river mile.

Fixed magnet samples contain tracer particles that were suspended in the water column. Magnets were deployed in 18 locations throughout the LDW. Some locations represent a single height in the water column while others represent three heights. Sampling was concentrated near the downstream end of the LDW to emphasize particles leaving the waterway.

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Recommendations

The following recommendations are made as a result of this 2009 tracer study.

Study design

- Future investigations should manufacture as many tracers as the budget allows. Releasing more tracer into the study area improves the probability of recovering tracers and obtaining at least qualitative results.

Field sampling

- Soluble filters should be used for filtration of surface water samples so that all tracer particles can be counted and measured, and total sample mass can be estimated.
- Passive magnet samplers should be deployed at a constant depth when the study area is influenced by tides. Alternatively, in-situ temperature recorders could measure magnet submergence time.
- Surface sediment sampling methods should be revised, or new sampling methods developed (magnetic sampler), to eliminate losses of recently-settled silt tracers.
- Studies in complex, dynamic environments should use acoustic Doppler current profilers to assess and better understand the heterogeneity of the water column.
- Sampling to identify the tracer plume should begin well in advance of when the tracer particles are expected to arrive. Continued sampling should be at predetermined intervals to help understand the timing, concentration, and behavior of the initial tracer plume.

Laboratory analysis

- Methods for concentrating, counting, and measuring tracer particles should be modified for samples that are expected to contain a large fraction of native magnetic material.
    - A greater fraction of tracer particles should be counted and measured manually.
    - Only the fluorescent-magnetic particles in a sample should be counted and measured (not native particles) with automated instrumentation.

Applications

- Applications of sediment tracer technology in the Puget Sound region should be evaluated. Possible applications include:
    - Assess performance of a sediment cap.
    - Track solids from stormwater discharges.
    - Evaluate best agricultural management practices to control erosion.

References

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Attachment 1.

Assessment of the Hydraulic Characteristics of Native Sediments (Lower Duwamish Waterway) and Tracer Design and Testing

This document was prepared under contract with Partrac Ltd. and is intended for a technical audience. The important elements are described in the summary report.

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Assessment of the Hydraulic Characteristics of Native Sediments (Lower Duwamish Waterway) and Tracer Design and Testing

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Exec Summ.	As per PARTRAC Review.docx from J. Sloane (22.05.2009); ref p.3 sand tracer
Introduction	As per PARTRAC Review.docx from J. Sloane (22.05.2009); ref. p.5
Table 2 & graphics	As per PARTRAC Review.docx from J. Sloane (22.05.2009); ref. p.12 & 13
Table 3	Corrections as per PARTRAC Review.docx from J. Sloane (22.05.2009);
PSA text	Various from p.17-28. Corrections as per PARTRAC Review.docx from J. Sloane (22.05.2009);
P.30 and p.40	Addition of note on textural tail loss during tracer wetting and preparation;
SVelocity text (3.5.2)	Corrections as per PARTRAC Review.docx from J. Sloane (22.05.2009);
References (p.29)	Additional references included on previous use of methodology;

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EXECUTIVE SUMMARY

This report provides an assessment of the physical-hydraulic character of suspended and deposited sediments from the Lower Duwamish Waterway and summarises specification of, and characterization of, manufactured silt and sand tracers.

Existing data are reviewed, and laboratory analyses of size, density, settling velocity, fluorescence presence, and para-magnetic character for real sediments are reported and discussed. These data have been used to derive specifications for sand and silt dual-signature tracers, but with several caveats. The major of these was that the sand fraction be in the very fine to fine sand range, and that the silt tracer corresponded to (in hydraulic terms) a medium silt fraction.

The above tests were repeated on the commissioned tracers as part of a similarity testing assessment.

93 kg of a dual-signature <u>sand</u> tracer with density, size and settling velocity attributes highly similar to native sand was manufactured for introduction into the surface waters of the LDW. Macroscopically the tracer resembled and behaved as mineral sand (naturally slightly compact, moisture redistribution upon disturbance, temporary clumping when troweled into the injection funnel). The sand tracer included a small silt fraction within which particle sizes <20 μm are dust from the manufacturing process and do not affect the tracking study, whereas those in the range 20 to 63 μm are genuine fluorescent-magnetic, mineral density (2650 kgm^{-3}) silt particles which do (although many of these may have been washed off during the tracer pre-wetting process).

160 kg of a dual-signature (reduced-density) <u>silt</u> tracer with settling velocity attributes highly similar to native very coarse silts was available for introduction into the surface waters of the LDW. In hydraulic terms the silt tracer was slightly coarser than specified, and the settling velocity spectrum was observed to overlap fractionally with the sand tracer. Macroscopically the tracer resembled and behaved like an estuary silt/mud (with elastic-plastic properties and discernible vertical consolidation gradients inside enclosed vessels).

For each tracer, tests confirmed a strong fluorescence signature and that 100% of tracer particles were highly para-magnetic.

CONTENTS

1. INTRODUCTION

1.1 Background

The Washington State Department of Ecology is studying the loading of PCBs from suspended solids entering the Lower Duwamish Waterway sediment cleanup site. An estimate of PCB loading will be derived from simultaneous measurements of flow and PCBs associated with suspended particulate in the upper Duwamish/Green River. Observations of the transport and deposition of fluorescent sediment particles – ones that mimic native suspended sediments and that will be released upstream of the cleanup site – will be used to make additional inferences about PCB loading. Together, these will be compared to predictions made by a sediment transport model and estimates of PCB loading from upstream sources.

A vicinity map showing the study area is shown in Figure 1. The Duwamish River, which drains to the Puget Sound estuary, is tidally influenced well beyond River Mile 12.4. A wedge of saline water can periodically underlie fresh surface water as far upstream as approximately River Mile 8.7; the wedge does not pass the East Marginal Way Bridge except during flows of <1000 cfs and large flood tides (Figure 1) .
.

The southern boundary of the cleanup site is located at approximately River Mile 5. Some characteristics of the cleanup site itself (downstream of River Mile 5) include:

- Length approximately 8 - 9 km.
- Width (main channel) approximately 150 - 215m.
- Inflow approximately = <10 - 340 m^3s^{-1} (mean approximately 40 m^3s^{-1}).
- Area of entire cleanup site approximately = 1,800,000 m^2.
- Area of southernmost 1 kilometer of the waterway (including turning basin that acts as sediment trap) approximately 350,000 m^2.
- Water volume within cleanup site approximately = 11,000,000 m^3 (assuming mean depth = 6m), but varies with tidal elevation.

A key element of the study will be to release fluorescent sediment particles into the water column of the Duwamish/Green River (Figure 1). These sediment particles are required to have size distributions, densities, and settling velocities similar to ones found in the river. Ecology are particularly interested in the potential transport and fate of fine suspended particles (<1- 62.5 μm) and fine to medium sands (63-500 μm) that enter the Lower Duwamish Waterway under different seasonal flow conditions. This is because Ecology plans to measure Total PCBs in these two particle size fractions of suspended sediment.

1.2 Goals, Objectives, and Scope

The Washington State Department of Ecology, hereafter called "AGENCY," initiated a Request for Qualifications and Quotations (RFQQ) mechanisms to solicit proposals from contractors that can assist the AGENCY in the direct assessment of transport and fate of suspended solids that enter the Lower Duwamish Waterway from the Upper Duwamish/Green River system. Partrac were the successful contractor within a competitive framework. The provision to Partrac was a) comment on the AGENCY's study design and implementation strategy, b) manufacture artificial fluorescent sediment particles to the AGENCY's specifications, c) analyze samples that contain recovered fluorescent particles, and d) interpret the analytical results.

Goals

The primary goal of the overall study is *to provide an estimate of PCB loading to the Lower Duwamish Waterway from suspended Upper Duwamish/Green River sediment in order to confirm sediment transport model predictions and preliminary loading calculations*.

Study goals pertinent to Partrac are to help the AGENCY show how far into or beyond the cleanup site fluorescent sediment particles that mimic those found in the upper Duwamish/Green river can be transported when released into the water column under moderate flow and ebbing tidal consitions, and to trace where they can settle to the bottom.

Objectives

- To evaluate the natural background fluorescence of suspended and bedded sediments found within the study area;
- To manufacture fluorescent sediment particles effectively mimic the characteristics of samples of fine suspended sediment collected from the Green River or fine bedded sediment collected from the Lower Duwamish Waterway;
- To release such particles into the water column of the Upper Duwamish/Green River during a period of moderate-high flow and ebbing tide; and; and
- To trace the movement of these particles into, and possibly through, the waterway.

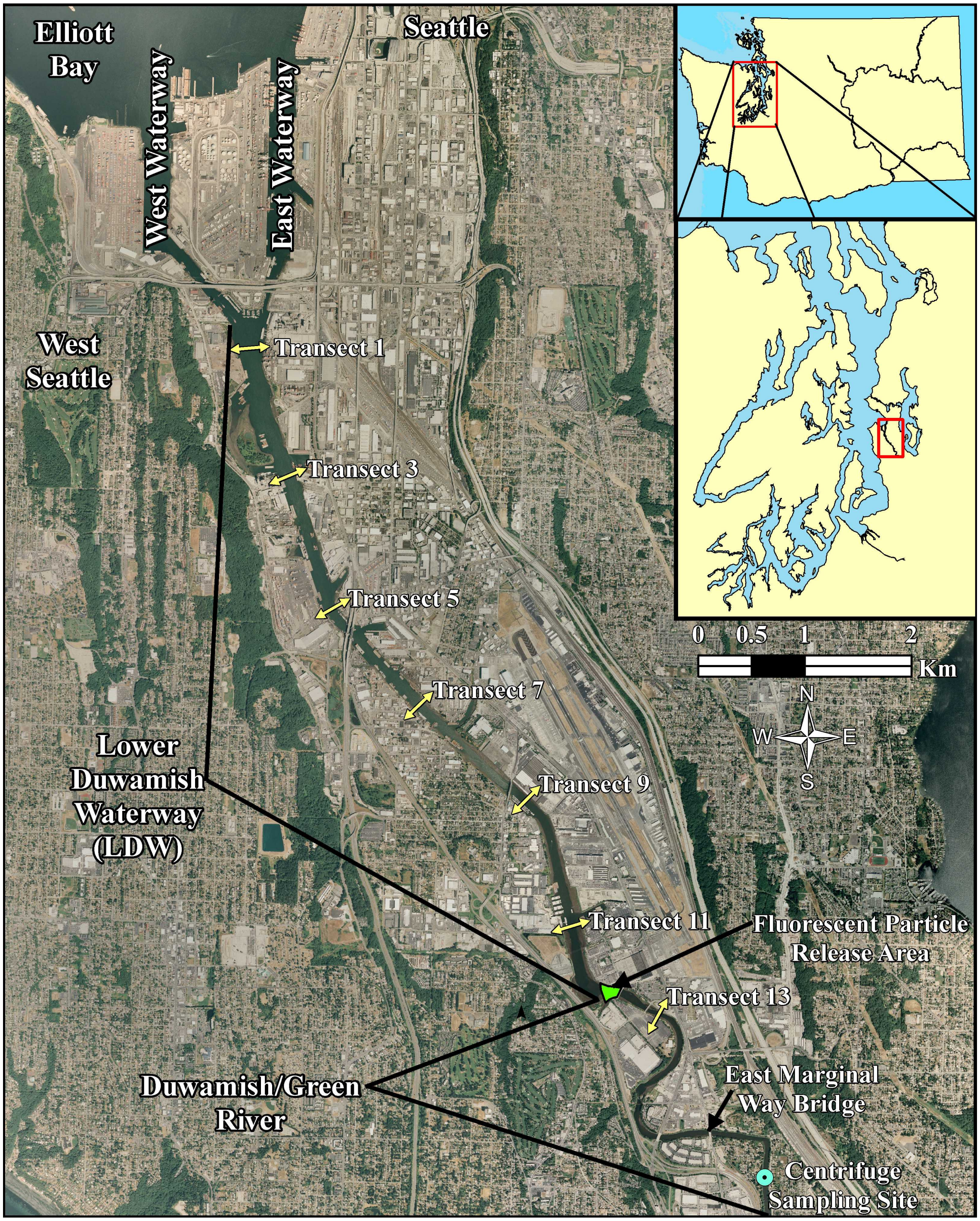

Figure 1 Aerial photograph of the Lower Duwamish Waterway sediment loading study showing the tracer release site and location of transect and other sampling areas.

2. SCOPE OF REPORT

This report extends a previous report issue (P1062.05.D001v02 - Native Sediment Characterisation Report.pdf). The previous report considered:

- Review of existing data sources; and
- Assessment of measurements (e.g. grain size, settling velocity etc.) made on provided sediment samples.

The report concluded on a set of physical-hydraulic characteristic specifications for the sand and silt tracers. This report summarises the testing of the manufactured tracers for physical-hydraulic characteristics, together with an assessment of the degree of hydraulic similarity between the native/archive sediments and the tracers.

3. REVIEW OF PROPERTIES OF WATERWAY SEDIMENTS

3.1 Introduction

A range of data types were collected *in lieu* of and to support tracer particle design. These included data from a streamside laser particle diffraction sensor (LISST), and data derived from analysis of bedded (settled) and suspended sediment sources. The LISST data were supplied to Partrac by J. Sloan in the form of a spreadsheet. Samples of bedded and suspended sediments were shipped to the Partrac offices for analysis in our laboratory.

3.2 Pre-Existing Size Data

Pre-existing particle size data were supplied to Partrac (filename ID - *gries ldw psd 06_23.07.08.pdf*). These data correspond to bedded (deposited) sediments from a variety of locations in the LDW as part of a previous SPI camera survey. Table 1 summarises data from these samples.

The samples span a range of particle sizes (from clay to gravel size), but the fines content (<63 μm) is mostly >60% and frequently >80% of the total with minor exceptions. The bed sediments are therefore dominantly muddy (cohesive) in character. Closer inspection of the size interval data (Table 1) shows that the modal grain size range occurs in the fine silt to coarse silt size range.

Table 1 **Grain size spectra from samples obtained during Ecology SPI Feasibility Study (LDW) (2006). Note organic matter was not removed prior to sample testing. Yellow hatched area indicates the 3 size classes dominating the mode; the strict mode is in bold.**

Sample No.	Gravel	Very Coarse Sand	Coarse Sand	Medium Sand	Fine Sand	Very Fine Sand	Coarse Silt	Medium Silt	Fine Silt	Very Fine Silt	Clay	Clay	Clay
Phi Size	> -1	-1 to 0	0 to 1	1 to 2	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to 8	8 to 9	9 to 10	<10
Sieve Size (microns)	> #10 (2000_	10 to 18 (2000 - 1000)	18-35 (1000 - 500)	35-60 (500-250)	60-120 (250 - 125)	120-230 (125-62)	62.5-31.0	31.0 - 15.6	15.6-7.8	7.8-3.9	3.9-2.0	2.0-1.0	<1.0
TRI037T	0.30	2.20	3.70	7.50	4.60	9.10	13.00	**16.90**	15.40	10.30	5.10	3.80	8.10
TRI037T	0.60	2.40	3.30	7.80	4.70	8.80	14.10	15.60	**16.10**	10.00	5.40	3.60	7.60
TRI037T	0.40	2.30	3.70	7.10	4.50	9.10	12.70	**16.30**	16.50	10.10	5.20	4.00	8.10
TRI050T	2.60	1.90	2.20	4.60	2.30	9.10	16.80	**20.20**	15.80	10.20	4.20	3.50	6.80
TRI016	0.10	1.40	2.40	4.40	4.30	8.80	11.60	15.60	**19.10**	10.40	5.90	5.30	10.80
TRI045	1.50	2.90	3.40	8.40	5.70	10.30	9.10	15.50	**17.70**	8.50	4.70	4.10	8.30
TRI048T	0.80	3.10	1.70	4.80	5.50	11.90	13.90	16.20	**18.10**	7.60	4.60	4.00	7.70
DR111	0.00	1.50	1.40	1.40	1.70	7.80	11.10	**23.70**	22.40	10.70	5.70	4.30	8.30
SPI 125	2.20	1.70	2.00	3.60	2.70	7.40	10.10	**20.30**	21.50	10.00	5.40	4.20	8.80
TRI015T	0.80	3.20	3.90	7.10	4.00	7.40	15.50	14.50	**15.60**	9.40	5.80	4.60	8.30
TRI010	0.00	2.10	2.10	5.80	6.30	10.00	13.10	13.70	**18.60**	9.10	6.10	5.00	8.10
TRIDR181	0.00	1.80	1.60	2.90	2.00	4.10	12.30	21.60	**23.00**	11.50	6.00	4.80	8.40
TRI069T	0.30	2.60	2.90	6.70	5.00	11.30	16.70	13.90	**15.90**	7.30	5.30	4.50	7.60
TRI095T	0.00	1.80	1.60	2.10	4.80	11.50	14.50	**23.50**	18.80	8.30	4.10	3.00	6.00
SPI128	0.10	1.10	1.80	4.00	6.80	**23.10**	16.10	18.40	11.90	5.40	3.30	2.60	5.40
TRI051	0.10	2.70	3.50	6.40	2.70	8.30	13.30	**21.00**	15.70	9.10	5.20	4.20	7.80
TRI047T	2.50	2.00	2.10	7.00	7.10	7.40	13.10	12.70	**16.90**	9.90	5.90	4.30	9.00
TRI008	0.10	1.90	1.70	5.70	6.10	9.70	13.30	**17.00**	15.80	9.70	6.30	4.50	8.40
TRI026	0.50	0.80	2.00	5.00	9.20	14.10	13.00	11.70	**14.60**	9.30	6.10	4.30	9.60

Sample No.	Gravel	Very Coarse Sand	Coarse Sand	Medium Sand	Fine Sand	Very Fine Sand	Coarse Silt	Medium Silt	Fine Silt	Very Fine Silt	Clay	Clay	Clay
DRI157T	1.20	2.90	8.80	23.90	9.20	**12.30**	11.40	10.90	8.30	3.90	1.90	1.60	3.50
B4b	1.10	3.50	5.40	9.00	6.90	9.40	13.00	**15.60**	13.10	7.90	4.60	3.90	6.60
CR-24	0.00	0.00	0.40	0.90	4.40	29.10	**36.30**	15.40	5.10	2.00	1.20	1.50	3.50
TRI056T	0.90	0.90	1.20	1.30	1.30	5.80	13.20	20.80	**22.00**	11.70	6.20	5.20	9.60
TRI056T	0.00	0.10	1.60	1.50	1.40	6.00	15.70	**20.20**	19.60	12.60	6.50	4.70	10.20
TRI056T	0.00	0.10	1.40	1.40	1.50	6.10	14.80	**21.30**	20.10	11.50	6.90	4.80	10.20
TRI05DUP	0.00	1.70	1.50	3.30	2.70	8.70	16.60	**19.50**	16.00	10.50	5.60	4.30	9.60
TRI052	0.00	1.60	1.90	3.40	2.60	9.00	**17.60**	17.20	16.30	11.10	5.20	4.80	9.20
S4-2T	0.20	0.90	1.70	3.20	3.00	5.20	11.80	20.40	**20.90**	12.50	5.90	5.10	9.30
EIT066	0.00	1.30	5.90	10.20	3.70	4.50	8.20	17.20	**19.40**	11.40	5.30	4.50	8.50
CR-02	0.10	1.20	1.60	2.10	2.70	8.40	25.90	**21.20**	13.70	7.10	4.30	3.20	8.40
SPI104	0.10	1.70	2.20	3.70	5.20	8.90	11.30	14.10	**16.50**	12.30	6.90	5.60	11.60
TRI036	1.00	1.40	1.60	2.50	3.60	7.90	14.20	**18.40**	17.50	10.80	5.70	4.60	10.70
TRI066	0.00	1.50	2.70	3.40	2.40	10.70	17.40	**18.50**	16.10	10.20	4.60	4.20	8.30
TRI004	1.40	1.40	2.00	3.10	7.00	7.30	10.20	**13.90**	15.80	11.80	7.20	6.20	12.70
TRI096	1.00	9.00	5.10	20.40	7.20	8.60	9.80	**11.10**	10.40	6.10	3.20	1.90	6.20
S$-1T	0.00	1.80	2.50	2.70	2.50	4.70	12.90	**23.80**	21.70	11.90	4.30	3.90	7.40
SPI108	0.40	1.10	1.90	6.10	14.70	**19.60**	13.10	10.50	10.50	7.30	4.30	3.40	7.20

3.3 *In Situ* Data

Data were collected using a LISST Streamside instrument on 16th to 17th July, 2008. The total concentration of suspended particles and the mean grain size ($\bar{d}$) are given in Table 2.

Table 2 LISST-StreamSide Data recorded by Ecology (Wednesday, July 16, 2008 18:54:02).

Plotted?	Date	Time	Total Concentration	Mean Grain Size
	MM/DD/YYYY	HH:MM:SS	ull^{-1}	µm
Not plotted	16/07/2008	18:54:45	0.1	10
	16/07/2008	19:24:45	7.8	130
	16/07/2008	19:54:45	1.9	10
	16/07/2008	20:24:45	2.2	11
	16/07/2008	20:54:45	1.7	9
	16/07/2008	21:24:45	2.0	10
	16/07/2008	21:54:45	2.2	10
	16/07/2008	22:24:45	2.4	10
	16/07/2008	22:54:45	2.6	11
	16/07/2008	23:24:45	2.2	10
	16/07/2008	23:54:45	2.3	11
	17/07/2008	00:24:45	2.1	10
	17/07/2008	00:54:45	2.0	10
	17/07/2008	01:24:45	1.9	10
	17/07/2008	01:54:45	1.9	10
	17/07/2008	02:24:45	1.8	10
	17/07/2008	02:54:45	1.8	10
	17/07/2008	03:24:45	1.9	10
	17/07/2008	03:54:45	2.1	11
Plot 1	17/07/2008	04:24:45	2.1	11
	17/07/2008	04:54:45	2.3	12
	17/07/2008	05:24:45	2.9	13
	17/07/2008	05:54:45	3.1	14
	17/07/2008	06:24:45	4.3	16
	17/07/2008	06:54:45	5.9	17
	17/07/2008	07:24:45	6.3	18
	17/07/2008	07:54:45	7.4	18
	17/07/2008	08:24:45	12.2	31
	17/07/2008	08:54:45	9.1	20
	17/07/2008	09:24:45	9.4	20

Plotted?	Date	Time	Total Concentration	Mean Grain Size
	MM/DD/YYYY	HH:MM:SS	ull^{-1}	µm
	17/07/2008	09:54:45	10.0	20
	17/07/2008	10:24:45	20.0	41
	17/07/2008	10:54:45	32.4	59
Plot 2	17/07/2008	11:24:45	13.4	27
	17/07/2008	11:54:45	11.5	24
	17/07/2008	12:24:45	8.0	17
	17/07/2008	12:54:45	7.9	16
	17/07/2008	13:24:45	5.2	12
	17/07/2008	13:54:45	1.3	12
	17/07/2008	14:27:45	1	12
	17/07/2008	14:31:29	1	12
	17/07/2008	14:46:29	1	12
	17/07/2008	15:01:29	3	11
	17/07/2008	15:16:29	3	10
	17/07/2008	15:31:29	3	12
	17/07/2008	15:46:29	3	11
	17/07/2008	16:01:29	3	12
	17/07/2008	16:16:29	3	11
	17/07/2008	16:31:29	3	11
	17/07/2008	16:46:29	3	11
	17/07/2008	17:01:29	3	11
	17/07/2008	17:09:29	3	11
	17/07/2008	17:24:29	3	12
	17/07/2008	17:39:29	3	12
	17/07/2008	17:54:29	3	10
	17/07/2008	18:09:29	3	10
	17/07/2008	18:24:29	3	10
	17/07/2008	18:39:29	3	10
	17/07/2008	18:54:29	3	10
	17/07/2008	19:09:29	3	10
		Mean	5	16
		Range	0-32	9-130
		Median	3	11
		5th Percentile	1	9
		95th Percentile	12	32
		20th Percentile	2	10
		80th Percentile	6	17

The maximum recorded $\bar{d}$ value is 130 µm; however the majority of the data fall in the range 9-59 µm. This indicates that the suspended sediments during the observation period are entirely silt-sized. A greater proportion of particles are found in the range 9-15 µm, which corresponds to fine silts (Table 2).

The size spectra represent collection of data through time, and it is interesting to see there is a progressive increase in both size and the width of the distribution through time; the distribution shifts to larger particles as the tide ebbs whereas the distribution shifts to finer particles as the tide floods (Figure 2).

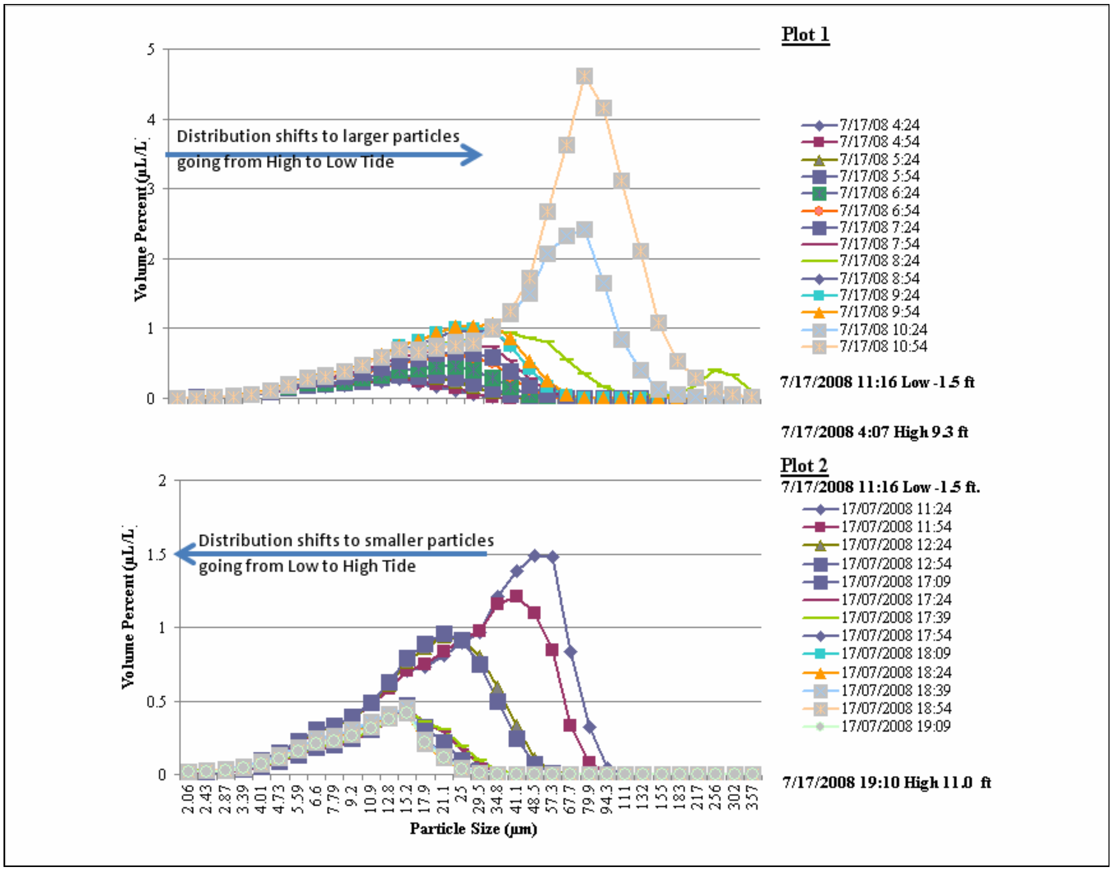

Figure 2 Particle size spectra of suspended particles collected using a LISST streamside instrument showing trends in size spectra with tidal phase (graphic supplied by J. Sloane, Ecology).

3.4 Supplied Samples

Partrac were supplied with a set of sediment samples retrieved from various locations in the Duwamish Waterway. These sediments comprised both bedded (settled) and suspended sediments. Table 3 summarises the sediment samples provided. Figure 1 shows the transect locations. Sample ID code MC signifies the sample is from the middle of the transect, and B signifies the sample is from the beach (near shore) of the river, L and R signify the right or left side of the transect.

Table 3 **Sediment samples collected 19.8.08 in the Lower Duwamish Waterway, River Miles 0.0-5.6 near Tukwila, WA. (Co-ordinates in NAD83).**

Location			Grab Characteristics					Collected Sediment Characteristics		
Station ID	Lat DD	Long DD	Depth (ft)	#Kept	#Rejected	Redox depth (cm)	Fullness (cm)	Colour	Texture	Oil Sheen
MC-1	47.56596	122.3478	48	3	0	0-0.5	5	Light brown	Gritty silt	No
MC-3	47.55518	122.34267	37	2	0	0-1	6	Dark brown	Gritty silt	No
MC-5	47.54415	122.33670	27	2	0	0-1	6	Light brown	Gritty silt	No
MC-7	47.5361	122.32572	20	2	0	0-0.5	10	Dark brown	Gritty silt	No
MC-9	47.52837	122.31210	16	2	0	0-1	11	Dark brown	Gritty silt	No
MC-11	47.51777	122.30619	12	2	0	0-2	10	Brown	Gritty silt	No
MC-13	47.51040	122.29506	11	2	2	0-2	5	Dark brown	Sand	No
B1R	47.56643	122.34636	29	2	0	0-0.5	5	Light brown	Gritty silt	No
B1L	47.56620	122.34942	21	1	0	0-1	10	Brown	Gritty silt	No
B3R	47.55545	122.34225	23	2	1	0-1	5	Brown	Sand	No
B3L	47.55508	122.34368	30	1	0	0.0.5	6	Brown	Gritty silt	Yes
B5R	47.54440	122.33642	7	2	1	0-0.5	4		Sand/gravel	No
B5L	47.54381	122.33755	19	2	0	0-0.5	6	Dark Brown	Silt	No
B7R	47.53633	122.32487	2	2	0	0-2	4		Coarse sand	No
B7L	47.53566	122.32583	6	1	0	0-1	11	Light brown	Gritty silt	No
B9R	47.52843	122.31177	7	1	0	0-1	11	Light brown	Gritty silt	No
B9L	47.52791	122.31284	7	1	0	0-1	11	Dark brown	Silt	No
B11R	47.51809	122.3052	6	1	0	0-1	11	Light brown	Gritty silt	No
B11L	47.51763	122.30679	3	1	0	0-1	11	Light brown	Gritty silt	No
B13R			n/a	0					Rocks	No
B13L	47.1040	122.29506	1	3	0	0-1	8	Light brown	Gritty silt	No
Settled										
63-250										
>250										

3.5 Sediment Testing Methodology

These sediments were tested for a range of physical and hydraulic properties which are relevant to formulation of a tracer for use in the LDW. The following tests were conducted on the sediments:

- Particle size analysis;
- Particle settling velocity;
- Particle density (specific gravity);
- Natural fluorescence signature;
- Natural magnetic signature;

The details of each test methodology is summarised in following sections. Not every sample was subjected to every test. Table 4 summarises the tests performed on each samples.

Table 4 Summary of tests performed on each sample.

Station ID	PSD	Settling Velocity	Density	Natural Fluorescence	Natural Magnetics
MC-1	•	•	•	•	•
MC-3	•	•	•		
MC-5	•	•	•		
MC-7	•	•			
MC-9	•	•	•	•	•
MC-11	•	•	•		
MC-13	•	•	•		
B1R	•	•	• (composited)		
B1L	•				
B3R	•	• (composited)	• (composited)		
B3L	•				
B5R	•	• (composited)	• (composited)	•	•
B5L	•				
B7R	•	• (composited)	• (composited)		
B7L	•				
B9R	•		• (composited)		
B9L	•			•	•
B11R	•	• (composited)			
B11L	•				
B13R	•	• (composited)	• (composited)		
B13L	•				
Settled	•	Insufficient material	•		
63-250	Insufficient material	Insufficient material	•		
>250	Insufficient material	Insufficient material	•		

3.5.1 Particle Size Analysis

Particle size analysis was carried out using two methods according to the size fraction of interest. For silts a Coulter LS230 was used. The technique uses the diffraction of a laser beam through a sediment sample. The LS230 also has PIDS (polarisation intensity differential scatter), which yields much higher resolution and sensitivity with different sized sub-micron particles. The instrument uses a Class IIIb fully protected solid-state diode laser with a power output of 5 mw and a wavelength of 750 nm and uses the Fraunhofer optical model to derive particle size distribution. The international standard used for particle size analysis was ISO 13320-1:1999(E).

A small amount of sample was added to the machine via a 2 mm and then 100 μm sieve until the obscuration reached between 8-12 %. The sample measurement duration was approximately 5 minutes. Each sample was run three times. Results are expressed as summary statistics for each run.

For sands (> 63 μm) grain size was measured using a settling velocity method (see Section 3.5.2).

3.5.2 Particle Settling Velocity

Settling velocity is measured in one of two ways according to particle size. Sediment comprising admixed silts and sands were initially sieved at 63 μm to separate the fractions.

Sand Fraction (> 63 μm):- A conventional sedimentation tower is used for settling velocity measurements on <u>non-cohesive sand</u>. This comprises a 2.5m high tower times 0.3m wide. This is filled with saline water (~35psu) and held as far as possible close to room temperature. A sample (ca. 5g) is introduced into the top of the column and held on a submerged plate for several minutes to de-air. Once this is completed, the sample is released and the particles settle vertically. A suspended plate, connected to a 2dp balance, at the base of the column collects the grains as they fall. A computer measures the mass of the plate through time, and this data is inverted to produce both a) a settling velocity spectrum and b) an equivalent grain size using the equation of Soulsby (1997):

$$\omega_s = \frac{\nu}{d}\left[(10.36^2 + 1.049 D_*^3)^{1/2} - 10.36\ \right] \qquad (1)$$

Where

$D_* = \left[\frac{g(s-1)}{\nu^2}\right]^{1/3} d_{50}$, and g is the acceleration due to gravity, s is the submerged density (the density of sediment divided by the density of seawater), ν is the kinematic viscosity and d_{50} is the mean grain diameter.

Silt Fraction (< 63 μm):- For silts, a unit mass of wet material is thoroughly mixed in a container and then left to settle for ca. 6 hours. An optical backscatter sensor (OBS) is used to measure the temporal reduction in sediment concentration. The settling velocity is computed from the following equation:

$$D = Cw_{50} \qquad (2)$$

Where D is the mass deposition rate (kg m^{-3}s^{-1}), C is the sediment concentration (kg m^{-3}) and w_{50} is the median settling velocity (ms^{-1}). This method is based upon Whitehouse et al., (2000).

3.5.3 Particle Density (ρ_s; Specific Gravity)

Particle density was measured on sediment sub-samples using a standard density bottle volumetric method (ISO/TS 17892-3; 2004). This determines the density of dry granular materials through determination of the volume of a known mass of soils by the fluid displacement. Dry masses were determined to an accuracy of 0.001g, and oven drying was conducted at 105°±5C. The pycnometer was calibrated before and after batch analyses. Distilled water was used throughout. A single operator was used throughout.

3.5.4 Natural Fluorescence Signature

Persistently occurring fluorescent particles in industrialised aquatic environments (e.g. from paint, chemical discharges, brighteners etc.) can be abundant in estuarine sediments. Prior to a particle tracing study samples need to be collected from across the environment of interest (both from suspension and settled bed areas) (see Table 3). Samples were diluted and examined under a standard fluorescent microscope.

3.5.5 Natural Magnetic Signature

Partrac's method of particle tracking utilises fluorescent-magnetic particles. A potential source of contamination in studies in the natural environment is the presence of natural magnetic minerals and magnetic, anthropogenic particles; both particle types are found in industrialised estuarine environments. Prior to any particle tracking studies an assessment of the natural abundance and attributes of natural magnetic minerals is required. Sub-samples from those obtained for fluorescence analysis (see above) were collected and flushed through a flow-through magnetic particle separator [MPS] to separate them from non-magnetic mineral and other fragments. The residual magnetic fraction was then weighed (to derive a mass concentration) and sized (using either a laser diffraction method or direct inspection using light microscopy)

3.6 Results

3.6.1 Particle Size Analysis

Silts

The particle size spectra for the silt fraction of samples is given in Appendix 2 and a summary table is provided in Table 5. The data indicate that the size spectra for the silts are largely similar. Samples comprise fine skewed (i.e. towards the coarse end of the spectrum), poorly sorted *medium to coarse* silts. Modal values range ca. 19 to 35 μm. Data from the settled sample are slightly coarser, with a mean grain size of 38 μm.

Sands

The particle size spectra for the sand fraction of samples is given in Appendix 3 and a summary table is provided in Table 6. The sand fraction comprises dominantly *fine sand* (125 to 250 μm) for 12 of the 15 samples processed, with three of these (MC9, MC11, B11) classified as *very fine sand*; the remaining three samples (MC3, MC13, B5) are all modally medium sand (250 to 500 μm). Some samples (e.g. B13, B3) contain very minor gravel fractions.

Table 5 **Particle size spectra (silts only) including statistical and descriptive information of tested samples (see Table 3). The yellow hatched area indicates the modal diameter(s); where these are numerically close, two have been highlighted.**

		P1062.01 MC-1	P1062.02 MC-3	P1062.03 MC-5	P1062.04 MC-7	P1062.05 MC-9	P1062.06 MC-11	P1062.08 B-1	B1062.09 B-3	B1062.10 B-5	B1062.11 B-7	P1062.12 B-9	P1062.13 B-11	P1062.14 B-13	P1062.15 Settled
	SAMPLE TYPE:	Unimodal, Poorly Sorted	Unimodal, Poorly Sorted	Unimodal, Poorly Sorted	Unimodal, Poorly Sorted	Unimodal, Poorly Sorted	Unimodal, Poorly Sorted	Trimodal, Poorly Sorted	Unimodal, Poorly Sorted	Bimodal, Poorly Sorted	Unimodal, Poorly Sorted	Bimodal, Poorly Sorted	Unimodal, Poorly Sorted	Unimodal, Poorly Sorted	Unimodal, Poorly Sorted
	TEXTURAL GROUP:	Mud	Mud	Sandy Mud	Mud	Sandy Mud	Mud	Mud	Mud	Mud	Sandy Mud	Mud	Mud	Sandy Mud	Sandy Mud
METHOD OF MOMENTS Arithmetic (□m)	MEAN (µm)	21.59	23.01	27.49	25.84	29.76	27.60	21.45	20.07	24.72	28.47	23.20	24.58	28.53	38.29
	SORTING	21.33	20.14	23.68	23.88	23.52	22.98	22.47	19.92	22.86	24.09	22.20	21.57	26.45	26.45
	SKEWNESS	1.610	1.483	1.143	1.364	1.024	1.099	1.661	1.712	1.388	1.082	1.488	1.316	1.274	0.712
	KURTOSIS	5.441	5.329	3.737	4.477	3.578	3.731	5.368	6.042	4.538	3.574	4.885	4.476	4.070	2.810
FOLK AND WARD METHOD (Description)		Medium Silt	Medium Silt	Coarse Silt	Coarse Silt	Coarse Silt	Coarse Silt	Medium Silt	Medium Silt	Medium Silt	Coarse Silt	Medium Silt	Coarse Silt	Coarse Silt	Coarse Silt
		Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted
		Fine Skewed	Fine Skewed	Fine Skewed	Fine Skewed	Very Fine Skewed	Fine Skewed	Fine Skewed	Fine Skewed	Fine Skewed	Fine Skewed	Fine Skewed	Fine Skewed	Fine Skewed	Fine Skewed
		Mesokurtic	Leptokurtic	Mesokurtic	Mesokurtic	Leptokurtic	Mesokurtic	Mesokurtic	Mesokurtic	Mesokurtic	Mesokurtic	Mesokurtic	Mesokurtic	Mesokurtic	Leptokurtic
	MODE 1 (□m):	19.69	19.69	23.63	19.69	31.05	25.88	19.69	19.69	19.69	25.88	19.69	21.57	21.57	34.01
	D_{10} (□m):	2.286	2.814	3.009	2.780	3.719	3.195	2.165	2.304	2.719	3.181	2.552	2.852	2.947	7.544
	D_{50} (□m):	21.59	23.01	27.49	25.84	29.76	27.60	21.45	20.07	24.72	28.47	23.20	24.58	28.53	38.29
	D_{90} (□m):	51.39	50.45	63.66	61.62	64.70	61.77	54.47	47.15	57.99	65.46	55.21	56.27	69.27	77.64
	% GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	% SAND:	6.8%	5.9%	10.5%	9.7%	11.0%	9.7%	7.9%	5.3%	8.6%	11.3%	7.8%	7.6%	12.6%	19.4%
	% MUD:	93.2%	94.1%	89.5%	90.3%	89.0%	90.3%	92.1%	94.7%	91.4%	88.7%	92.2%	92.4%	87.4%	80.6%
	% FINE SAND:	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%
	% V FINE SAND:	6.8%	5.9%	10.5%	9.6%	10.9%	9.7%	7.9%	5.3%	8.6%	11.3%	7.7%	7.6%	12.5%	19.4%
	% V COARSE SILT:	16.1%	19.1%	23.1%	20.3%	27.5%	24.9%	14.2%	14.9%	19.9%	24.3%	17.8%	20.7%	21.6%	33.2%
	% COARSE SILT:	26.3%	31.5%	28.1%	27.2%	29.1%	28.2%	24.7%	26.8%	27.1%	27.3%	26.9%	29.3%	24.6%	24.8%
	% MEDIUM SILT:	19.0%	19.0%	15.2%	17.0%	14.2%	15.5%	18.7%	19.4%	17.9%	15.2%	18.5%	17.8%	16.6%	12.2%
	% FINE SILT:	14.0%	10.7%	10.0%	11.4%	7.9%	9.5%	14.8%	15.0%	11.8%	9.7%	13.0%	10.7%	11.2%	5.2%
	% V FINE SILT:	9.4%	7.2%	7.2%	7.8%	5.1%	6.3%	10.9%	10.5%	8.0%	6.2%	8.7%	7.4%	7.2%	2.0%
	% CLAY:	8.4%	6.7%	6.0%	6.7%	5.3%	5.9%	8.8%	8.1%	6.8%	6.1%	7.3%	6.5%	6.3%	3.1%

Table 6 **Particle size spectra (sand only) including statistical and descriptive information of tested samples (see Table 3). The yellow hatched area indicates the modal diameter(s).**

		P1062.01 MC-1	P1062.02 MC-3	P1062.03 MC-5	P1062.04 MC-7	P1062.05 MC-9	P1062.06 MC-11	P1062.07 MC-13	P1062.08 B-1	B1062.09 B-3	B1062.10 B-5	B1062.11 B-7	P1062.12 B-9	P1062.13 B-11	P1062.14 B-13	P1062.15 Settled
	SAMPLE TYPE:	Unimodal, Moderately Well Sorted	Bimodal, Moderately Well Sorted	Bimodal, Moderately Well Sorted	Trimodal, Moderately Well Sorted	Bimodal, Moderately Sorted	Unimodal, Well Sorted	Unimodal, Well Sorted	Unimodal, Moderately Well Sorted	Polymodal, Moderately Sorted	Bimodal, Moderately Sorted	Trimodal, Moderately Sorted	Polymodal, Moderately Sorted	Trimodal, Moderately Well Sorted	Trimodal, Moderately Well Sorted	Polymodal, Moderately Sorted
	TEXTURAL GROUP:	Sand	Sand	Sand	Sand	Sand	Sand	Sand	Sand	Slightly Gravelly Sand	Sand	Sand	Sand	Sand	Slightly Gravelly Sand	Sand
METHOD OF MOMENTS Arithmetic (μm)	MEAN (μm)	195.5	279.1	180.6	179.4	180.5	134.1	486.8	179.0	249.2	314.1	251.6	189.0	149.8	225.4	236.0
	SORTING	89.73	110.6	109.5	98.27	147.6	48.08	164.8	65.12	116.6	189.1	138.5	115.9	98.67	150.5	190.8
	SKEWNESS	4.902	0.664	3.556	3.528	3.325	2.832	0.766	1.115	3.627	1.359	0.907	1.569	3.554	8.432	2.040
	KURTOSIS	129.5	2.899	24.35	28.02	17.16	13.46	3.622	4.163	88.78	6.690	3.095	5.400	21.77	126.1	6.024
FOLK AND WARD METHOD (Description)		Fine Sand	Medium Sand	Fine Sand	Fine Sand	Very Fine Sand	Very Fine Sand	Medium Sand	Fine Sand	Fine Sand	Medium Sand	Fine Sand	Fine Sand	Very Fine Sand	Fine Sand	Fine Sand
		Moderately Well Sorted	Moderately Well Sorted	Moderately Well Sorted	Moderately Well Sorted	Moderately Sorted	Well Sorted	Well Sorted	Moderately Well Sorted	Moderately Sorted	Moderately Sorted	Moderately Sorted	Moderately Sorted	Moderately Well Sorted	Moderately Well Sorted	Moderately Sorted
		Coarse Skewed	Symmetrical	Very Coarse Skewed	Very Coarse Skewed	Very Coarse Skewed	Coarse Skewed	Symmetrical	Coarse Skewed	Fine Skewed	Fine Skewed	Coarse Skewed	Very Coarse Skewed	Very Coarse Skewed	Symmetrical	Coarse Skewed
		Mesokurtic	Platykurtic	Platykurtic	Leptokurtic	Mesokurtic	Leptokurtic	Leptokurtic	Mesokurtic	Platykurtic	Platykurtic	Platykurtic	Platykurtic	Mesokurtic	Mesokurtic	Leptokurtic
	MODE 1 (μm):	162.3	324.5	125.1	148.8	114.7	125.1	458.9	136.4	297.6	385.9	162.3	105.2	96.48	210.4	771.8
	% GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.2%	0.0%
	% SAND:	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	99.7%	100.0%	100.0%	100.0%	100.0%	99.8%	100.0%
	% MUD:	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	% V COARSE GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	% COARSE GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	% MEDIUM GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	% FINE GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	% V FINE GRAVEL:	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.0%
	% V COARSE SAND:	0.0%	0.0%	0.3%	0.2%	0.6%	0.0%	0.6%	0.0%	0.0%	0.5%	0.0%	0.0%	0.0%	0.2%	0.0%
	% COARSE SAND:	0.8%	3.9%	1.5%	0.9%	3.3%	0.0%	37.8%	0.0%	1.4%	14.1%	5.9%	2.1%	1.1%	1.8%	10.4%
	% MEDIUM SAND:	19.1%	51.0%	18.1%	15.7%	15.0%	3.8%	56.7%	14.4%	45.4%	42.2%	35.1%	22.6%	10.8%	30.0%	13.6%

	P1062.01 MC-1	**P1062.02 MC-3**	**P1062.03 MC-5**	**P1062.04 MC-7**	**P1062.05 MC-9**	**P1062.06 MC-11**	**P1062.07 MC-13**	**P1062.08 B-1**	**B1062.09 B-3**	**B1062.10 B-5**	**B1062.11 B-7**	**P1062.12 B-9**	**P1062.13 B-11**	**P1062.14 B-13**	**P1062.15 Settled**
% FINE SAND:	62.9%	44.3%	44.2%	56.1%	25.3%	40.6%	4.9%	64.7%	39.0%	27.9%	41.4%	33.9%	27.1%	51.3%	48.4%
% V FINE SAND:	17.2%	0.8%	35.9%	27.2%	55.7%	55.6%	0.0%	20.9%	13.9%	15.3%	17.7%	41.4%	61.0%	16.6%	27.6%
% V COARSE SILT:	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
% COARSE SILT:	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
% MEDIUM SILT:	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
% FINE SILT:	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
% V FINE SILT:	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
% CLAY:	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

3.6.2 Particle Settling Velocity

Settling velocity exerts a fundamental control on the behaviour of the particles suspended in a fluid. It is thus essential to know the settling velocity spectrum on the natural sediments. Settling velocity is measured in two different ways according to the size of the particles. For entirely sandy (>63 μm) sediments, settling velocity can be measured in a sedimentation tower. For silts and finer grained sediments, settling velocity can only be measured through the reduction in turbidity through time of a unit weight of suspended particles. Following particle size analysis no sample material was available for settling velocity analysis for the provided suspended sediment samples ('settled'; '63-250'; '>250').

Sand

The settling velocity data for sand is transformed into equivalent grain size (EGS; see Appendix 1). EGS ranges from 4 phi to -2 phi (i.e. the entire sand range from 63 microns to 2 mm). B5 is extremely coarse and probably contains some gravel (see Table 3 for visual descriptions). Samples vary from highly uni-modal (e.g. B1, M13) to bi-modal (e.g. M9). Inspection of the EGS data show a significant fraction exists in the 2 to 4 phi range (63 to 250 μm) for many samples (excepting the gravelly sediments at B5). Some samples display either a second mode around 1 to 2 phi (e.g. B3, M3).

For clarity, the sedimentation tower data have also been expressed in terms of a (mean) linear settling velocity (unit ms^{-1}) (Table 7). These range from 0.006 to 0.204 ms^{-1}, with the greatest settling velocity corresponding to sample B5 (very coarse sand-fine gravel material). Those samples classified as fine to very fine sands have mean settling velocity values in the range 0.006 to 0.040 ms^{-1}, with an average value of 0.013±0.01 ms^{-1}.

Table 7 **Mean settling velocities derived from tower sedimentation studies.**

Station ID/Sample	Mean Settling Velocity, $\bar{W}_s$ (ms^{-1})	Textural Description
MC-1	0.015	Fine sand
MC-3	0.039	Medium sand
MC-5	0.008	Fine sand
MC-7	0.012	Fine sand
MC-9	0.007	Fine sand
MC-11	0.006	Very fine sand
MC-13	0.060	Medium sand
B1	0.011	Fine sand
B3	0.040	Fine sand
B5	0.204	Medium sand
B9	0.009	Fine sand
B11	0.006	Fine sand
B13	0.015	Fine sand

Silt

Figure 3 shows time-series data from sedimentation studies on the silt fraction. For clarity only five sample runs are presented. The data are consistent and reveal three distinct particle populations (indicated by the letters A, B and C). Initially sedimentation rates are high (region A) and the slope of the curve is, for the majority of samples, highly similar. Median settling velocities are of the order 0.0003 to 0.0004 ms^{-1}. Region A will correspond to the coarsest fraction within the samples (i.e. the coarse silt, or the coarsest grains within this fraction). Region B likely corresponds to medium to fine silts; sedimentation rates are correspondingly lower but once again are highly similar for samples tested. The Region B median settling velocities (w_{50}) for the tested samples range from 0.00013 to 0.00024 ms^{-1} with a batch standard deviation of 0.00005 ms^{-1}. Region C of the sedimentation curves represent the finest fraction within samples i.e. very fine silts and clays, with w_{50} values consistently $<10^{-5}$ ms^{-1}.

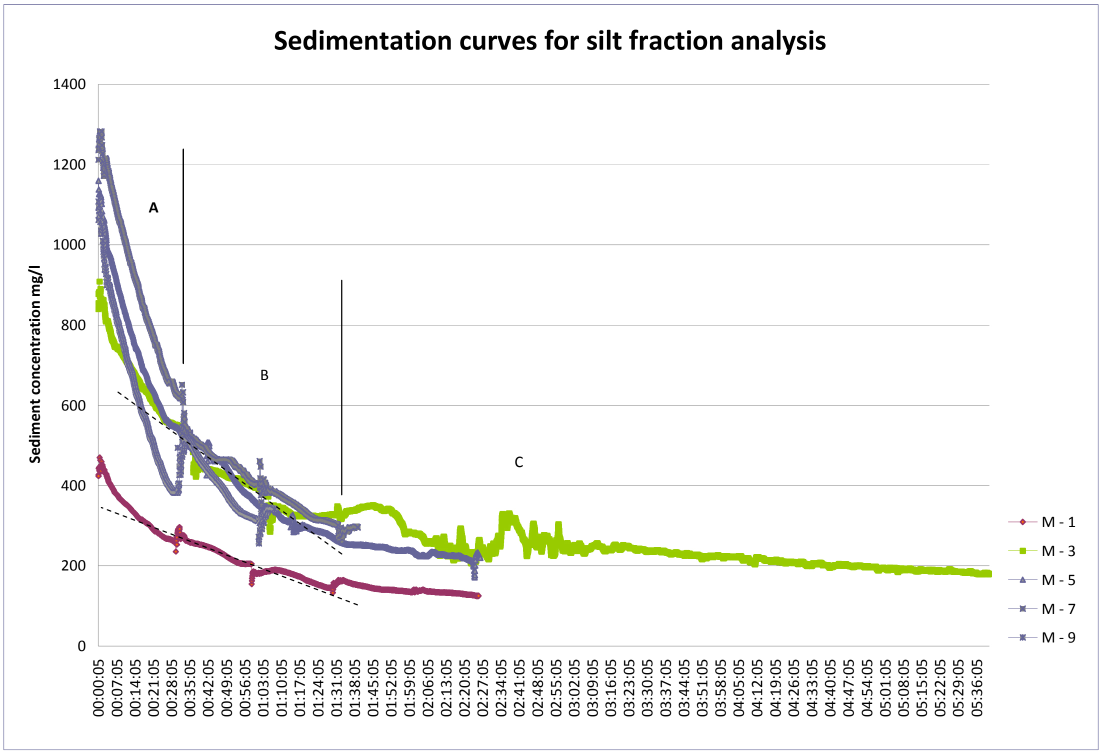

Figure 3 Sedimentation curves for silt fraction analysis (five samples only). Regions A, B and C indicate relatively fast, intermediate and very low settling velocity. The dotted lines are parallel to the curves of Region B and provide a means to compute the settling velocity (w_{50}). The discontinuities in the time-series arise from calibration sampling and are an artefact. The method of analysis accounts for these interruptions.

3.6.3 Particle density (specific gravity)

Table 8 summarises the data from particle density analysis.

Table 8 Summary of particle density data.

Test No.	Particle Density (kgm^{-3})
B - 1	2966
M - 1	2662
B - 3	2478
M - 3	2388
B - 5	2524
M - 5	2716
B - 9	2506
M - 9	2811
B - 13	2829
M - 13	2920
B - 7	1273
M - 7	2675
B - 11	2699
M - 11	2722
Mean	**2580±400**
60 - 250 µm	1740
250 µm +	1460
Settled	2928

The majority of samples exhibit values within the range expected for mineral grains (2500 to 2900 kgm^{-3}). Values are lower for two of the suspended sediment samples (hashed yellow in Table 8), and this may be due to the inclusion of amorphous organic material within and on the surfaces of grains (and these are not removed as part of the analysis)

3.6.4 Natural Fluorescence Signature

Examination of 4 samples (refer to Table 4) for the presence of naturally fluorescent particulate material revealed only 2 fluorescent green particles of size <200 µm in 2 of the 4 samples. The mass concentration of these is < ~10^{-5}.

3.6.5 Natural Magnetic Signature

A residual, naturally occurring magnetic material was extracted from the same samples used for fluorescence presence (see above). A microphotograph of the material is given in Figure 4. A mean mass concentration for the extracted material from the 4 samples was 0.09 mgg^{-1}. The size of these magnetic particles varied from 100 µm - 1.5 mm in size, and these particles did not fluoresce. Further studies will be carried out on these to determine in more detail the particle size distribution.

Figure 4 Microphotograph of naturally occurring magnetic material from bedded sediments in the LDW. The largest grain in the centre of the image is ca. 120 µm in diameter.

4. TRACER DESIGN

A range of different data types have been collected together from both pre-existing data sources, and from the analysis of samples provided. There is a sufficient quantity of data to design the silt and sand tracer.

4.1 Sand Tracer

The sand tracer is comparatively simple to design as these size grains are non-cohesive in character. The equivalent grain size (EGS) data are the most useful data in terms of tracer design as they derive from a hydraulic measurement (i.e. settling tests), and it is the hydraulic attributes of sediment particles which most closely governs their behaviour in a fluid medium. For sand sediments our understanding of the focus in the LDW study is on the fate of the finer sand grains, rather than coarse sands and gravel, and therefore any tracer should reflect this objective. A significant fraction in the range 2 to 4 phi is present in many of the samples tested, although sample B5 is a very coarse, gravelly sample, and the several samples have a secondary mode in the range 2 to 1 phi. We suggest that a uni-modal dual-signature tracer within the size range **60 to 250 µm** and of density as close to 2600 kgm^{-3} is ordered. The sedimentation tower tests provide a specification in terms of the mean settling velocity ($\bar{w}_s$), which is for the range $0.006 < \bar{w}_s < 0.040$ ms^{-1}, with an average value of 0.013 ± 0.01 ms^{-1}.

Manufacturing limitations for sands are not severe, and the specification is achievable. The precise position of the mode is the single major variable during manufacture. However since the tracer is designed to be *generally* representative for a defined given size range, and the mode amongst provided samples (in terms of size and settling velocity) displays a natural variability, this is not considered an issue.

4.2 Silt Tracer

Various lines of evidence may be used to design an appropriate silt tracer. Firstly, the analysis of bedded samples from the LDW collected during SPI camera surveys indicate dominantly cohesive muds which can be categorised through the modal index as medium or fine silts (occasional coarser samples were noted e.g. SPI 128, DRI 157T). Analysis by Partrac of similar bedded samples also indicate cohesive muds with modal diameters in the medium and coarse silt range. Finally, *in situ* size data from the streamside LISST instrument deployments can be used. The data available for the submission of this report indicates grains/aggregates in suspension to be in the range 9-59 µm with generally a greater proportion of particles are found in the range 10-15 µm.

The sedimentation tests performed on provided samples provide data can be used to support the size data; as for the sand tracer, these tests are especially useful because they represent the hydraulic nature of the sediments, which relates most closely to the behaviour of particles in a moving flow. The derived settling velocity data gives median settling velocity values typical of estuarine systems. Whitehouse et al., (2000), for instance, present a summary of w_{50} values from European estuaries and these generally range 0.0001 to 0.001 ms^{-1}. It is important to recognise that the sedimentation analysis of itself indicate a *range* of settling velocity values within each sample, from faster settling and lower settling fractions, and that any hydraulically similar tracer will also exhibit a range of settling velocities.

It is technically possible to target any specific silt size fraction[1], even the very fine fraction (Region C), and thus tracer design in contingent upon the size fraction of most interest to Ecology. The very fine fraction exhibits such low settling velocities that it is, to all practical extents, neutrally buoyant in even slowly moving estuarine and river flows. This size material is often referred to in literature sources as 'permanently suspended material' (PSM). In terms of recontamination of the LDW, those fractions which possess significantly greater settling velocities are of interest as they have the potential to settle onto the floor of the estuary.

Our understanding of the focus of Ecology in this study with respect to the fines is on *medium silts* (15 to 30 μm). Although no independent grain size data are available from the sedimentation tests (Figure 2), and therefore it is not possible to know the size of the material just from the sedimentation curves, it is reasonable to pre-suppose that Region B corresponds to the medium silt size fraction (the coarser silts settle faster – Region A; the very fine silts and clays settle very slowly – Region C). Differences exist between samples for median settling velocity w_{50} , but the Region B settling velocity range is centred around <u>0.00015 to 0.00025 ms^{-1}</u>.

Manufacturing considerations must be taken into account in the tracer design, as must the desire to have a non-overlapping size spectra for the sands and silt tracers. If the latter condition is to be satisfied, then the silt tracer must be <63 μm (<60 μm for practical purposes) in size. The lower limit for manufacture of a dual signature particle is ca. 30 to 40 μm (this limit exists due to the incorporation of magnetic inclusions within the tracer particles). These pre-conditions indicate that the silt tracer must be within the size range **30/40 μm to 60 μm**. In order to manufacture a tracer particle batch of this size with a median settling velocity of 0.00014 to 0.00025 ms^{-1} the density of the particle must be adjusted. This approach has been used before in studies on silt transport and organic-rich sediment transport, and is based upon the use of Equation 1 to inter-change density and size to contrive a settling velocity range (e.g. Louisse, et al., 1986; Suijlen and van Leussen, 1990; Partrac, 2007, 2008).

Iteration of various combinations of particle size and density with Equation 1 yield the curve shown in Figure 5. This indicates that tracer particles in the size range 30 to 60 μm and with a matrix density of 1200 kgm^{-3} will display settling velocities in the range ca. 0.00008 to 0.0003 ms^{-1}. Choice of this specification particular specification would yield a tracer that reflects the medium/-fine silt material as tested (Region B; Figure 3) in the samples tested. In addition, the tracer would have a non-overlapping size distribution with the sand tracer. As noted for the sand tracer, the modal value of any manufactured tracer can be variable, although it can be adjusted to some extent (this requires post-production sieving and mixing). In our experience the manufacturing process frequently produces a modal diameter at the distribution midpoint, which would equate to ~45 μm.

*Remember, this value is **<u>not</u>** equivalent to a mineral particle of the same density, as it is a density adjusted particle*. This would hydraulically match the median settling velocity of the silt samples tested (Figure 5).

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[1] The requirement for a non-overlapping size distribution with the sand tracer in practise will limit what is possible.

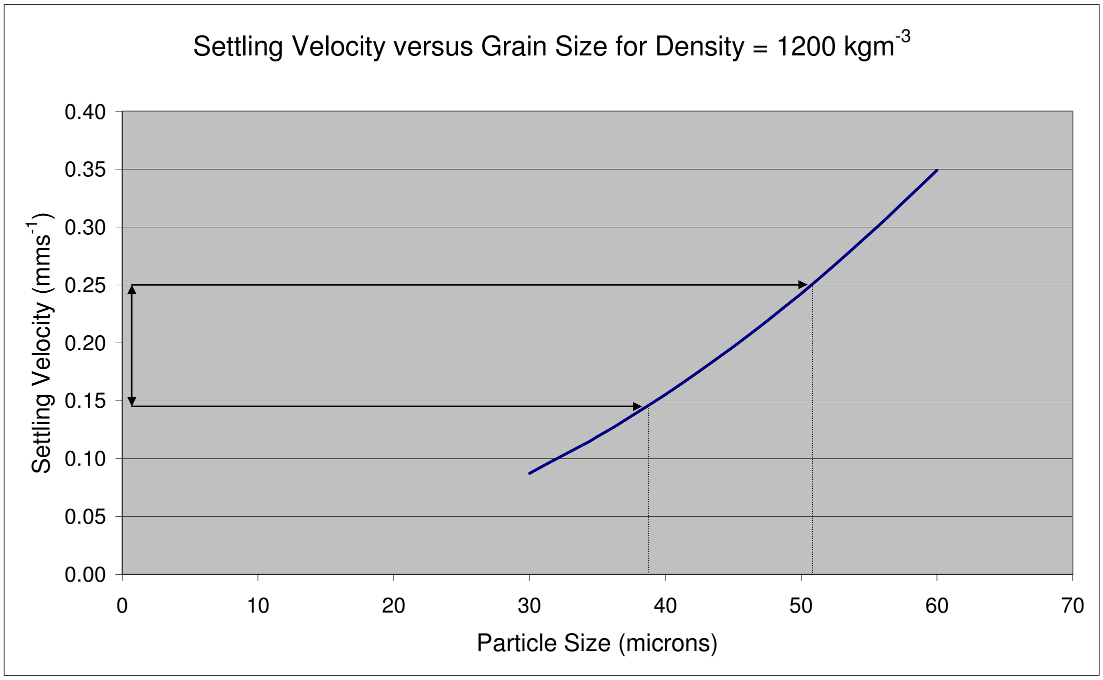

Figure 5 Relationship between particle size and settling velocity for a particle density of 1200 kgm^{-3}.

Table 9 summarises the tracer specification for both silt and sand tracers.

Table 9 Summary of the tracer specification for sand and silt tracers.

Tracer	Size Range (μm)	Density (kgm^{-3})	Settling Velocity (ms^{-1})	w_{50} Range (ms^{-1})	Colour	Para-magnetic
Sand	60 to 250	2650	0.013 ($\bar{w}_s$)	0.006 – 0.040	Red	Y
Silt	30 to 60	1200	0.00015 (w_{50})	0.00013 – 0.00024	Yellow	Y

5. TRACER PRODUCTION AND TESTING

5.1 Sand Tracer

The specified sand tracer was manufactured (100 kg), and a sub-sample of the tracer was retained for characterisation testing. The methodology used is given in Section 3.5. Figure 6 shows the tracer following pre-wetting in a tub prior to injection.

Figure 6 **Plan view of the sand tracer in a drum prior to injection. The tracer was observed macroscopically to behave like mineral sand (naturally slightly compact, moisture redistribution upon disturbance, temporary clumping when troweled into the injection funnel).**

The tracer was tested for:

- particle density;
- particle size distribution;
- settling velocity;
- fluorescence tincture;
- (para-)magnetic character.

The particle density was 2512±19 kgm^{-3} (n=4).

The particle size distribution is shown in Figure 7, and a summary of the distribution statistics is provided in Table 10. The size spectrum indicates that the tracer is dominantly sand-sized, with 93% of the batch (i.e. 93 kg) between the specified range of 60 to 250 μm (Table 10), and the modal diameter (134 μm) on the fine sand/very fine sand boundary. However, in manufacture a small silt fraction was produced (~7%). Within this tail, particle sizes <20 μm are dust from the manufacturing process and therefore do not affect the tracking study, whereas those in the range 20 to 63 μm are genuine fluorescent-magnetic, mineral density (2650 kgm^{-3}) silt-size particles which do. Any fine tail is ordinarily removed through pre-sieving. However, with the time constraints on the project it was not possible to sieve and separate this fine fraction in advance of injection, and although some of this material may have been washed away during tracer pre-wetting this must be remembered during sample analysis.

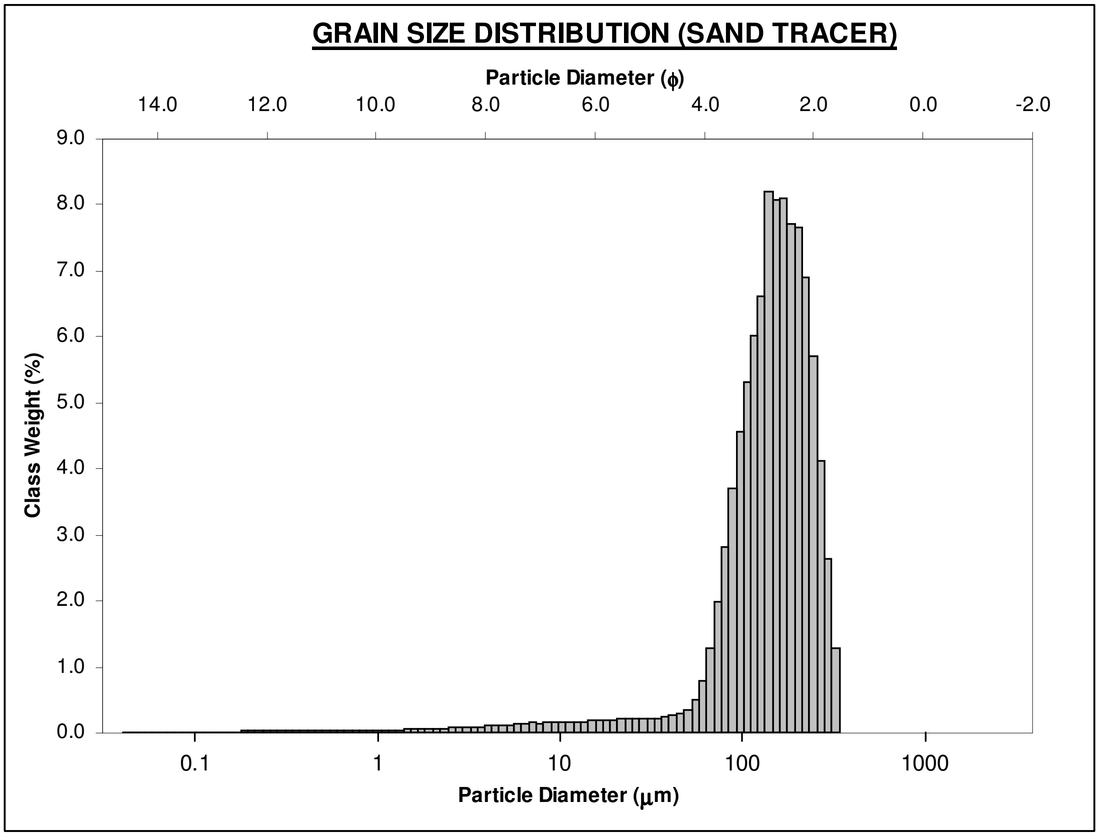

Figure 7 Particle size distribution of sand tracer.

Table 10 Summary of the sand tracer size and (mean) settling velocity statistics.

	Size Range (µm)	d_{10} (µm)	d_{50} (µm)	d_{90} (µm)	Mode (µm)	%Sand	%Silt	Mean Settling Velocity ($\bar{w}_s$) (ms^{-1})	$\bar{w}_s$ Range (ms^{-1})
Tracer Sand	20 - 310	73	128	248	134	92.6	7.4	0.022	0.002 to 0.029

The settling velocity spectrum is shown in Figure 8. The mean settling velocity ($\bar{w}_s$) is 0.022 ms^{-1}, and the range of values (within the sample tested, not across multiple samples) is 0.002 to 0.029 ms^{-1} (Table 10).

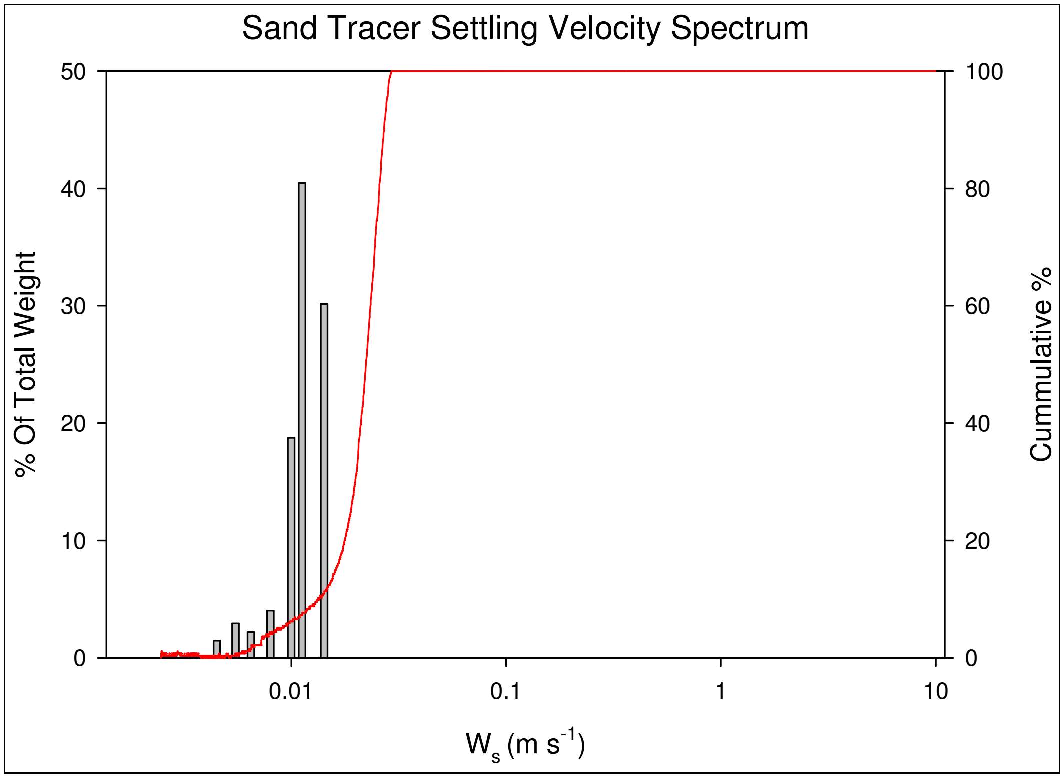

Figure 8 Settling velocity spectrum of the tracer sand.

The fluorescence tincture of the tracer sand was ascertained through the use of illuminated fluorescence macro-photography (Fig. 9a) and fluorescence microphotography (Fig. 9b). Each approach shows that the tracer is highly fluorescent under black light. The difference in colour is attributable to the difference visually between a bulk sample and an individual illuminated grain.

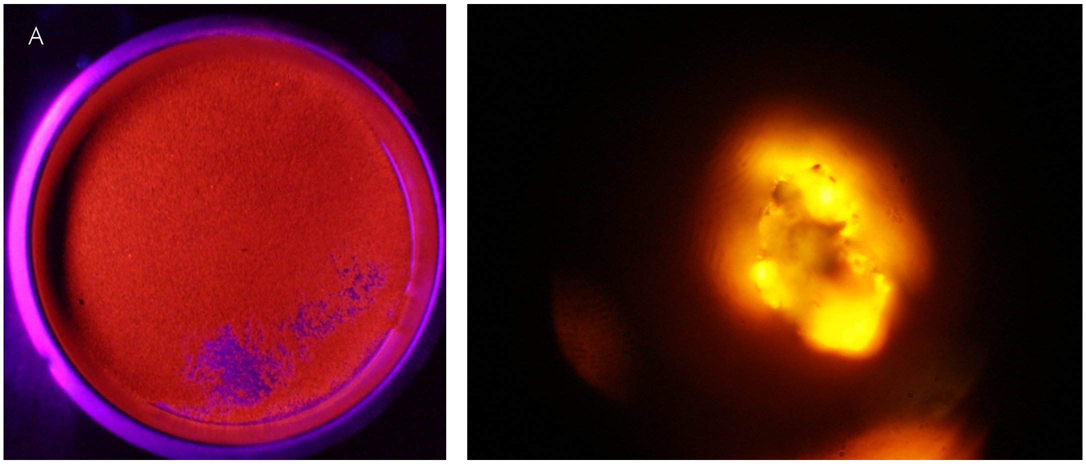

Figure 9 **Fluorescence photograph images of the sand tracer a) *en masse* (in a petri dish) and b) for a single grain.**

The para-magnetic character of tracer grains is usually quantified through the use of the *magnetic susceptibility* measure. This essentially determines how *easily* a granular material acquires a magnetic field when subjected to an alternating, mono-frequency electric current. In this study the facility to measure this was not available. A simple measure of the para-magnetic character was whether the tracer was strongly attracted to the pole magnets which would be used in the study for sample collection/extraction. Tracer sand was sprinkled onto the base of a water-filled tub, and then the magnet was gradually moved towards the tub base; at ~2.5 cm distance the tracer started to spring from the base and adhere to the magnet. At ~1cm all the particles in the tub were adhered to the magnet surface. This test was repeated with several different sub-samples, and from this it is judged that the sand tracer is highly para-magnetic and that 100% of the particles within the non dust fraction are para-magnetic.

5.2 Silt Tracer

The specified silt tracer was manufactured (160 kg)[2], and a sub-sample of the tracer was retained for characterisation testing. The methodology used is given in Section 3.5. Figure 10 shows the tracer following pre-wetting in a tub prior to injection.

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[2] Assessment of the mass of tracer required for a study during manufacturing is not simple due to the issue of yield (the mass of tracer source materials is usually far in excess of the required quantity for a study). In this instance, yield estimates were slightly out resulting in a greater mass of suitable tracer available for the study.

Figure 10 **Plan view of the silt tracer in a cool-box prior to injection.**

The particle density (ρ_s) was 1205±14 kgm^{-3} (n=4).

The particle size distribution is shown in Figure 11, and a summary of the distribution statistics is provided in Table 11. The silt tracer is - in descriptive terms - dominantly a silt, but with a very fine sand component. An ultra-fine tail (<20 μm) is present which is simply non-magnetic dust resulting from the manufacturing process and will not contribute to the study; in terms of mass this is ~10% of the mass (d_{10}=21 μm; Table 11) which is ~16 kg. The mass available to be tracked using the dual signature methodology is thus ~144 kg. 72% of the total mass is <63 μm in size, which corresponds to ~99 kg in terms of the injected mass if the dust fraction is taken into account; within this the modal diameter is 58 μm (Table 11). A sand fraction (>63 μm) is present which constitutes ~45kg of the injected mass, with maximum grain sizes of 162 μm, although some of these larger particles may be due to bubbles as a result of the small surfactant which was added during analysis. *It is important to note that this sand fraction comprises reduced density particles (*ρ_s*=1210 kgm*$^{-3}$*) and cannot be considered hydraulically equivalent to the sand tracer.* As for the sand tracer, sieving would ordinarily be used to separate (and discard) the sand fraction to generate a non-overlapping particle size distribution with the sand tracer. However, with the time constraints on the project it was not possible to sieve and separate in advance of injection, and this must be accounted for during sample analysis.

Table 11 **Summary of the silt tracer size and (median) settling velocity statistics. The annotations A, B and C refer to the sections of the curve on Figure 12.**

	Size Range (μm)	d_{10} (μm)	d_{50} (μm)	d_{90} (μm)	Mode (μm)	%Sand	%Silt	Median Settling Velocity (W_{50}) (ms^{-1})	W_{50} Range (ms^{-1})
Tracer Silt	7 – 162*	21	50	79	58	28	72	A 0.001188 B 0.000253 C 0.000037	0.000037 to 0.001188

*The high end grain sizes are likely due to bubbles from the addition of detergent.

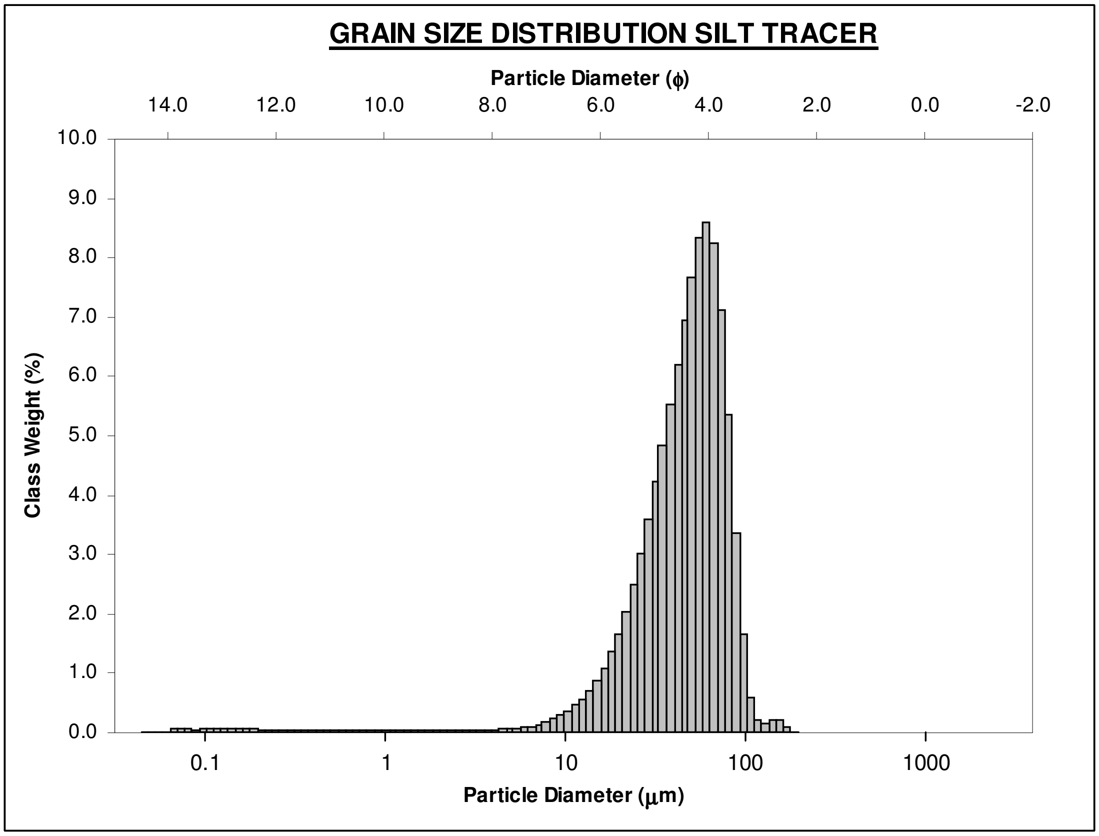

Figure 11 **Particle size distribution of silt tracer. The higher end grain sizes are likely due to bubbles in the fluid stream from the added detergent. The tracer was observed macroscopically to behave like a fine estuary mud (elastic-plastic properties, discernible vertical consolidation gradients inside the vessel).**

The skewness within the size distribution is also reflected in the settling velocity data.

The sedimentation curve for the silt tracer is presented in Figure 12. The curve can be interpreted in the manner previously adopted (see Section 3.6.2), and three regions (high sedimentation rate/settling velocity; medium, low) have been highlighted on the graph. Table 11 summarises the median settling velocities (w_{50}) derived from the analysis. These show that w_{50} for region A (the fastest settling fraction) is 0.001188 ms^{-1}, that for region B is 0.000253 ms^{-1} (which is at the top of the specified value range derived from the analysis of natural silts; see Section 3.6.2), and that for the slowest settling fraction (region C) is 10^{-5} ms^{-1} (which in real terms represents a permanently suspended fraction).

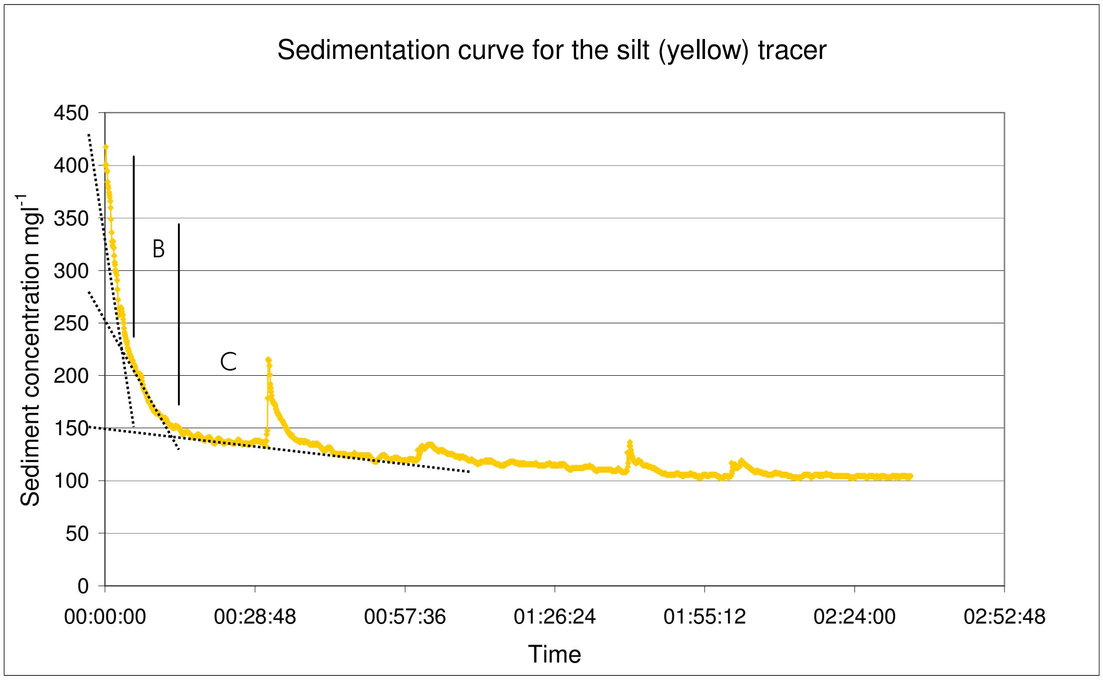

Figure 12 Sedimentation curve for the silt tracer. Regions A, B and C indicate relatively fast, intermediate and low/very low settling velocity. The discontinuities reflect consecutive sampling of the water for sediment concentration determinations. The mean settling velocity for each region was computed as for the natural estuary silts (see Fig. 3).

The fluorescence tincture of the tracer silt was ascertained through the use of illuminated fluorescence microphotography (Fig. 13). The tracer is highly fluorescent under black light.

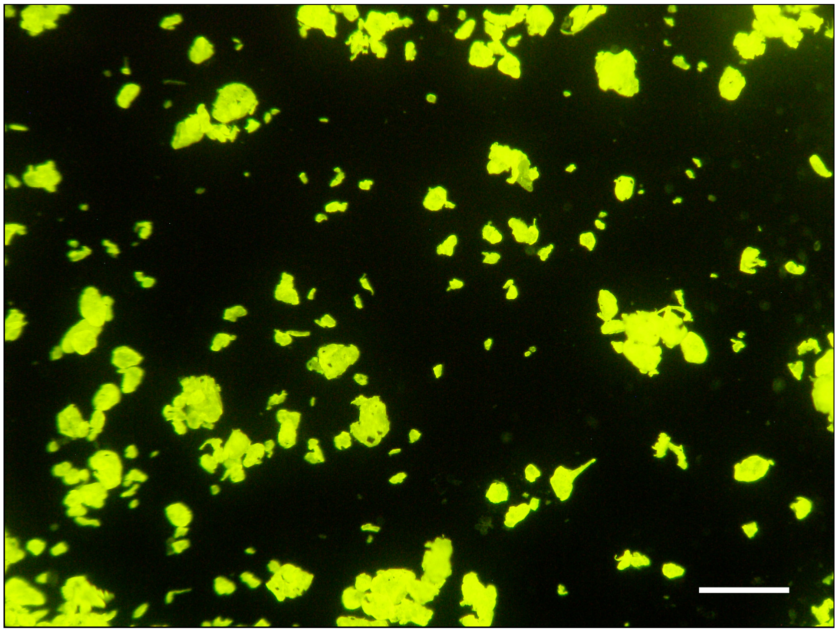

Figure 13 **Fluorescence microphotograph of the silt tracer. The scale bar is 100 µm.**

The para-magnetic character of tracer grains was established in the same manner as the sand tracer. The tests showed that the silt tracer is highly para-magnetic and that 100% of the particles are para-magnetic.

5.3 A Note on Laser Diffraction Size Analysis

Laser diffraction was the method of choice used within this study to determine particle size. However, all laser diffraction particle size analysis systems which may be used to measure the size distribution of a collection of particles tend to over-estimate the maximum size present (Blott and Pye, 2006). That is because of the way the laser software algorithms interpret the recorded diffraction data. Our experience indicates that, in the case of truncated distributions such as those in individual sieved fractions, the laser software tends to 'smooth' the data to produce what it regards as a more likely 'natural' distribution. The 'true' is better represented by sieving than by laser granulometry; however, the laser method is used here for expedience. It is possible that a sieve analysis of the tracer sand would indicate very little, if any, material > 125 um for the silt tracer, but this has not been substantiated. Blott and Pye (*op. cit.*) have also shown that laser analysis tends to over-estimate the mean and median size of sand samples by an average of c. 15% compared with values obtained by sieving, due in part to a particle shape effect. These observations are relevant to this study as they relate to our specific analytical method.

5.4 Hydraulic Similarity Assessment

Assessment of the hydraulic similarity is the process where the hydraulic properties of the manufactured tracer sediments (which are a function of physical attributes such as size and density) are compared to those of native sediments. Table 12 summarises the hydraulic indices for the native silt and sand together with the manufactured tracer silt and sand. Note that a direct comparison is not entirely possible due to certain specific requests for tracer particle characteristics made by Ecology. Note further density determinations were not made on natural silt (hydraulic similarity assessments are based on settling velocity data).

Table 12 **Summary of the tracer specification for sand and silt tracers together with data for natural sediments. A, B and C for the silt tracer refer to the regions on the settling velocity curves.**

	Specified/measured size range (μm)	**d_{50} (μm)**	**Density (kgm^{-3})**	**Mean/Median Settling Velocity (ms^{-1})**	**Settling Velocity Range (ms^{-1})**
Native Sand	63 to 2000+*/***	Varied**	2580±400	0.013±0.01	0.006 to 0.040
Tracer Sand	20 to 310	128	2512±19	0.022	0.002 to 0.029
Native Silt	Medium to coarse silt	20 to 40 μm	N/A	0.00015 (B)	0.00013 to **0.00024 (B)**
Tracer Silt	7 to 162	50	1205±14	**0.000253 (B)** 0.000037 (C)	0.001188 to 0.000037

* see Section 3.6.1
** 12 of 15 samples tested were fine sand (d_{50}≈180-190 μm), with 3 of these very fine sand (d_{50}≈90-100 μm);
***Tracer of 60 to 250 μm size range was verbally specified by Ecology.

5.4.1 Sand

For sands it was indicated by Ecology that the fine/very sand fraction (<250 μm) was of concern; thus, although extensive testing of the sand fraction was undertaken (Table 6; Appendix 3), revealing in some samples far larger sediment grains (e.g. MC-5), efforts were directed to producing a tracer within this textural range. Largely this was achieved (d_{90}=248 μm), insofar as 93% (93kg) of the batch was within the specified size range. The median size of the tracer sediments (d_{50}) is 128 μm which is reasonably centrally located between the upper and lower grain size limits (Fig. 7).

The ratio of the mean density of the native sands and the tracer sands was effectively unity indicating a suitable density matching. The median settling velocity for the tracer was slightly higher than that for the native sands, but centrally located within the range of measured native sand values.

The presence of the textural fine tail *per se* would not form an issue were it sieved out prior to tracer injection. However, as this was not possible, due consideration must be given to it in nthe data analysis stage. The fluorescent magnetic material between ~20 and 63 μm may potentially 'contaminate' the yellow silt tracer masses within samples (this will be detected in the image analysis), whereas the non-fluorescent, magnetic material < 20 μm in size will add only to the background natural magnetic signature within the estuary.

For the purposes of the practical study, it can be considered that 93 kg of sand tracer of a density, size and settling velocity corresponding to very fine-fine sand were available for injection into the surface waters of the LDW.

5.4.2 Silt

The silt tracer is coarser than expected and whilst 72% (=99 kg) of the tracer is <63 μm, there is a small fine sand component (Fig. 11). In order to judge the similarity of the tracer to natural silts, and to assess the likely behaviour in the LDW, it is preferable to consider the settling velocity data. Firstly, both the native silts and tracer display a very fine, likely permanently resuspended fraction (corresponding to region C on

Figs. 3 and 12), with w_{50} ~10^{-5} ms^{-1}. Similarly, both the native silts and the tracer display a distinct region B (intermediate settling velocity) curve, although the w_{50} value for the tracer is at the upper limit of the native silts tested (the two data values are in **bold** in Table 12). This analysis indicates that regions B and C of the sedimentation curves are largely comparable between the native silts and the tracer.

A significant difference in settling velocity is, however, apparent in a comparison of region A data; w_{50} values for the native silts range 0.0003 to 0.0004 ms^{-1}, whereas that for the tracer is 0.001188 ms^{-1} (Table 12; i.e. a single order of magnitude greater), and these data are consistent with the particle size data. The settling velocity of the tracer within region A is *less* than the *minimum* measured setting velocity for the sand tracer as tested (i.e. sieved at 63 µm[3], 0.002 ms^{-1}; Table 10), which indicates that this fraction is, in hydraulic terms, a coarse or very coarse silt. The region A settling velocity value for the tracer is higher than comparable values for most natural silt samples tested (~70% of which comprise coarse silts; Table 5), and this further points to the region A tracer fraction as being skewed towards the coarsest silt range in particular.

The mass percentage within each of the three regions contained in the manufactured tracer batch can be determined from the sedimentation curves (Table 13). The material with the fastest settling velocity (curve region A) comprises 75.2 kg; the sum of tracer within regions B and C collectively is 84.8 kg. Thus, whilst size analysis indicates 99 kg of tracer material of size <63 µm, the settling velocity data indicate that 84.8 kg is expected to mimic medium to fine silt transport within the estuary and 75.2 kg is expected to mimic the coarse-very coarse silt fraction.

Table 13 **Absolute tracer masses contained within each of the discrete sedimentation curve sections (refer to Fig. 12). Sub-totals for regions B and C are indicated in red.**

Curve Section	Mass %	Mass Relative to Injection Mass (kg)
A	47	75.2
B	36	57.6
C	12	27.2
	Total	160.0 (84.8)

Collectively the characterisation tests on the silt tracer indicate a batch which ranges, in hydraulic terms, from very coarse through to fine-medium silts; importantly, although the sand and silt tracer particle size distributions overlap, the settling velocity distributions do so only fractionally (see footnote). In this regard, and in spite of a rather wider spectrum than desired, **it can be considered that 160 kg of silt tracer of appropriate hydraulic characteristics were available for injection into the surface waters of the LDW.** The mass of tracer exceeds that ordered, but this acts only to increase the power of the study.

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[3] The issue of an overlap in settling velocity between the sand tracer fine tail and the coarsest silt tracer grain requires examination. Settling velocity values for 40 µm and 50 µm sand density particles are 0.00092 and 0.0012 ms^{-1}, respectively (following Soulsby, 1997), which compare with the value of 0.001188 ms^{-1} for the silt tracer region A. The overlap is therefore considered marginal.

6. CONCLUSIONS

This report provides an assessment of the physical-hydraulic character of suspended and deposited sediments from the LDW and summarises specification of, and characterization of, manufactured silt and sand tracers.

Existing data are reviewed, and laboratory analyses of size, density, settling velocity, fluorescence presence, and para-magnetic character for real sediments are reported and discussed. These data have been used to derive specifications for sand and silt dual-signature tracers, but with several caveats. The major of these was that the sand fraction be in the very fine to fine sand range, and that the silt tracer reflected in hydraulic terms a medium silt fraction.

The above tests were repeated on the commissioned tracers as part of a similarity testing assessment.

93 kg of a dual-signature <u>sand</u> tracer with density, size and settling velocity attributes highly similar to native sand was manufactured for introduction into the surface waters of the LDW. Macroscopically the tracer resembled and behaved as mineral sand (naturally slightly compact, moisture redistribution upon disturbance, temporary clumping when troweled into the injection funnel). The sand tracer included a small silt fraction within which particle sizes <20 µm are dust from the manufacturing process and do not affect the tracking study, whereas those in the range 20 to 63 µm are genuine fluorescent-magnetic, mineral density (2650 kgm^{-3}) silt particles which do (although some of this material may have been washed away during the tracer pre-wetting).

160 kg of a dual-signature (reduced-density) <u>silt</u> tracer with settling velocity attributes highly similar to native very coarse silts was available for introduction into the surface waters of the LDW. In hydraulic terms the silt tracer was slightly coarser than specified, and the settling velocity spectrum was observed to overlap fractionally with the sand tracer. Macroscopically the tracer resembled and behaved like an estuary silt/mud (with elastic-plastic properties and discernible vertical consolidation gradients inside the vessel).

For each tracer, tests confirmed a strong fluorescence signature and that 100% of tracer particles were highly para-magnetic.

7. REFERENCES

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4. Partrac Ltd., 2008 Quantifying Floc Transport in Vegetated and Non-vegetated Habitats in the Florida Everglades. Report P1031.05.D003v01, 88pp.

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7. Whitehouse, R., Soulsby, R., Roberts, W., and Mitchener, H., 2000. Dynamics of Estuarine Muds. Telford. 209pp.

8. APPENDIX I SETTLING VELOCITY-EGS PLOTS

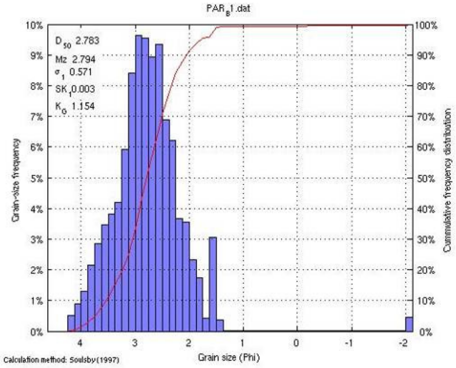
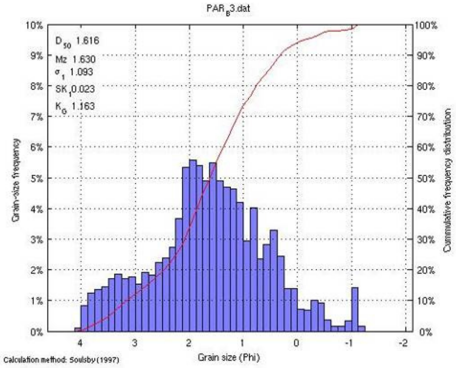


Figure 5 B1



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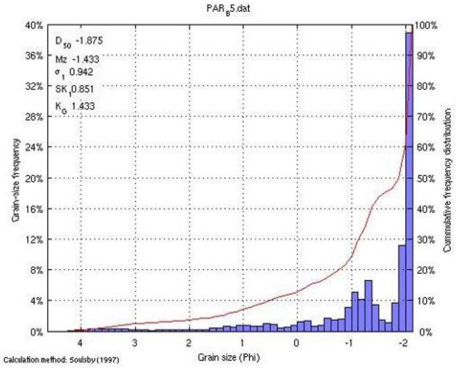

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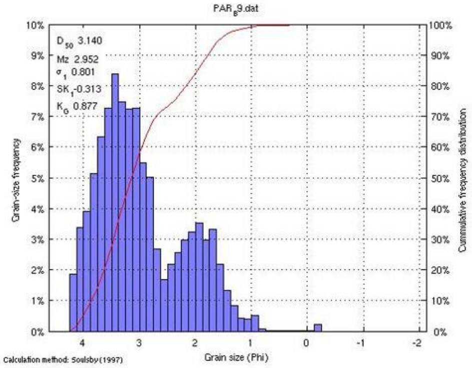

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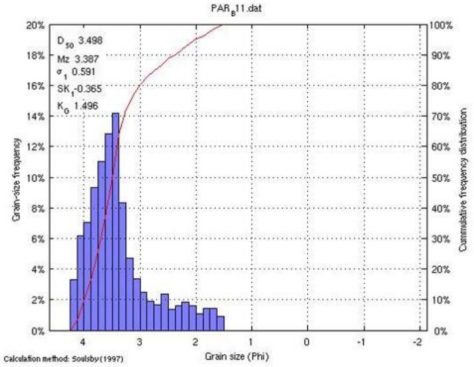

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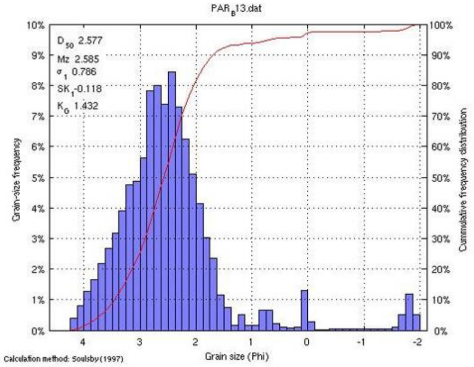

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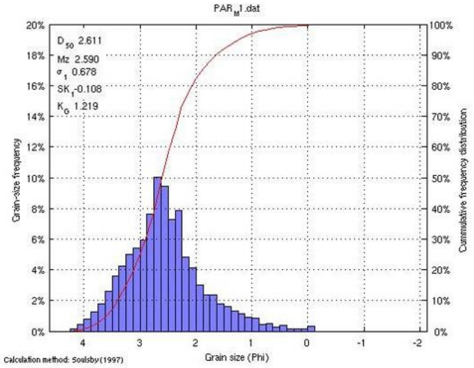


Figure 11 MC1

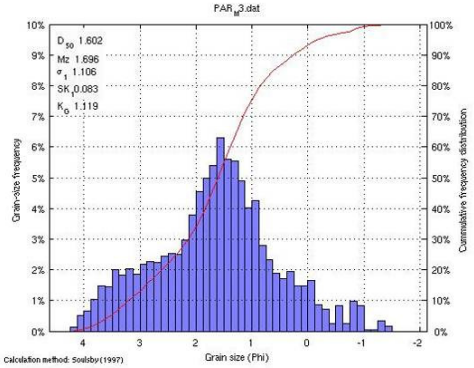


Figure 12 MC3

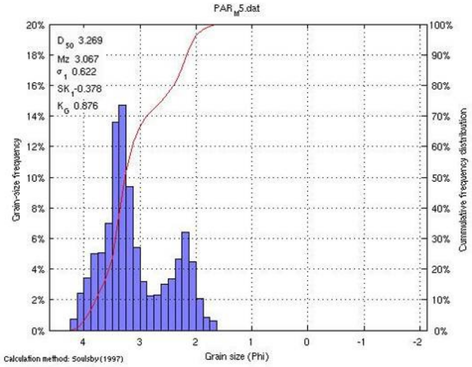


Figure 13 MC5

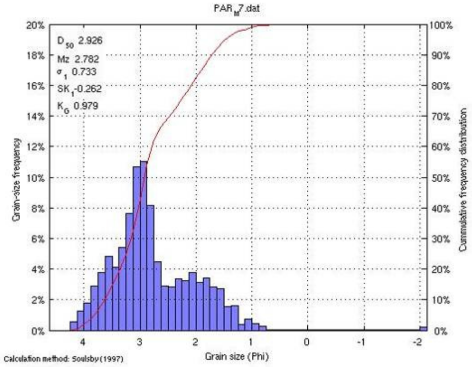


Figure 14 MC7

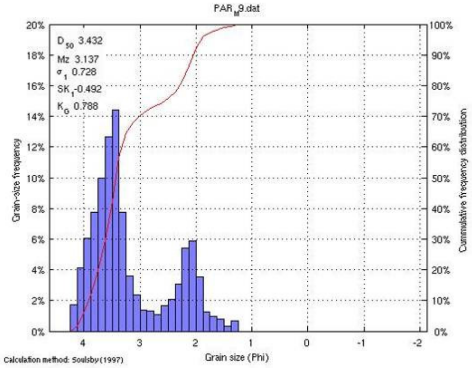


Figure 15 MC9

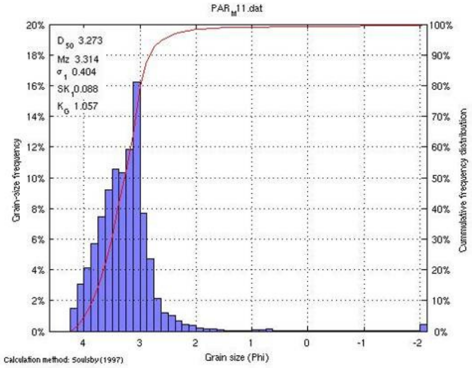


Figure 16 MC11

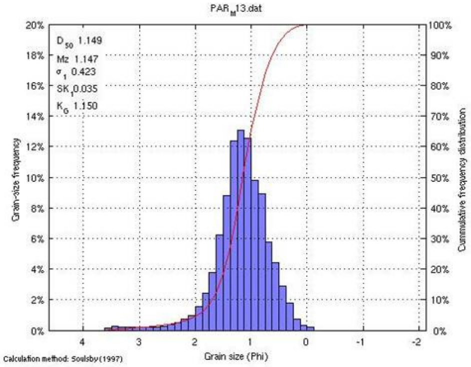
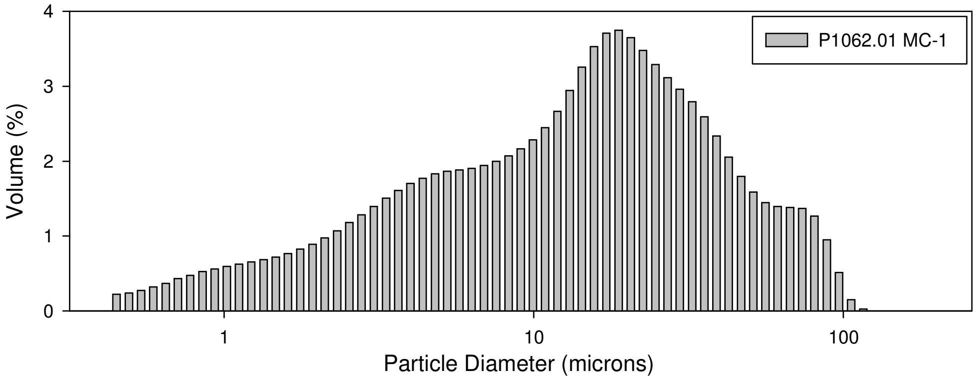
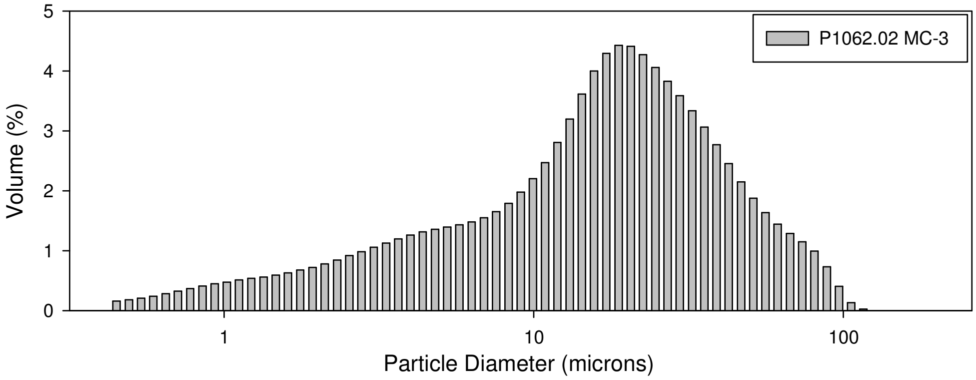
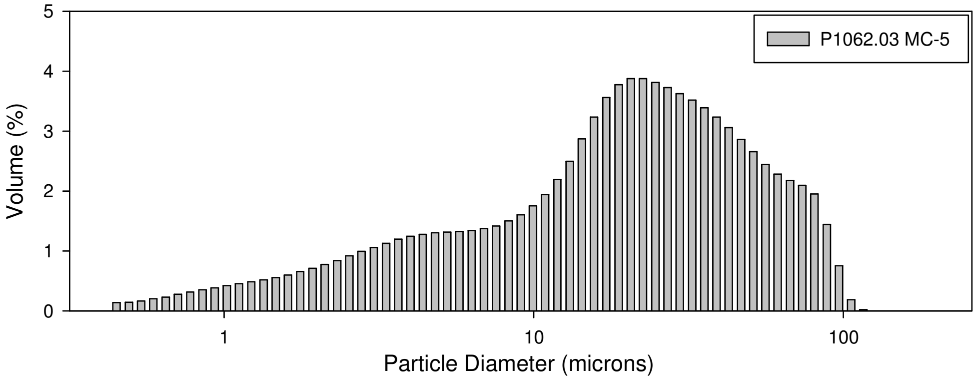


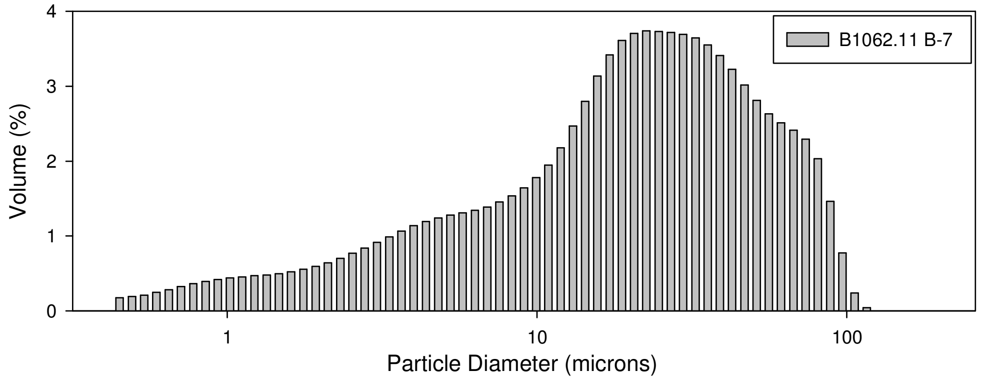
Figure 17 MC13

9. APPENDIX II PARTICLE SIZE PLOTS (SILT FRACTION ONLY)





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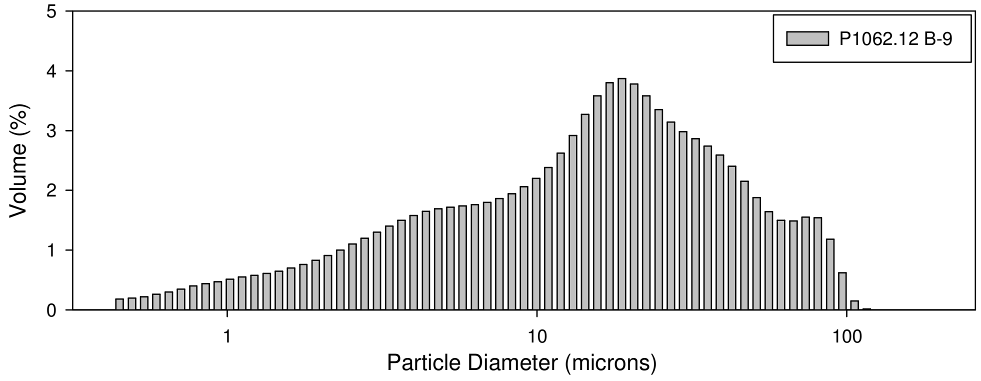
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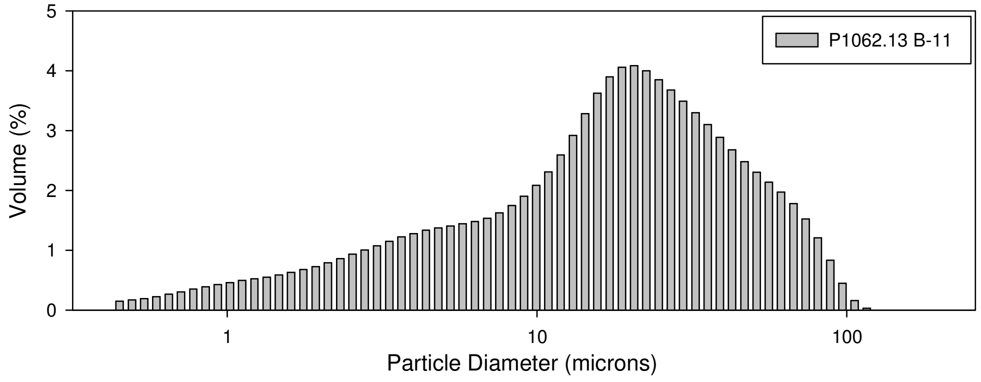
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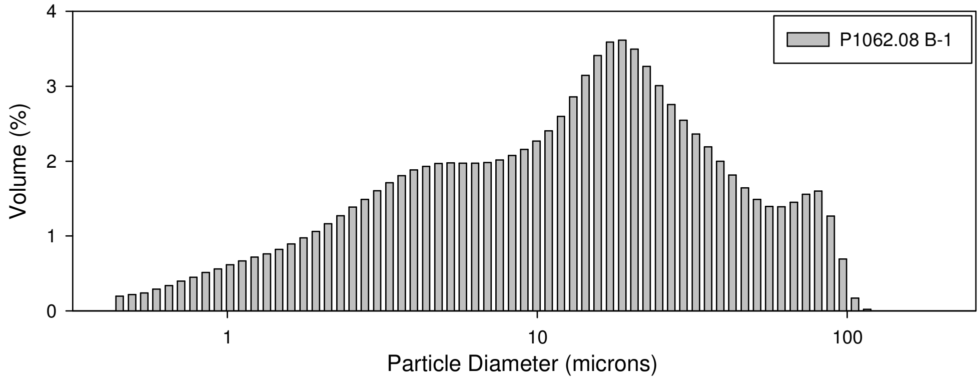
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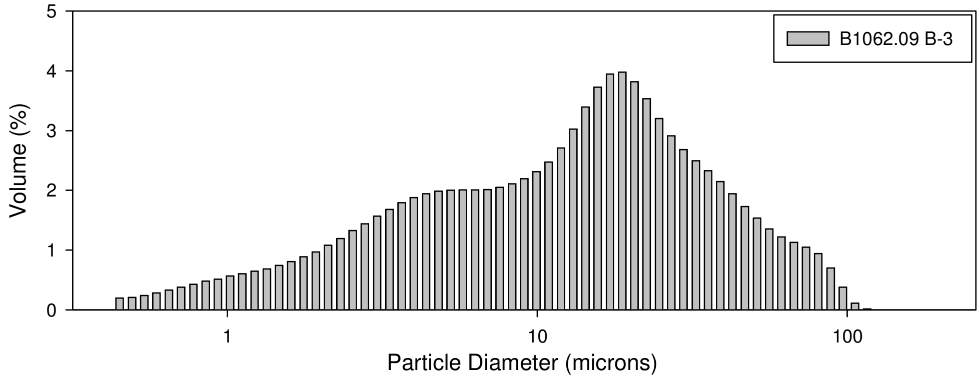
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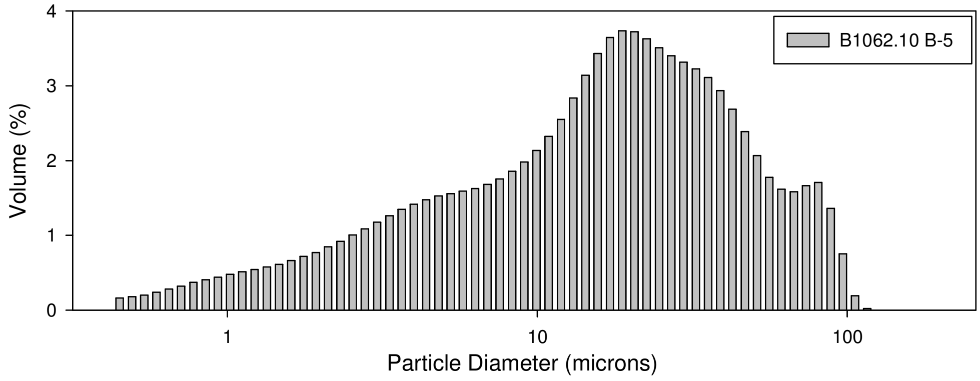
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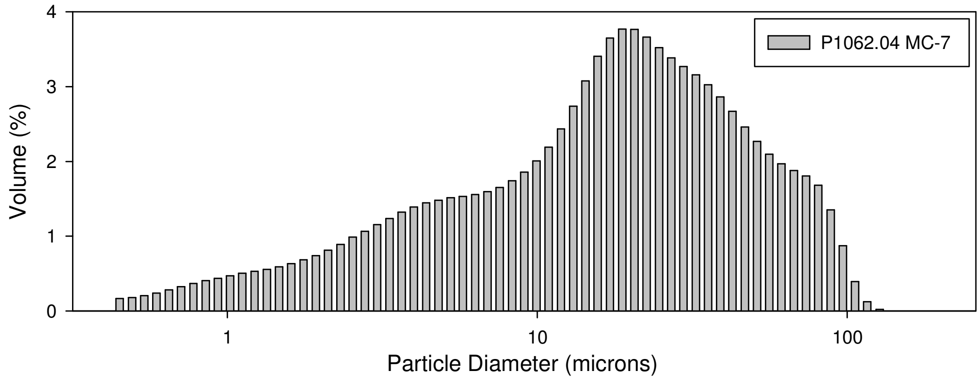
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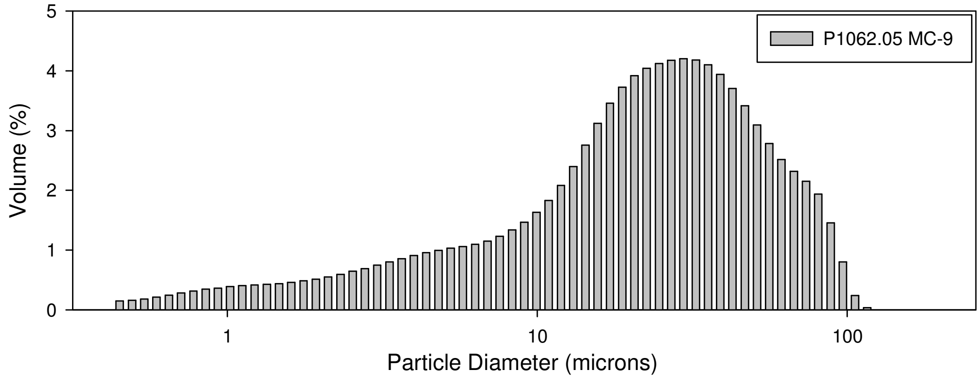
1
10
100
Particle Diameter (microns)
P1062.04 MC-7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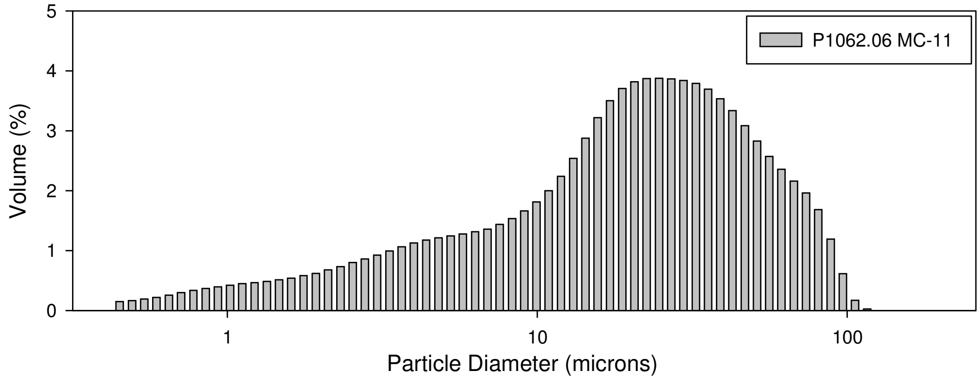
3
4
5
1
10
100
Particle Diameter (microns)
P1062.05 MC-9


Volume (%)
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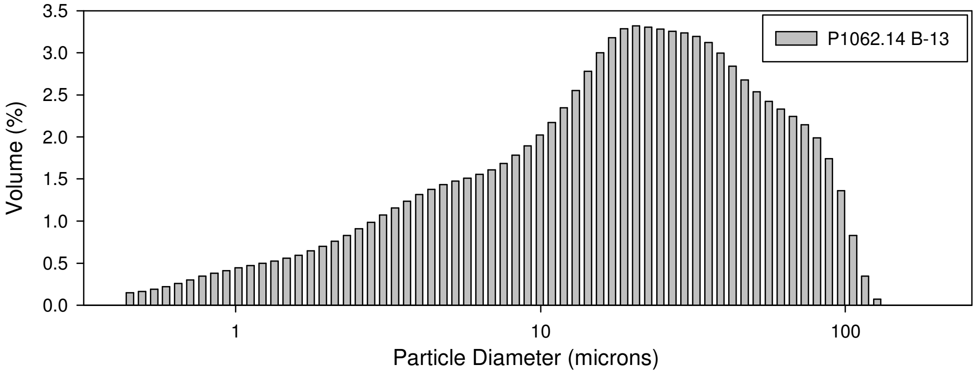
4
5
1
10
100
Particle Diameter (microns)
P1062.06 MC-11


Volume (%)
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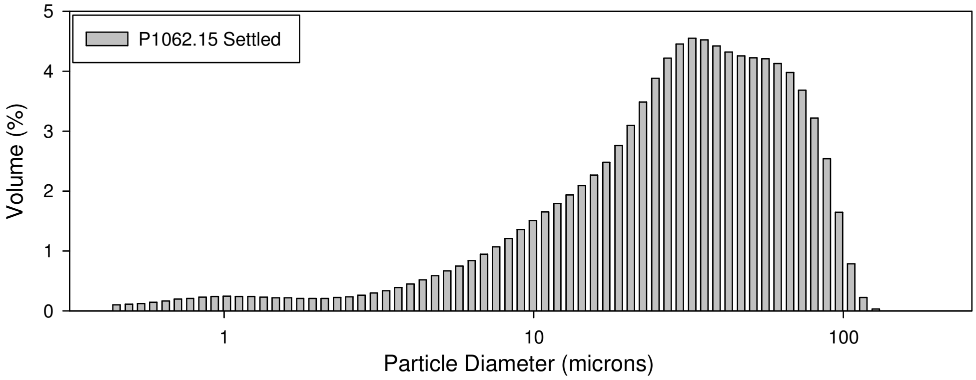
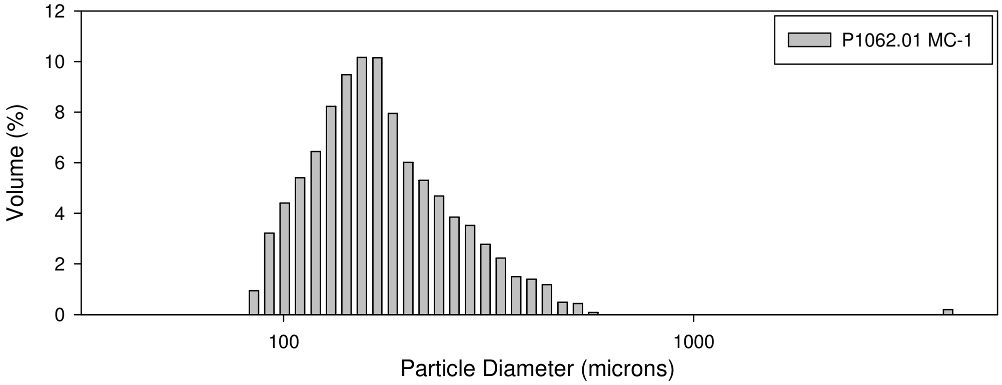
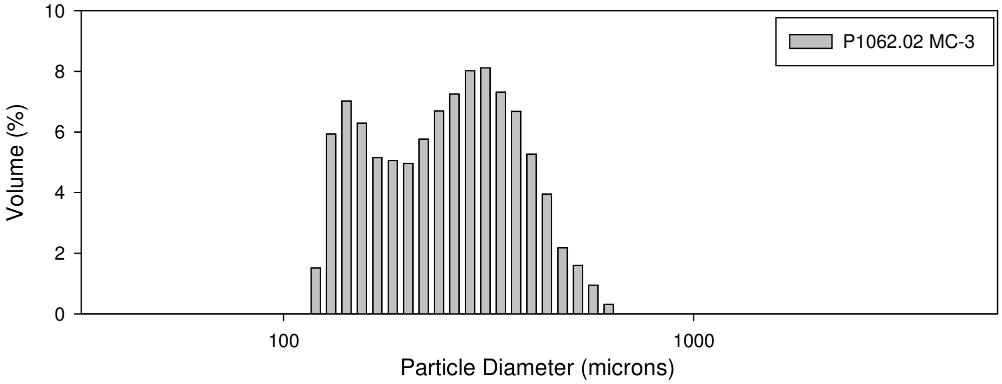
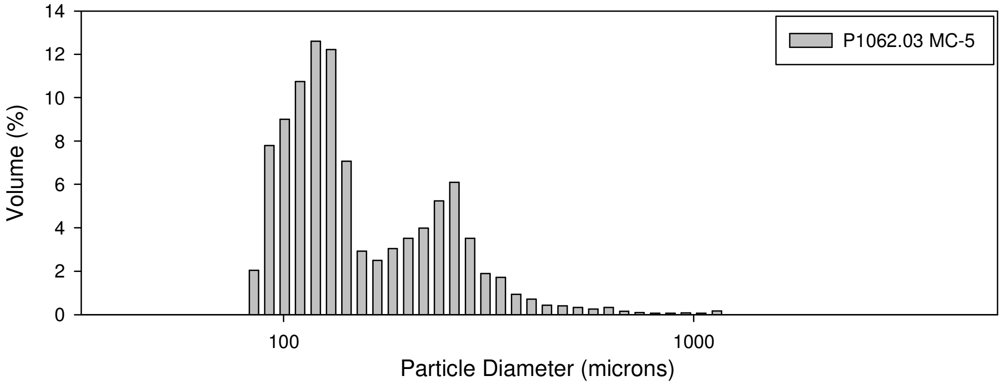
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1
10
100
Particle Diameter (microns)
P1062.14 B-13

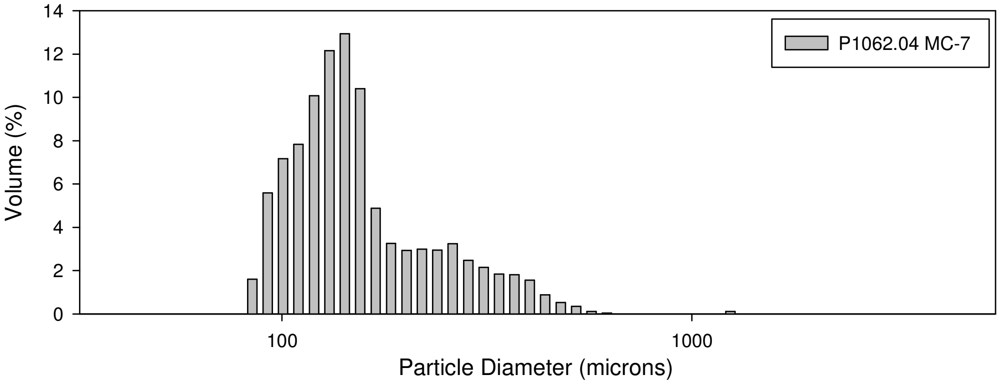

Volume (%)
5
4
3
2
1
0
1
10
100
Particle Diameter (microns)
P1062.15 Settled

10. APPENDIX III PARTICLE SIZE PLOTS (SAND FRACTION ONLY)








P1062.04 MC-7
Volume (%)
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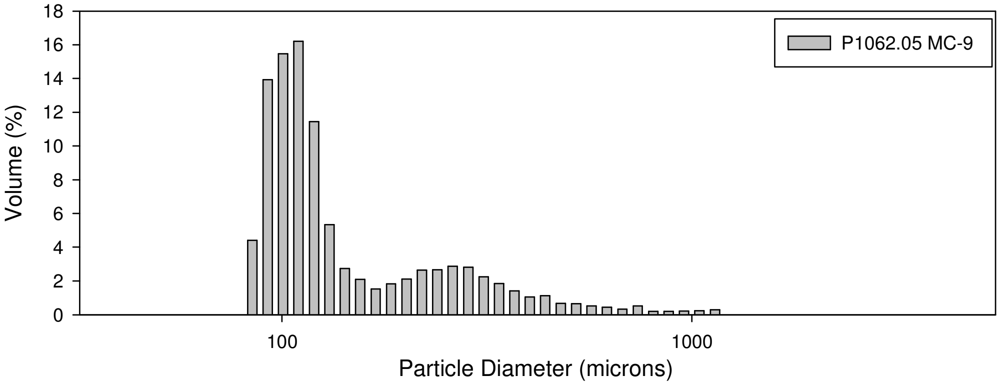
4
6
8
10
12
14
100
1000
Particle Diameter (microns)


P1062.05 MC-9
Volume (%)
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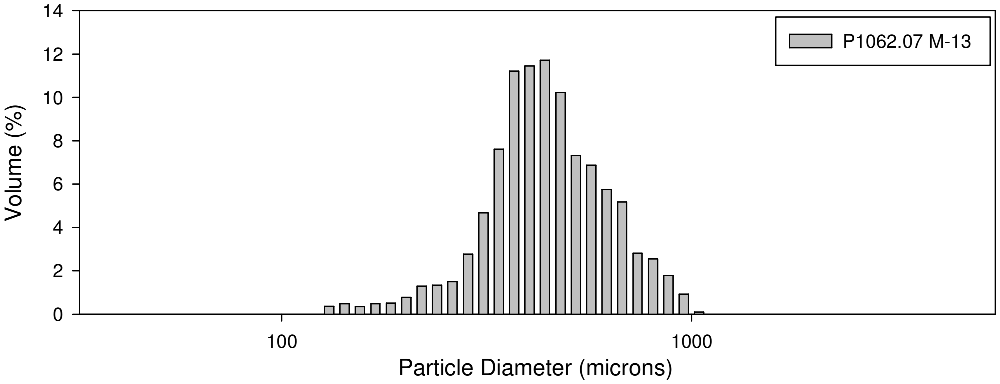
4
6
8
10
12
14
16
18
100
1000
Particle Diameter (microns)


P1062.07 M-13
Volume (%)
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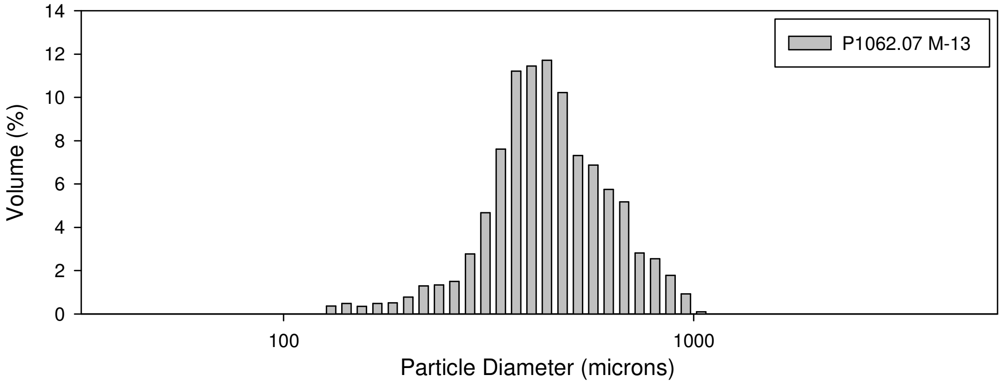
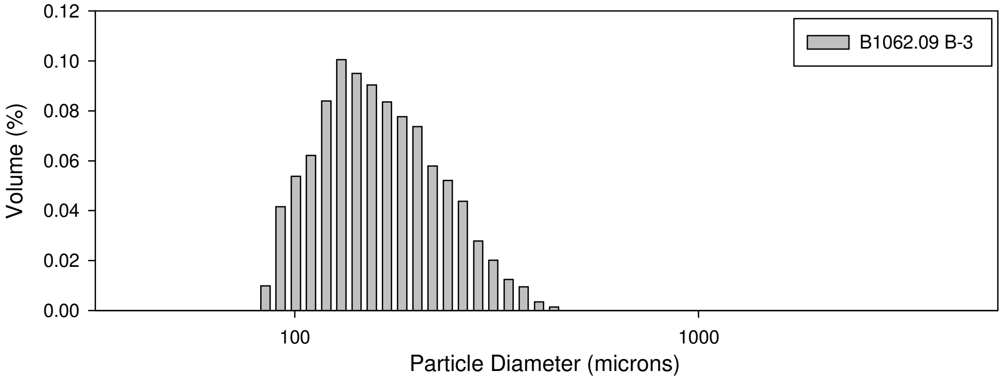
6
8
10
12
14
100
1000
Particle Diameter (microns)


14
12
10
8
6
4
2
0
Volume (%)
100
1000
Particle Diameter (microns)
P1062.07 M-13


0.12
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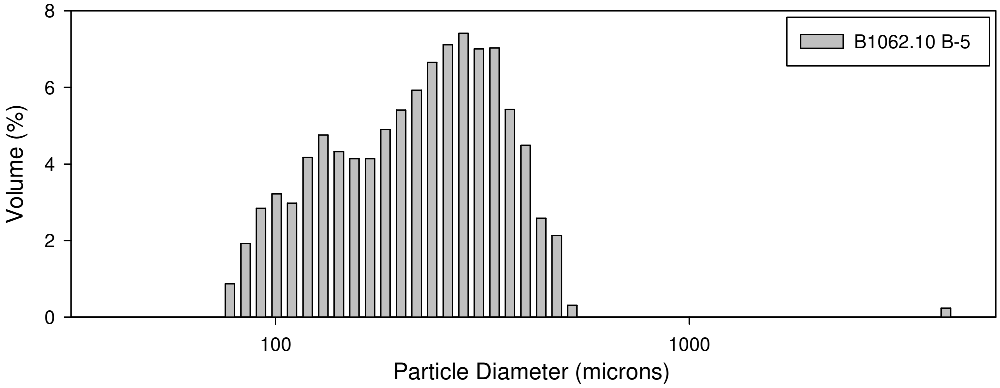
0.08
0.06
0.04
0.02
0.00
Volume (%)
100
1000
Particle Diameter (microns)
B1062.09 B-3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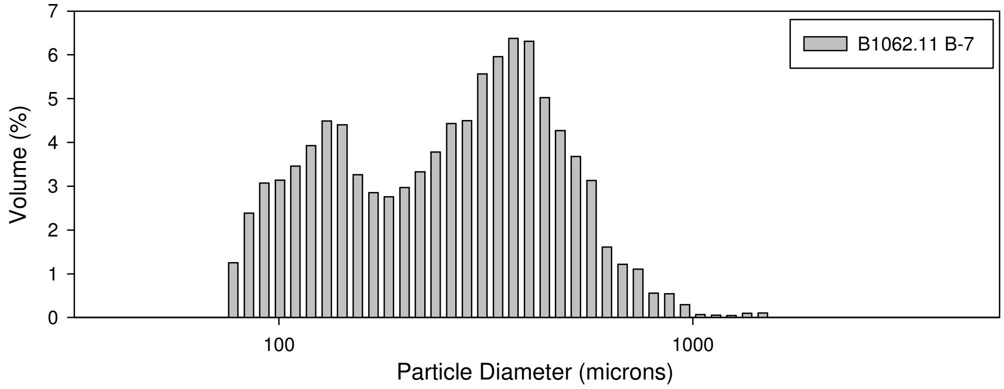
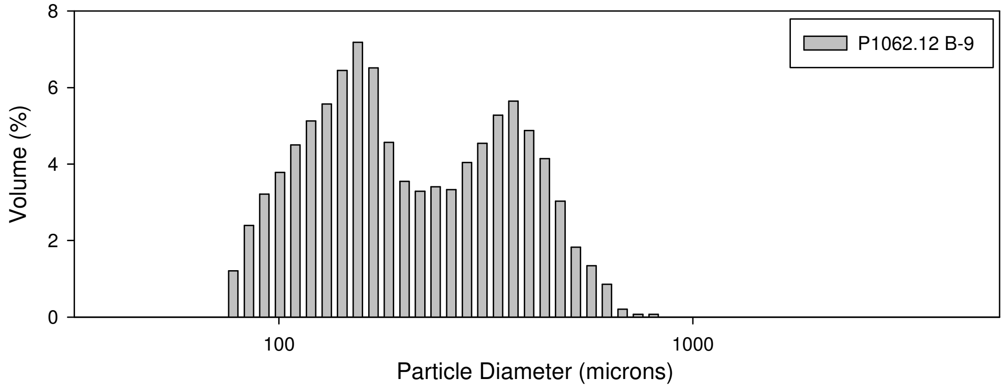
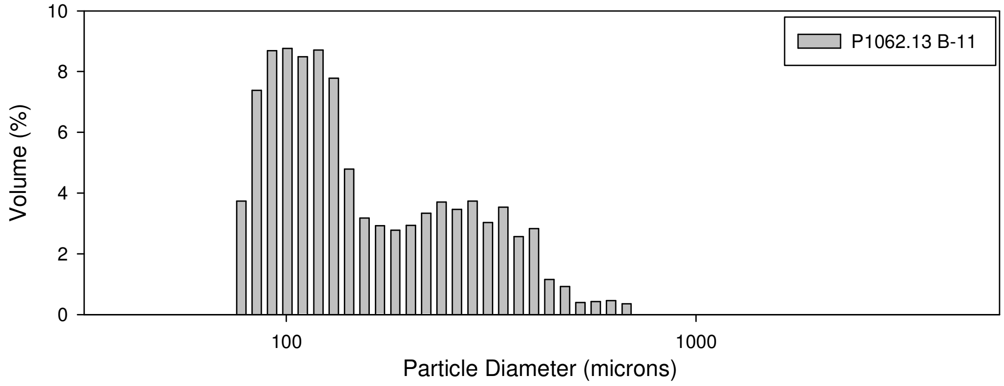
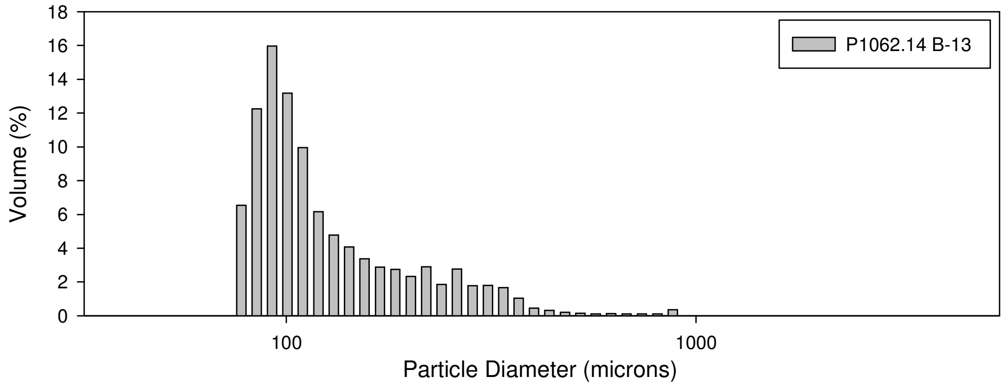
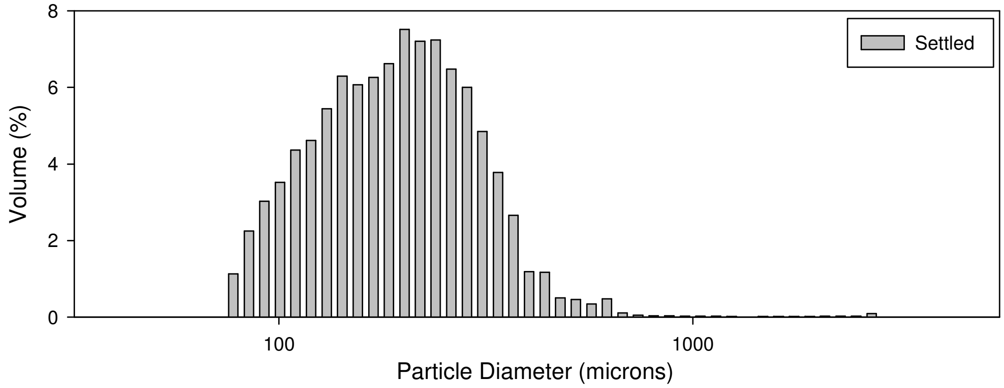
2
0
Volume (%)
100
1000
Particle Diameter (microns)
B1062.10 B-5


7
6
5
4
3
2
1
0
Volume (%)
100
1000
Particle Diameter (microns)
B1062.11 B-7


8
6
4
2
0
Volume (%)
100
1000
Particle Diameter (microns)
P1062.12 B-9


10
8
6
4
2
0
Volume (%)
100
1000
Particle Diameter (microns)
P1062.13 B-11


P1062.14 B-13
Volume (%)
0
2
4
6
8
10
12
14
16
18
100
1000
Particle Diameter (microns)


Settled
Volume (%)
0
2
4
6
8
100
1000
Particle Diameter (microns)

Attachment 2.

Tracking Short-Term Movements of Suspended Sediment in the Lower Duwamish Waterway

This document was prepared under contract with Partrac Ltd. and is intended for a technical audience. The important elements are described in the summary report.

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Tracking Short-Term Movements of Suspended Sediment in the Lower Duwamish Waterway

FINAL REPORT

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Changes from the Previous Version	
Section	Description of Changes
Various	Refer to file **Partrac Comments on Draft Final.doc**.
5.3.3	Clarification of the methodology used for the blank magnets
6.3.2	Comments on image analysis methodology; new reference included (Forsyth, 2000)
6.3.1	Comments in relation to improved sampling design

Recipient	**Distribution Method**		
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Tom Gries, Washington Ecology		X	X

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EXECUTIVE SUMMARY

The Washington State Department of Ecology is studying the loading of PCBs from suspended solids entering the Lower Duwamish Waterway sediment cleanup site. A key element of this study is to release fluorescent sediment particle analogues into the water column of the Duwamish/Green River in order to:

- assist Ecology in the direct assessment of transport and fate of suspended solids that enter the Lower Duwamish Waterway from the Duwamish/Green River system;
- to show how far into or beyond the cleanup site fluorescent sediment particles that mimic those found in the Duwamish/Green river can be transported when released into the water column under various conditions, and
- to trace the movement of these particles into, and possibly through, the waterway; and, in particular,
- to trace where they can settle to the bottom.

Partrac Ltd. were commissioned to

- To manufacture fluorescent sediment particles that effectively mimic the characteristics of samples of suspended sediment collected from the Green River or bedded sediment collected from the Lower Duwamish Waterway;
- To release such particles into the water column of the Duwamish/Green River on one occasion that represents moderate flow and ebb tide conditions; and
- To trace the movement of these particles into, and possibly through, the waterway.

Following extensive testing of the physical-hydraulic characteristics of the native sediments within the Lower Duwamish Waterway, a specification was derived for a fluorescent-magnetic silt tracer and a fluorescent-magnetic sand tracer. These were manufactured, tested for their hydraulic similarity to the specification[1] and to a set of measurement quality objectives, and then sanctioned for introduction into the waterway by Ecology.

Ecology were responsible for the design of the field programme (tracer injection methodology, sampling) with some input from Partrac. A method which involved gentle flushing of tracer down a sub-surface pipe, was designed to introduce ('inject') each tracer into the surface waters of the Lower Duwamish Waterway, and this proved highly successful. A 2 month sampling strategy combining an array of fixed (11000 gauss) magnets, bed sampling, and filtration of pumped water samples and dipped (towed) field portable magnets was designed and successfully implemented within the waterway from RM4+ to RM0. Although the magnetic tracer method is a mass-based methodology, an image analysis method was used to determine the tracer mass in collected samples due to the presence of native magnetic material. This provided quantitative data, although QC procedures determined the method under-estimated tracer mass within samples by a factor between 1.6 and 3.2. Issues associated with sampling fine bedded sediments in an un-biased manner, coupled with the frequent very low tracer mass values in samples (due to dilution and dispersion within the waterway) indicate the appropriate manner in which to present and interpret data is through an ordinal (low-medium-high) rather than quantitative approach. However, the study demonstrated the ability to recover magnetic tracers from a relatively large, diluting system using limited tracer mass and with different sampling methods. It is considered that the data collected contribute directly to fulfilling the project objectives.

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[1] These tests were summarized in the report P1062.05.D001v03 - Native Sediment and Tracer Characterisation Report.pdf

The results show that sand tracer was deposited within a footprint region to a distance ~500 m downstream of the injection location. Some of the very fine sand tracer (particle sizes ~60 to 70 μm) were found both in suspension and in bedded samples to RM 3.4, and very low concentrations were detected in occasional samples at the Western Gateway region (~RM0). These data indicate severe longitudinal concentration and size gradients within the estuary. Fixed magnets did not record sand tracer in suspension during the 1 and 2 month sampling periods, which indicates that the tracer sand was likely an immobile sediment pool, most of which was on the seabed within the upper estuary.

Silt tracer was found on most fixed magnets throughout the Lower Duwamish Waterway. Sampling using dipped magnets and pumped water sampling on the day of tracer injection confirmed longitudinal (and lateral) tracer transport to the vicinity of RM 0. Concentrations were universally low (10^{-4} to 10^{-6} g), nonetheless these observations directly confirm advective transport (and lateral turbulent mixing and diffusion) of tracer over these distances during a single tidal ebb duration. Whilst there was indication of deposition of coarser silt tracer particles, there was no consistent trend (i.e. decrease) in suspended tracer particle size with distance downstream. The entire range of silt tracer particles (~10 to 60 μm) was found in suspension throughout Week 1 and Month1 sampling intervals.

The distribution of silt tracer particles size within bedded sediments is highly similar to those in suspension, which suggests concurrent deposition of silt tracer. This is explained through the existence of velocity gradients within the estuary (e.g. close to the seabed). The pool of suspended tracer at the end of Day 1 provides a mobile pool of material available for transport through months 1 and 2. An inter-comparison of the fixed magnet data for Week 1 and Month1 is not yet possible and will be reported subsequently. The distribution of tracer in bedded samples through Months 1 and 2 is highly similar to that observed for Week 1, which indicates that the pattern may have arisen due to deposition during the early phase of the study and changes little during time.

Some recommendations are presented to highlight where improvements can be delivered for future studies of this type.

CONTENTS

1. INTRODUCTION

1.1 Background

The Washington State Department of Ecology is studying the loading of PCBs from suspended solids entering the Lower Duwamish Waterway sediment cleanup site. An estimate of PCB loading will be derived from simultaneous measurements of flow and PCBs associated with suspended particulates in the Duwamish/Green River. Observations of the transport and deposition of fluorescent sediment particles – ones that mimic native suspended sediments and that will be released upstream of the cleanup site – will be used to make additional inferences about sediment loading. Together, these will evaluate predictions made by a sediment transport model.

The Lower Duwamish Waterway cleanup site is located between river mile 0.0 and approximately river mile 5.0 in the Duwamish/Green River. Figure 1 shows the study area and vicinity. The Duwamish/Green River, drains to the Puget Sound estuary, and is tidally influenced well beyond River Mile 12.4. A wedge of saline water can periodically underlie fresh surface water as far upstream as approximately River Mile 8.7, but is seen upstream of the East Marginal Way Bridge only during flows of <1000cfs and large flood tides (Figure 1).

Characteristics of the Lower Duwamish Waterway cleanup site itself (downstream of River Mile 5) include:

- Length approximately 8 - 9 km.
- Width (main channel) approximately 150 - 215m.
- Inflow approximately = <10 to 340 $m^3 s^{-1}$ (mean approximately 40 $m^3 s^{-1}$).
- Area of entire cleanup site approximately = 1,800,000 m^2.
- Area of southernmost 1 kilometer of the waterway (including turning basin that acts as sediment trap) approximately 350,000 m^2.
- Water volume within cleanup site approximately = 11,000,000 m^3 (assuming mean depth = 6 m), but varies with tidal elevation.

A key element of this study will be to release fluorescent sediment particles into the water column of the Duwamish/Green River. These sediment particles are required to have size distributions, densities, and settling velocities similar to ones found in the river. Ecology is particularly interested in the potential transport and fate of fine suspended particles (<1- 62.5 μm) and fine to medium sands (63-500 μm) that enter the Lower Duwamish Waterway under different seasonal flow conditions. This is because Ecology has measured PCBs in these two particle size fractions of suspended sediment.

1.2 Goals, Objectives, and Scope

Ecology initiated a Request for Qualifications and Quotations (RFQQ) mechanisms to solicit proposals from contractors that can assist the Ecology in the direct assessment of transport and fate of suspended solids that enter the Lower Duwamish Waterway from the Duwamish/Green River system. Partrac was the successful contractor within a competitive framework. The provision to Partrac was a) comment on the Ecology's study design and implementation strategy, b) manufacture artificial fluorescent sediment particles to the Ecology's specifications, c) to assist with release of tracers into the Lower Duwamish Waterway, d) analyze samples that contain recovered fluorescent particles, and d) interpret the analytical results.

1.2.1 Goals

The primary goal of the overall study is to provide estimates of contaminant loading to the Lower Duwamish Waterway from suspended Duwamish/Green River sediment in order to confirm sediment transport model predictions and preliminary loading calculations.

Study goals pertinent to Partrac are to help the Ecology show how far into or beyond the cleanup site fluorescent sediment particles that mimic those found in the Duwamish/Green River can be transported when released into the water column under various conditions, and to trace where they can settle to the bottom.

1.2.2 Objectives

- To evaluate the natural background fluorescence of suspended and bedded sediments found within the study area;
- To manufacture fluorescent sediment particles that effectively mimic the characteristics of samples of suspended sediment collected from the Green River or bedded sediment collected from the Lower Duwamish Waterway;
- To release such particles into the water column of the Duwamish/Green River on one occasion that represents moderate flow and ebb tide conditions; and
- To trace the movement of these particles into, and possibly through, the waterway.

***Figure* 1 Aerial photograph of the Lower Duwamish Waterway sediment loading study showing the tracer release site and location of transect and other sampling areas (Figure courtesy of Ecology).**

Scope of Report

This report is a final report to Ecology which follows completion of "Assessment of the Hydraulic Characteristics of Native Sediments (Lower Duwamish Waterway) and Tracer Design and Testing". The scope is to deliver the full dataset to Ecology together with an interpretation of the data collected. This report presents:

- Field sampling programme design;
- Pre-wetting procedures and tracer injection (release) methodology;
- Tracer recovery sampling methods;
- Analytical methodology, including an assessment of data quality relative to table of measurement; quality objectives (MQOs), and comparison to agreed tracer specifications;
- Results from QA samples in relation to the image analysis methodology;
- The full dataset as a digital email attachment;
- Assessment of the 'equivalent grain size' procedure for silt tracer particles;
- A discussion of the transportation of silt and sand tracers; and
- Summary conclusions and recommendations.

2. FIELD SAMPLING PROGRAMME DESIGN

A field sampling programme was devised largely by Ecology, with some input from Partrac, to assess the patterns of tracer dispersion throughout the Lower Duwamish Waterway. The field sampling programme comprised:

- Arrays (three per unit; upper, middle, lower vertically) of fixed magnet stations attached to permanent structures throughout the Lower Duwamish Waterway;
- Day-of-release water column sampling using dipped magnets;
- Day-of-release water column sampling (pumped filtration) stations/transects;
- Bedded (deposited) sediment stations, comprising randomly selected locations and subjectively selected locations.

The location of the dipped magnet stations/transects and filtration stations/transects are presented in Figure 2. Note also the vessel transects, conducted using a small boat (one located upstream near the tracer injection point, and one downstream). The locations of the bedded sediment sampling stations are presented in Figure 3, 4 and 5. Figure 6 shows the locations of the fixed magnets.

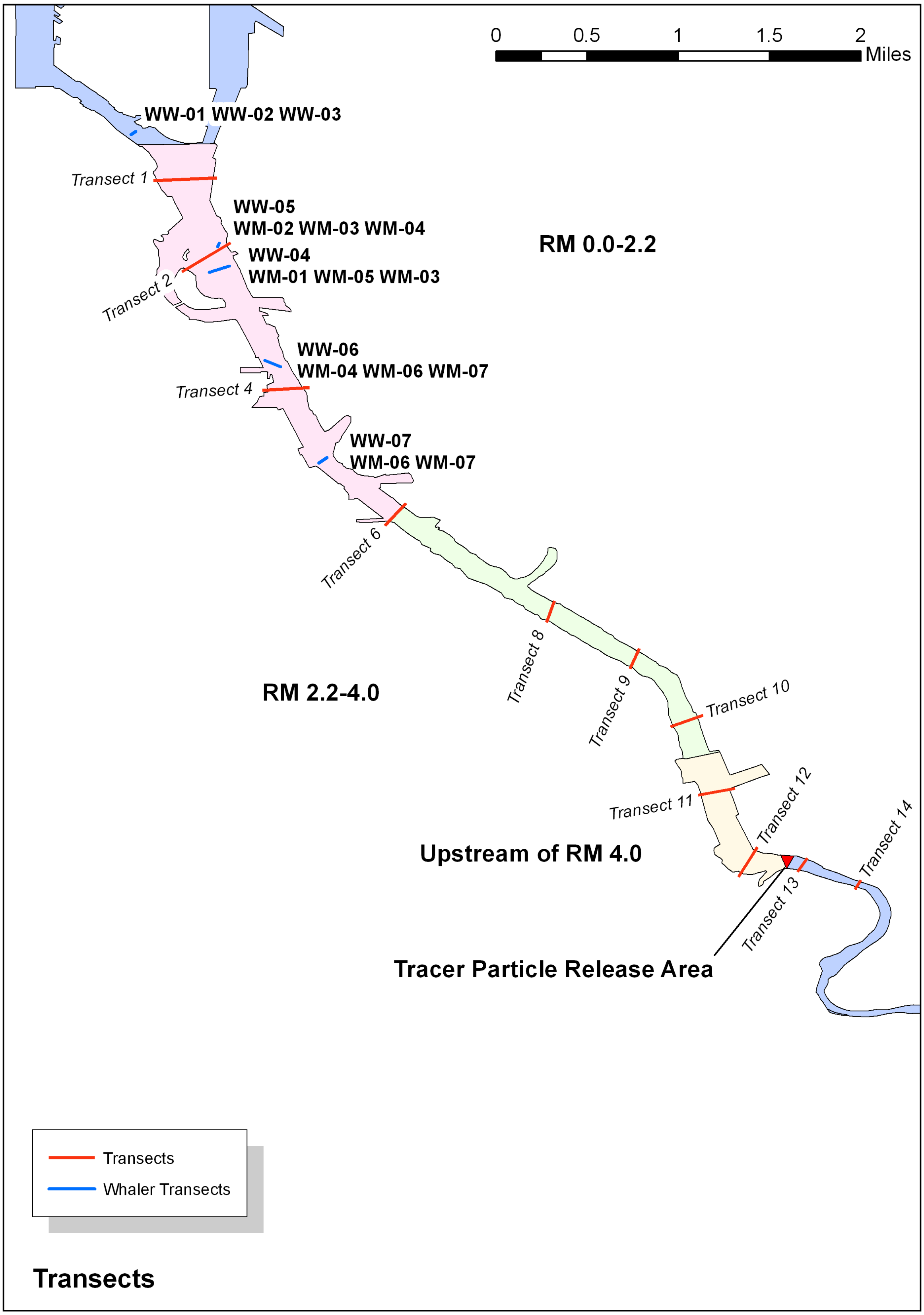

Figure 2 Location of small vessel transects. Dipped magnets and filtration were used along the transects to collect water samples and evaluate them for presence/mass of tracers.

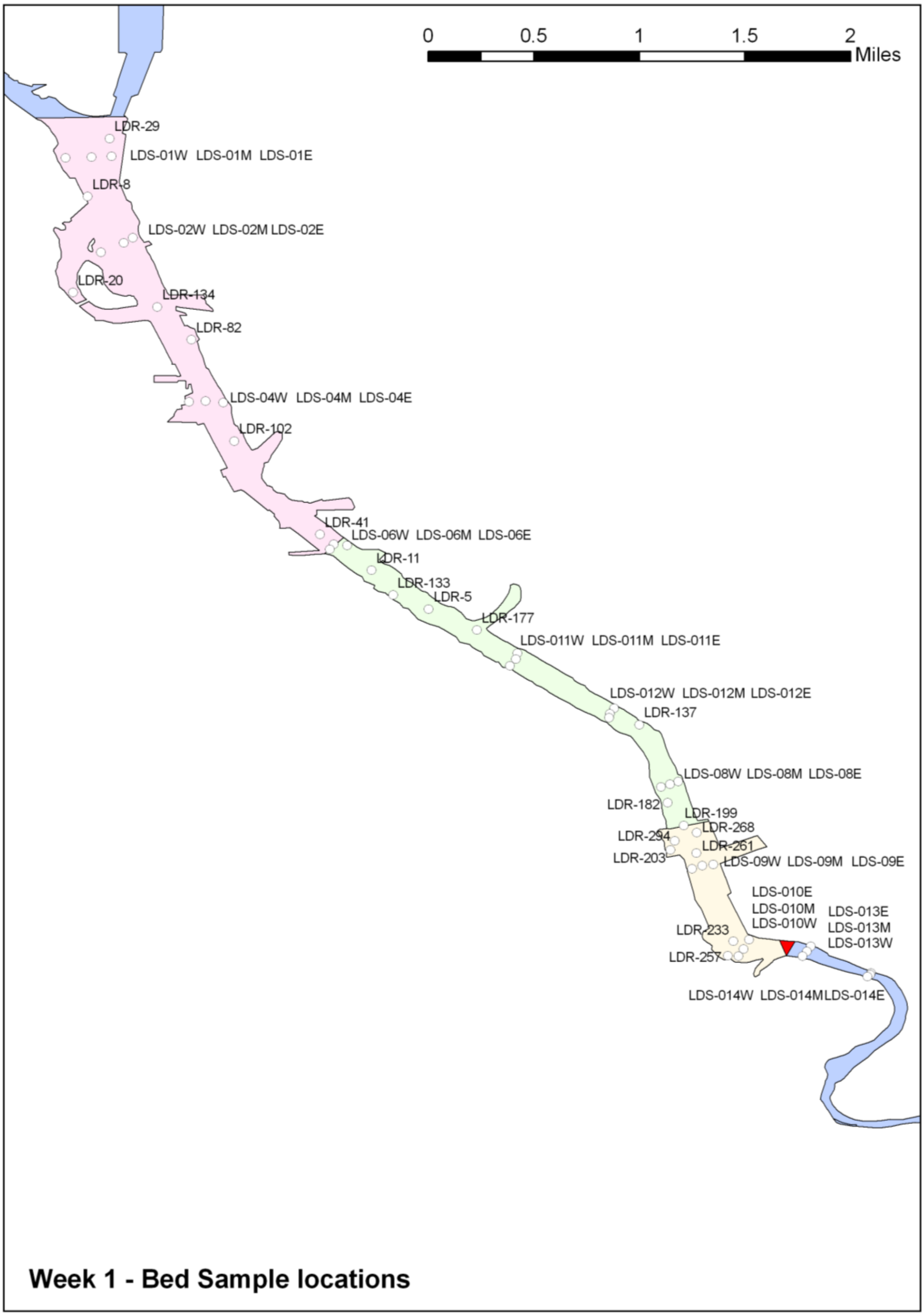

Figure 3 Bed sample locations (Week 1).

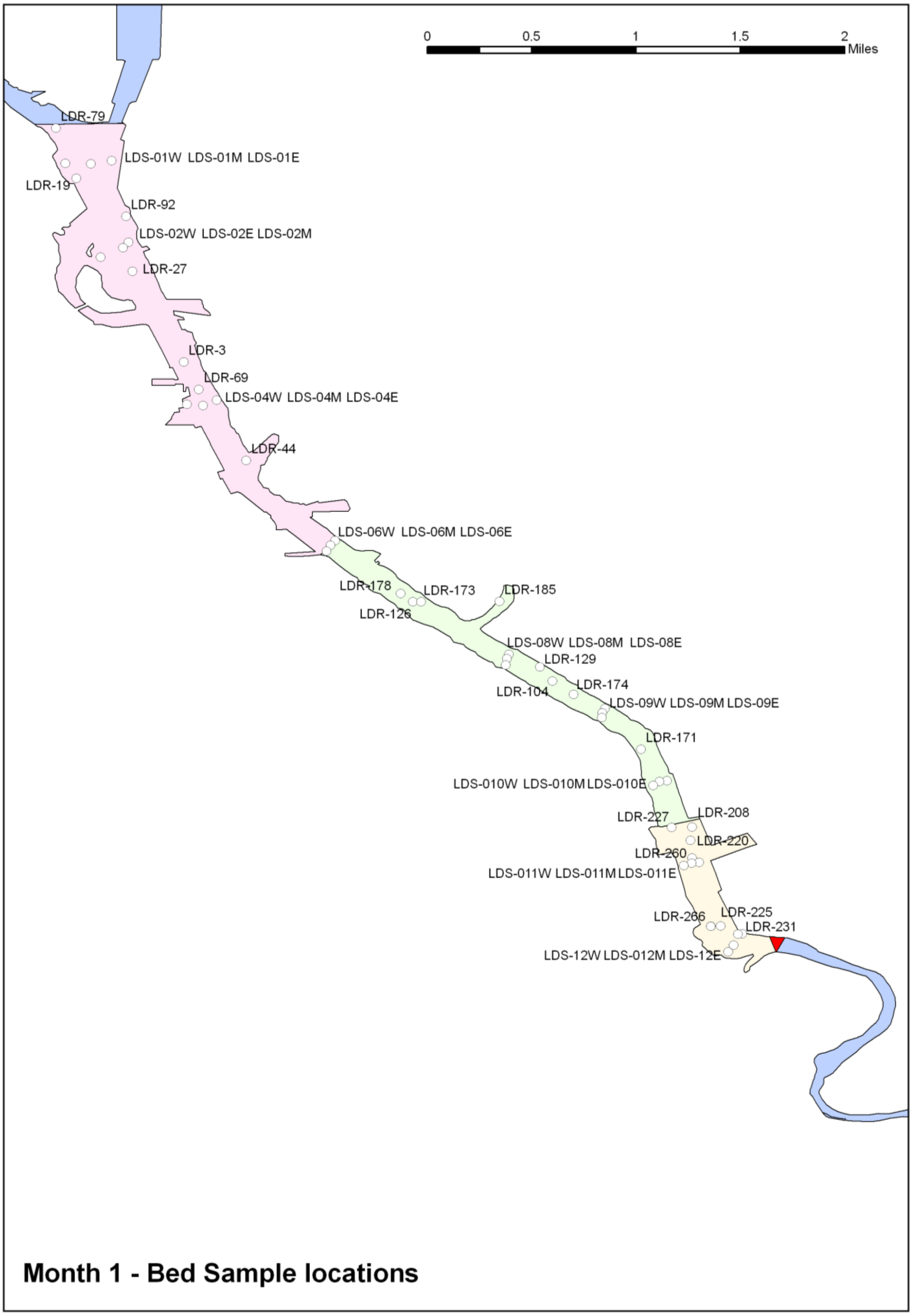

Figure 4 Bed sample locations (Month 1).

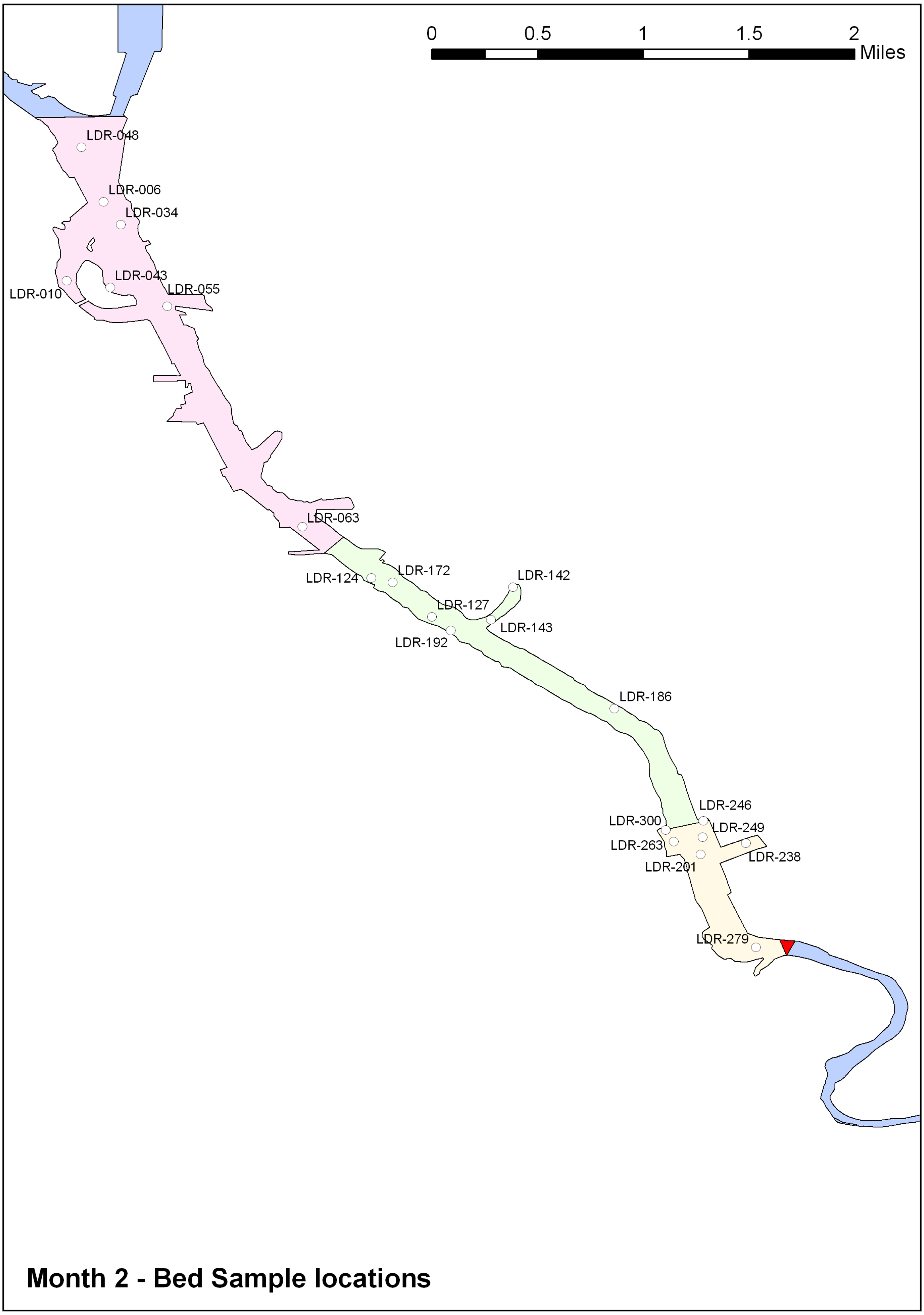

Figure 5 Bed sample locations (Month 2).

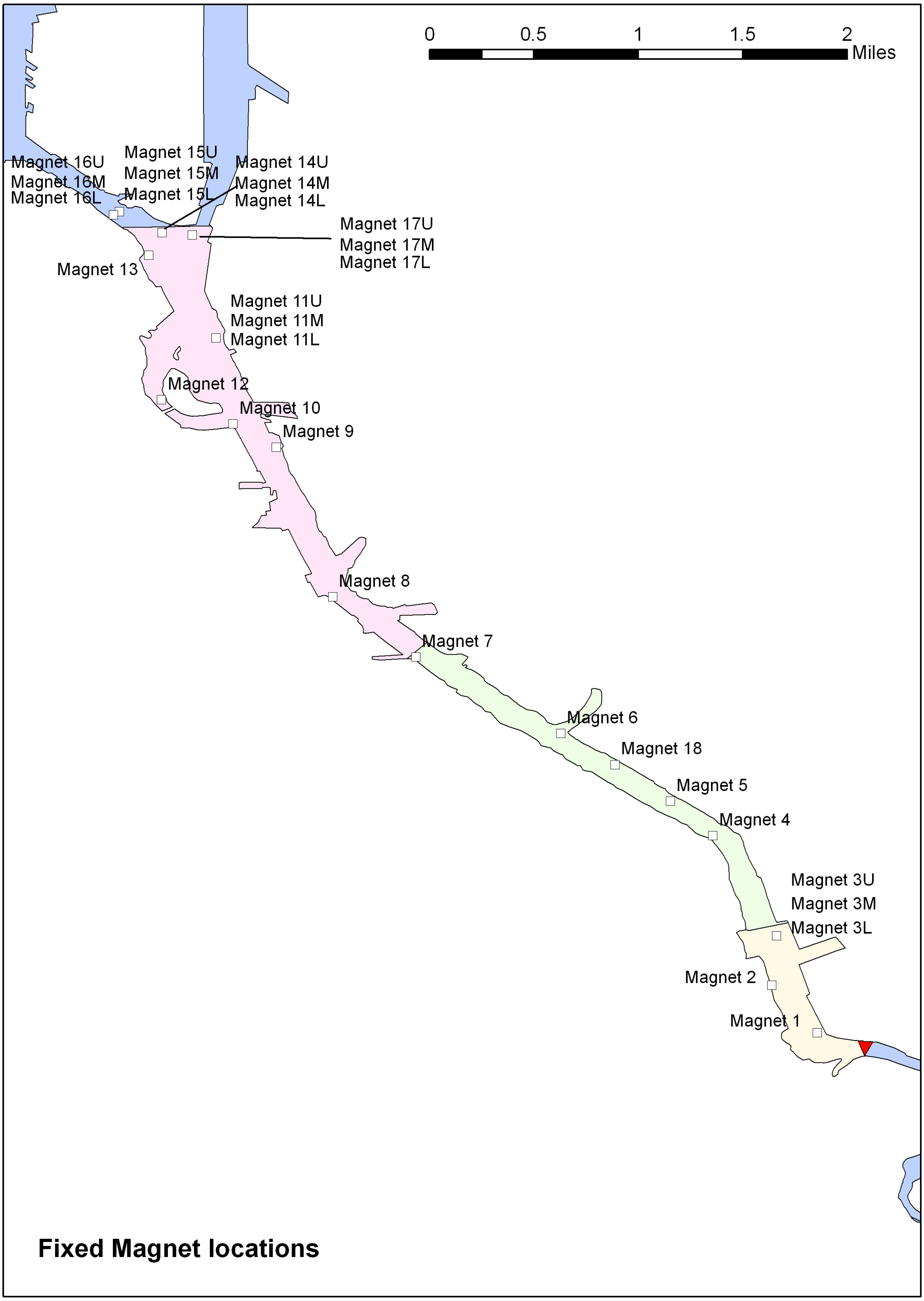

Figure 6 Fixed magnet locations. A complete suite of fixed magnets were sampled for Week 1 and Month 1; only magnets #15 and #16 were sampled during Month 2.

3. PREPARATION OF TRACER FOR RELEASE

The two tracer batches arrived in Ecology's premises in a series of aluminum drums (sand tracers) and reinforced boxes (silts tracers). Prior to release into the estuary each tracer batch needed to be pre-wetted and transferred into suitable containers which could then be loaded onto the deployment vessel (Fig. 7). Pre-wetting is necessary to ensure that each particle can pass into the water surface without surface tension effects (which rise in importance for finer grains) dominating the particle behavior; pre-wetting, in fact, would be a necessary interim step for dry mineral sediments being used in a similar context.

Pre-wetting was achieved by sequentially mixing ~10 kg quantities of tracer with freshwater mixed with a few drops of detergent; the detergent is the agent which disrupts the surface tension forces. The mixing procedure effectively produces a tracer-water 'paste' or 'slurry', and this is then decanted into cooler storage boxes (Fig. 7). Any supernatant water is drained off.

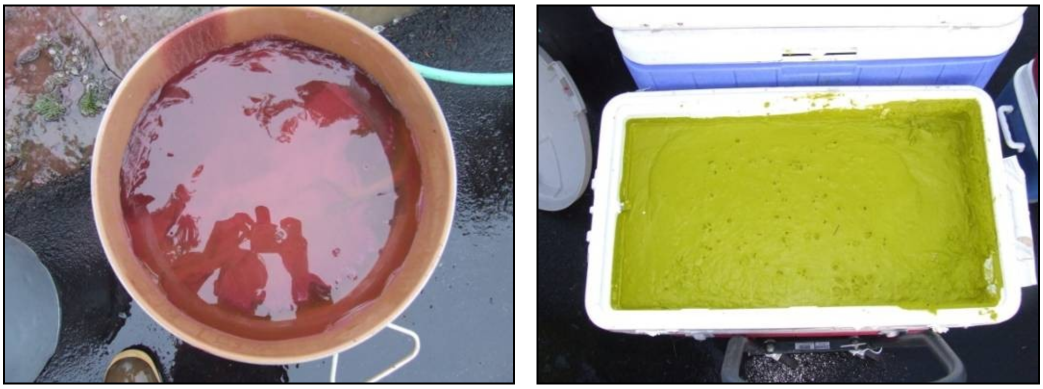

Figure 7 Plan view of both the sand (red) and silt (green) tracers in a cool-boxes following pre-wetting and prior to injection.

3.1 Field Injection of Tracer

The tracer was injected into the surface waters of the Lower Duwamish Waterway using one of Ecology's survey craft. On this, a funnel arrangement was rigged up at the vessel stern down which samples (scooped from each of the cooler boxes) could be flushed (Fig. 8); low- and high-flow hoses were available to flush the tracer material down the chute. The tracer was introduced into the water at a depth of ~0.3 to 0.5 m beneath the surface. Visual observations of the water during tracer injection indicated the formation of a submerged, diffusive plume which was advected downstream by the river/tidal flow (Fig. 9). All the silt tracer (160 kg) was introduced first, followed by the sand tracer (93 kg)[2].

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[2] Note the sand quantity contained up to 7 kg of particles <63 μm in size, although some of this mass was inevitably lost during the tracer preparation.

Figure 8 Photograph showing the method of introduction of tracer. The tracer is scooped from the cooler boxes and flushed down the tube using a low-flow hose; tracer enters the water sub-surface.

Figure 9 Photograph of the sub-surface plume of silt tracer formed during injection of the tracer material.

Figure 2 shows the location within the Lower Duwamish Waterway where the tracer was introduced (shown as a red area on the map).

4. FIELD SAMPLING[3]

4.1 Field Sampling and Tracer Recovery

4.1.1 Water Column Sampling

4.1.1.1 Filters

Procedures for the recovery of tracers suspended in the water column close to the release area were based on use of a filtration methodology following SOP EAP041 (*Collecting freshwater suspended particulate matter using In-Line filtration*). For this study deviation occurred from this SOP in that no decontamination was conducted. During these filter sampling efforts water samples for total suspended solids (TSS) were also collected. TSS was analyzed using EPA Method 2540D. A similar sampling procedure was undertaken for tracers downstream (RM 0.0-2.2), however a 9 mm Buchner funnel was used with a 8 µm pore size filter in place of an in-line apparatus. Filter samples were collected before, during, and after release of tracers on Day 0.

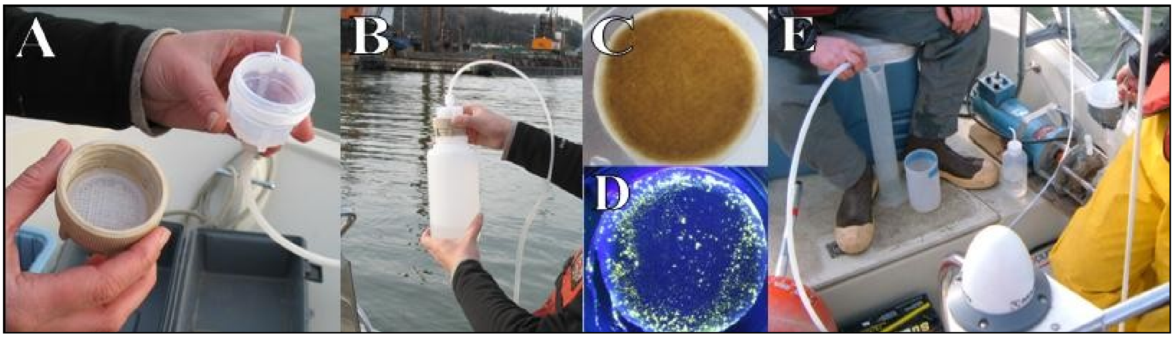

Figure 10 Images of filter sampling: A) In-line filter apparatus, B) In-line filter during sampling, C) In-line filter under normal light,

D) In-line filter under fluorescent light, and E) Buchner funnel filter set-up (images courtesy of Ecology).

4.1.1.2 Magnets

During the release powerful 11,000 gauss pole magnets encapsulated in a clear plastic sheath suspended from a rope (referred to as 'dipped' magnets) were dragged through the water near RM 0 to act as water column samplers. Magnet GPS start and end, time and depth in water were recorded. Material (tracer, natural suspended magnetic particles) adhering to the magnet were collected by removing the magnet, carefully sliding the plastic sheath off, and carefully rinsing the sheath into a container or placing the whole sheath into a bag. The sheath was inspected for residual sediment and replaced if acceptable.

Fixed-location magnet sampling devices were mounted in the Lower Duwamish Waterway prior to tracer release (Fig. 10). Blank/background samples were collected from four magnets before the tracer was released. Fixed magnet samples were collected, using the same methods as the dip-magnets, at Week 1, and again at Month 1. Two magnets samplers with three magnets each were left in place and collected at Month 2 (Table 2 and 11).

---

[3] Modified from Ecology report.

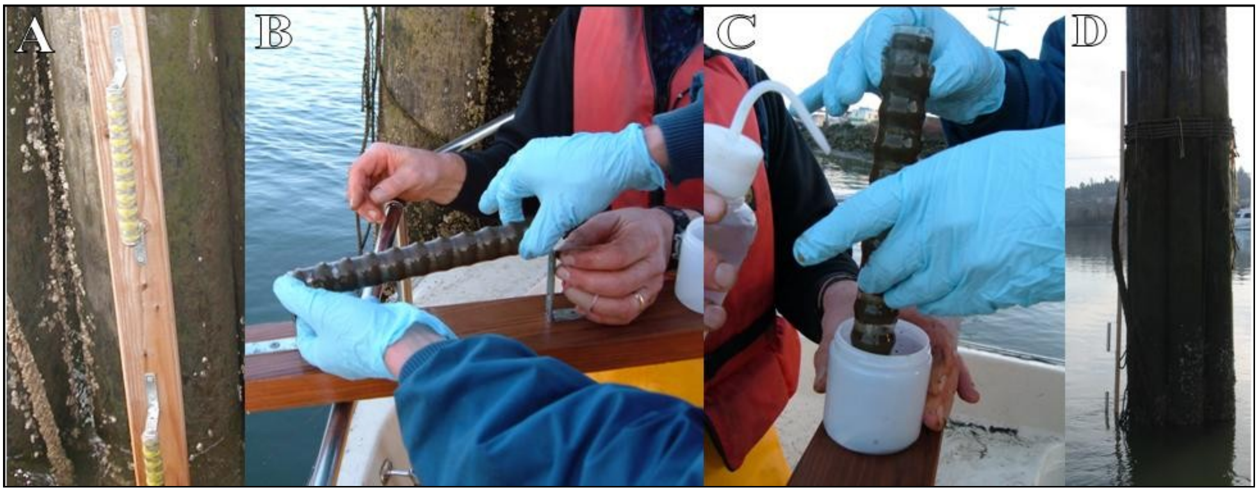

Figure 11 Magnet sampling images: A) Bar magnets mounted to a piling with visible yellow silt tracer, B) Removing the plastic sheath from magnet, C) Rinsing sheath into a plastic jar, D) Magnets mounted on piling (images courtesy of Ecology).

4.1.2 Sediment Sampling

Collection of bedded sediment samples occurred 1 week, 1 month, and 2 months post release. Two additional samples were collected near Kellogg Island prior to release to be used for quality control sediments. Procedures outlined in SOP EAP040 were followed for Ekman, petite ponar, standard ponar, and single Van Veen sediment grabs. The choice of sampling method depended on water depth, boat configuration, and bottom substrata. Similar to the filter sample methodology, pre-sampling cleaning was not conducted. Sampling gear was cleaned with brush and copious amounts of site water between sampling locations in order to avoid cross-contamination.

Overlying water was collected from several sediment grabs. Magnetic particles were removed from the water using a bar magnet, until no further magnetic particles were recovered. These samples were then qualitatively examined for the presence of tracer particle. Concentrated overlaying water samples from Month 2 sampling efforts were added to their corresponding sediment sample (Table 1).

Table 1 Summary tabulation of sediment samples for which there was minimal loss of sediment due to overlaying water collection or de-watering

Collection Date	Samples collected from the intertidal zone, above water line	Overlaying water collected, concentrated and added to sediment samples
April 7th, 2009	LDR-010 LDR-043	LDR-246 LDR-249
April 10th, 2009		LDR-186 LDR-238 LDR-127 LDR-172 LDR-048

i) Subjective Grabs. Transects perpendicular to the axial estuarine flow and approximately 0.4 miles apart were sampled during both the Week 1 and Month 1 sampling periods. Three samples were collected from each selected transect, M, E, and W. Not all transects were sampled due to sample number constraints, however the same transects were sampled for the Week 1 and Month 1 recovery efforts (Table 4 and Figures 3 and 4).

ii) Random Grabs. A 'create random points' tool (within ArcGIS, ESRI) was used to place 100 random points in each of the three reaches. Seven of these points were randomly selected from each reach and sampled, and no location was sampled more than once (Table 2 and Figures 3, 4 and 5).

Table 2 Water column and sediment sample collection schedule. The total sample count is 229.

Period	Sampling Dates	Magnet	Filter Samples	Subjective sediment samples (LDS)	Random sediment samples (LDR)	QC samples
Pre and during deployment	2/12; 2/13	4				
Day 0		7 dipped	20			
Week 1	2/17; 2/18; 2/19	30		33	20	
Month 1	09/03; 11/03; 12/03; 16/03	32		27	23	3
Month 2	4/7; 4/10	6		0	21	3
Totals		**79**	**20**	**60**	**64**	**6**

5. SAMPLE PROCESSING

5.1 Introduction and Sample Login QA

Samples were collected by Ecology staff, sealed in appropriate sampling vessels (pots, bags) and posted to Partrac's offices. Shipments were received according to five discrete field sampling campaigns (Table 3).

Table 3 Summary of sample numbers/type received and processed, with notes. Note there are no bedded samples from the injection day (2/13/09).

Period	Sampling Dates	Magnet	Filter Samples	Subjective sediment samples (LDS)	Random sediment samples (LDR)	QC	Notes
Pre and during deployment	2/12; 2/13	4					Magnets 1, 5, 9, 15 blank
Day 0		7 dipped	20				And 20 filtered samples
Week 1	2/17; 2/18; 2/19	30		33	20		Magnet 8 U,M,L reported as one sample
Month 1	09/03; 11/03; 12/03; 16/03	32		27	23	3	LDR-270 – no sample
Month 2	4/7; 4/10	6		0	21	3	
Totals		**79**	**20**	**60**	**64**	**6**	**229**

Upon arrival of each shipment, the cooler box[es] delivery was recorded in a delivery file (digital). If there were prior samples being processed in the laboratory the box was kept separately and not opened until existing samples were sent for processing and the laboratory cleaned (a process verified using a UV lamp to inspect work surfaces and utensils). At the appropriate time the box was opened and individual samples crossed-checked with the enclosed inventory, and recorded as received to a separate digital file. Samples were then labelled with a unique (random) number and immediately stored in a refrigerator at 4 °C until they were processed.

5.2 Analytical Methods for Sample Processing

Many samples, namely those representing bedded (deposited) sediments, required pre-processing in order to extract the magnetic tracer grains. For *in situ* magnets the magnetic separation process is already accomplished, and for filter papers a methodology involving direct examination with no separation was used.

5.2.1 Bedded Samples

Bedded samples were initially rinsed through a 500 μm sieve to remove macro-detritus and coarse sediment grains. The resultant slurry was then flushed through a commercial, static magnetic particle separator (MPS; following generally the methodology of Hillier and Hodson, 1997); this instantly separates magnetic material, which is retained within the MPS, from non-magnetic material, which is flushed into a container below. The non-magnetic residue was consecutively re-introduced into the MPS until no further magnetic separation was evident. The magnetic fraction was retrieved from the MPS (this is achieved by physically removing a wire wool mesh onto which the grain are attached), and the material washed using minimal fresh water into a labelled sample pot. Every effort was made to thoroughly clean the MPS between samples, and visual checks were made periodically using a UV lamp.

Computation of tracer mass must also take into account the efficiency of the magnetic separation process. For bedded samples, the separation efficiency (β) of the MPS was established for differing ratios of tracer content (mass tracer to mass non-tracer, ratio from 0.0001 to 0.1) and found to be 98.1%. This factor was integrated into tracer mass calculations for bedded samples.

5.2.2 *In Situ* Magnets

For *in situ* magnets where the magnetic particle separation is already achieved in the field minimal sample pre-processing was necessary. Samples were initially rinsed through a 350 μm sieve to remove macro-detritus and coarse sediment grains. The coarse fraction was discarded. The magnetic fraction was then re-processed using the MPS in the manner described above. Although the *in situ* magnets are sufficiently powerful to retain magnetic particles, this was performed largely as it proved the simplest means of removing adhering non-magnetic fine material i.e. this was a sample cleaning step. Following flushing through the MPS the material was washed using minimal fresh water into a labelled sample pot.

Filter papers were not pre-processed using the MPS. The filter papers were simply stored in the refrigerator until they were processed using image analysis.

5.2.3 Image Analysis using a Fluorescence Microscope

The methodology deployed in this study derives tracer mass per unit length/time-scale, however the presence of overlapping size distributions for the sand and silt tracers, and the presence of non-fluorescent magnetic material in the estuary waters, means that it is necessary to undertake an image analysis step to provide a tracer mass.

Image analysis was undertaken using a Zeiss™ fluorescent microscope using appropriate excitation and emission filters. Excepting the filter paper samples, samples were first thoroughly homogenised using a glass stirring rod; a sub-sample was then collected and dispersed into a small haemocytometer counting chamber equipped with a graticule for particle size measurement. 300 particles were counted for each sample, and the number and size of respective tracer grains (both colours where necessary) and the number only of non-tracer (i.e. natural magnetic fraction) grains was determined. Figure 12 gives examples of the microscope view of three discrete silt tracer grains under ambient light and following application of the appropriate emission filter.

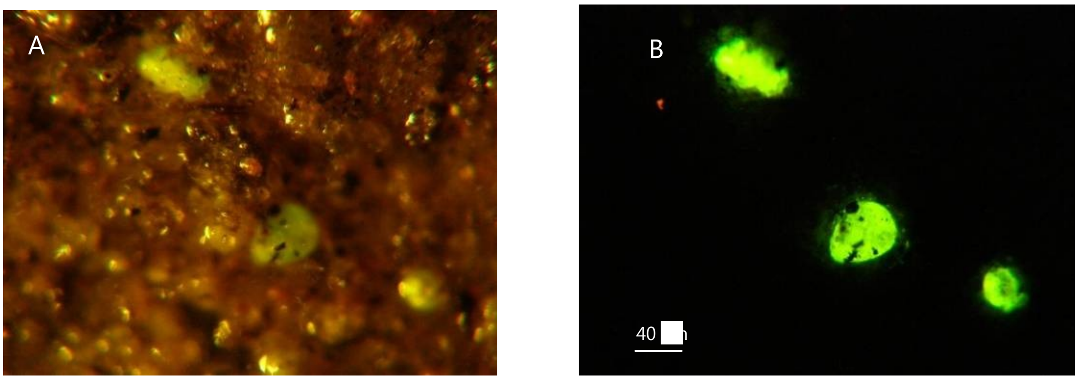

Figure 12 Close-up photomicrographs of silt tracer admixed with a natural magnetic fraction showing the field of view A) before and B) after application of emission filters.

Tracer size was recorded as the lengths of the short and long axes; these values were transformed to a mean particle size (where more than one particle is observed, the mean diameter of each particle is determined and the data presented in terms of the size range encompassed by these determinations). The sub-sample was then recovered, dried (at 105°C for 24 hours) and weighed. The dry mass of the parent sample was also dried at 105°C for 24 hours and weighed.

5.2.4 Filter Paper Methodology

An example of a filter paper obtained during the field study is given in Figure 13 (further photographs may be found in Appendix 2). Upon receipt at the laboratory it was clear that there would be no way of separating the tracer from the filter paper effectively, and therefore a method was devised (in conjunction with Ecology) to quantify the tracer present on the surface. Random locations on the filter paper surface amounting to 10% of the surface area were selected (this was measured using a lens mounted graticule); within each of these the number and size of tracer particles was determined. This value was then multiplied up to give a tracer particle number for the filter paper. All filter papers (both large and small) have been treated in this manner. Although inclusive of very fine mineral grains (which can be seen embedded in the pores of the filter paper but for which the mass cannot be accounted), the filter paper dry mass was also recorded.

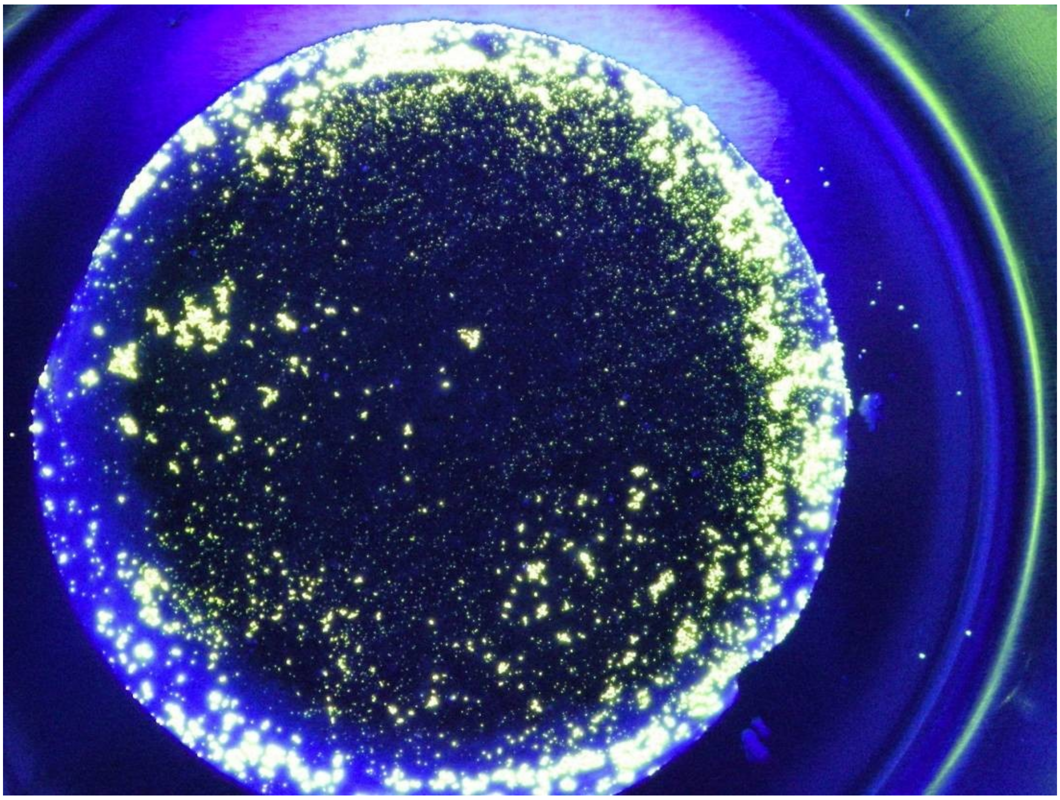

Figure 13 Illuminated fluorescence macro-image of the surface of a filter paper (sample P5511) showing abundant silt tracer. Note that good quality photographic images were only possible when the tracer abundance was high.

5.2.5 Derivation of Tracer Mass

The analytical procedure above provides the ratio of tracer to non-tracer particles in the sub-sample. The tracer size, numerical abundance and dry mass values are combined with measured tracer density values (1210 kg m^{-3} for silt, and 2512 kg m^{-3} for sand) to produce a tracer mass. The flow-chart in Figure 12 summarizes the calculation method the data normalization procedure is discussed below). Analysis of four samples (acid-washed local estuary mud, d_{50}~35 μm spiked with a known mass of [silt] tracer particles and processed as described) indicates that the estimated tracer mass derived from image analysis under-estimates the actual mass and requires a multiplication to give a correct tracer mass (

Table 4). The factor is 2.207. Note the fundamental units of tracer mass are simply **g** (rather than a content value i.e. g g^{-1} dry weight, or a concentration e.g. g l^{-1}).

Table 4 Summary of data from mass estimates derived from image analysis from known (spiked) samples.

Internal QC Sample #	Spiked Tracer Mass (g)	Predicted Mass from Sub-Sample (g)	Spike Mass (g)/Sub-Sample Mass
1	0.001000	0.000401	2.493766
2	0.001000	0.000455	2.197802
3	0.001000	0.000470	2.127660
4	0.001000	0.000498	2.008032

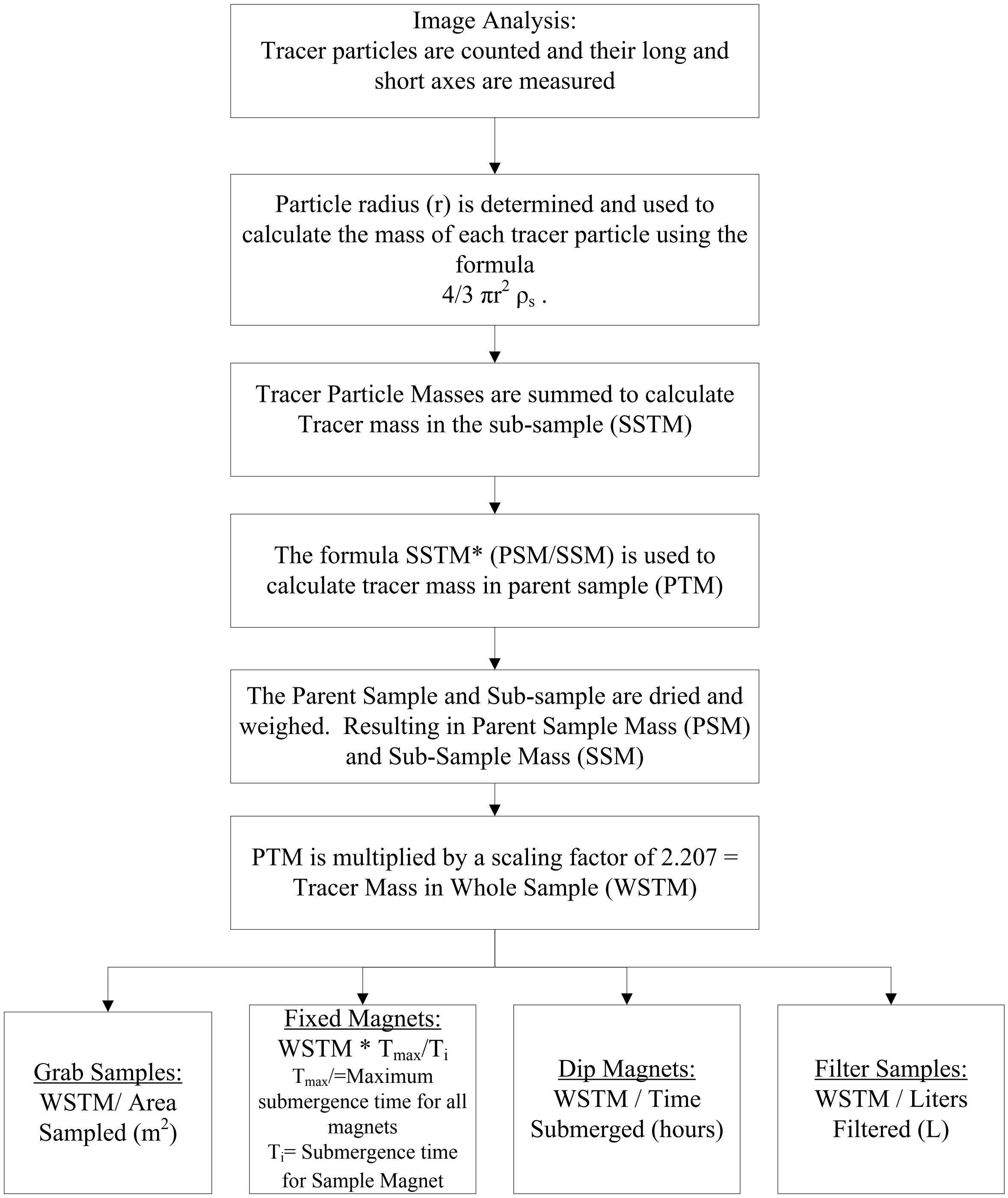

Figure 14 Calculation methodology from image analysis to normalized data (r is (grain long axis+ grain short axis)/2; ρ_s is the sediment density).

5.2.6 Data Normalization

The following normalizations to the raw data have been applied:

- for bedded samples, tracer mass has been expressed per unit area (i.e. square meter; $/m^2$);
- for fixed passive magnet samples, which have differing submergence periods, tracer masses have been adjusted by the ratio $\frac{T_{\max}}{T_i}$ where T_{max} is the maximum submergence duration of any magnet during a specific sampling period (e.g. Week 1, Month 1, Month 2), and T_i is the submergence period for a specific magnet for the same sampling period (i.e. T_i is always less than T_{max}). This approach was agreed with Ecology;
- for dipped magnets the tracer mass has been normalized to the duration of the tow; and
- for filter paper samples tracer mass is expressed per unit volume (i.e. per litre of water sampled).

Tracer size data is given either as a discrete value or as a range of particle sizes present. Complete size data for recovered tracers are in the attached file P1062.03.03.D004v01 - Results (particle sizes).xls.

5.3 Quality Control and Quality Assurance

5.3.1 Image Analysis Sampling Variability Assessment

With the image analysis methodology, it is necessary to sub-sample the parent sample (which comprises only tracer and naturally magnetic material). In spite of efforts to fully homogenize samples, there is a degree of variability associated with the sub-sampling process. This was investigated using real samples collected from the estuary. Ten consecutive (duplicate) sub-samples were sampled from the following real samples: LDS-09W (12/03/09), LDS-10E (18/02/09), LDS-14M (19/02/09), LDR-10 (07/04/09). The results reveal values for the co-efficient of variation ranging from 45% to 86%. Thus, quoted values for tracer mass prior to normalization possess this (natural) range of variability and these percentage error bars can be placed on the dataset.

The testing of these samples also indicates that the probability of detecting tracer is ~81% i.e. for ten attempts to measure/detect tracer, on average two attempts will give non-positive tracer identifications.

5.3.2 Ecology Analytical Blanks

Table 5 QC blanks, data summary. Shaded areas for blue and green indicate QC blanks prepared on a mass percentage basis; those in pink and yellow indicate QC blanks prepared on a particle number concentration basis.

QC Type	Sample #	Tracer	Dry Weight of Tracer Added (g)	Sediment Estimated Dry Weight (g)	Tracer Mass from Image Analysis (g)
Sediment Blank	LDR-282		None added	35.8002	0.000000
Sediment Blank	LDR-009			27.2862	0.000000
Matrix (Sediment) Spike	LDR-56	Silt	0.0203	36.1559	0.047785
		Sand	0.0783		0.138447
Matrix Spike	LDR-264	Silt	0.013	27.3499	0.041475
		Sand	0.1062		0.0000000
			No. of Particles		
Matrix Spike	LDR-195	Silt	185	36.2660	0.0000000
		Sand	147		0.0000000
Matrix Spike	LDR-130	Silt	151	54.0334	0.0000000
		Sand	92		0.0000000
Filter blanks	PP513				No tracer found
	WM-01	Likely deployed during tracer release			Silt tracer found
	WM-02				Silt tracer found
Magnet blanks					
(see Table 7)	M1		N/A	N/A	No tracer found
	M5				No tracer found
	M9				No tracer found
	M15				No tracer found

The inter-comparison of analytical results with QC blanks for bedded samples, fixed magnets, and filtration samples is presented in Table 5. Sample types for which no tracer was added and none was found are for bedded sediment (LDR-282, LDR-009), for the filter blank PP513, and all the fixed magnet blanks (M1, M5, M9, and M15). Thus, there were no false positive results. The gain in mass for PP5513 was 0.00788 g l^{-1}, and this is placed in the context of all filter paper samples more generally in Table 6.

Comparison of data derived from the image analysis of samples with deliberately spiked samples can be considered in two lots. For QC samples compiled by addition of a known (dry) mass of tracer, the analysis indicates an over-estimation by approximately a factor of ~1.6 to 2 (for LDR-56) to ~3.2 (for LDR-264).

A comparison based upon number concentration (i.e. where the tracer blanks were prepared by adding a known number of silt and sand tracer particles to sediment) the analysis did not detect tracer presence. Note that the bedded sample blanks were prepared using between ~27 and 54 g of dry sediment.

Dipped magnet blanks were prepared (WM-01 and WM-02) but silt tracer was reported for each of these samples. However, Ecology has indicated that these blanks appear to have been prepared too close in time to the injection of silt tracer as to be coincident with tracer introduction.

Table 6 Summary of mass concentrations of filter papers in comparison to blank value (in yellow). Values in green represent single samples for which the blank exceeds the data value.

Location	Sample Code	TSS Concentration ($g\ l^{-1}$)
Filtered (u/s)	P5501	0.01115
Filtered (u/s)	P5502	0.00975
Filtered (u/s)	P5503	0.01012
Filtered (u/s)	P5504	0.00867
Filtered (u/s)	P5505	0.00738
Filtered (u/s)	P5506	0.00876
Filtered (u/s)	P5508	0.01830
Filtered (u/s)	P5509	0.00857
Filtered (u/s)	P5510	0.00742
Filtered (u/s)	P5511	0.00863
Filtered (u/s)	P5512	0.00677
Filtered (u/s)	P5513	0.00788
Filtered (d/s)	WW01	0.01920
Filtered (d/s)	WW02	0.00448
Filtered (d/s)	WW03	0.00374
Filtered (d/s)	WW04	0.03131
Filtered (d/s)	WW05	0.00500
Filtered (d/s)	WW06	0.03198
Filtered (d/s)	WW07	0.00306
	Average	**0.01117***

*** Not including blank value**

5.3.3 Fixed Magnet Blanks

The Week 1 magnets used to collect samples of suspended tracer material were fixed in place within the estuary prior to the release of tracer. The direct consequence of this is that these magnets potentially accumulated naturally occurring suspended magnetic particles during the period prior to the release of the tracer (subsequent sampling periods started with clean magnets and for these this is not an issue). Use of the parent sample mass in calculations to derive adhering tracer mass is not straightforward for Week 1 magnets, since a proportion of the parent sample mass could have accumulated before the tracer release. A correction is thus necessary to adjust measured parent sample masses for this occurrence.

Four blank fixed magnets were deployed in advance of the study (Table 7), and these can be used to implement this adjustment since the dry mass on these magnets represents adherence/capture of natural magnetic particles suspended in the estuary water due to natural processes. There is generally a decrease in the quantity of naturally magnetic particles captured by the blank magnets with distance downstream (Table 7). In order to provide a correction across all the Week 1 fixed magnet data an equation has been derived using the four blank magnets only, which predicts the background natural magnetic mass (expressed as g day^{-1}) versus distance down the estuary:

$$y = 0.0454x^2 - 0.1331x + 0.2005 \qquad r^2=0.9175 \qquad 1.$$

where y is the accumulated dry weight of magnetic particles (g day^{-1}) and x is the river mile distance. Equation 1 is used to generate values for the theoretical accumulation of natural suspended magnetic particles within the estuary for each magnet deployed during Week 1. These values were then subtracted from the measured parent sample masses for each of the magnets recovered during Week 1 sampling. Note that application of this equation to the Week 1 fixed magnet data-set give results for tracer mass values of zero for the following magnets: #15U&M; 16 U&M&L; 17U&L, i.e. the theoretical accumulated mass was greater than the recorded parent sample mass.

Table 7 Summary of accumulated dry mass of natural magnetic particles on four blank fixed magnets.

Blank	River Mile	Accumulated Dry Weight of Natural Magnetic Particles (g)	Time Submerged (days)
M1	4.5	4.038	7.44
M5	3.3	1.184	7.42
M9	1.1	1.296	7.43
M15U	0	0.937	4.99
M		(single composite value)	5.59
L			6.05

5.4 Standard Analytical Methods for Particle Attributes (Size Distribution, Settling Velocity and Density)

The analytical procedures for the above sedimentological attributes followed standard (published) internationally recognized methods (Table 8; Appendix 4). For measures such fluorescence character/identification, we followed the method of Herman and Tanke (1998). For magnetic separation we used the method of Hillier and Hodson (1997). Further details of these analytical methodologies and their application is presented in the report P1062.05.D001v03 - Native Sediment and Tracer Characterisation Report.pdf.

Table 8 Summary of the primary reference material and standard methodologies used in this study.

Parameter	Silts <63 µm	Sands >63 µm
Particle Size Distribution	Coulter LS230 with PIDS BS / ISO 13320-1:1999	Conventional Sedimentation Tower : ISO 11277 (1998)
Settling Velocity	Conventional Sedimentation Tower with OBS. Method followed was that outlined in Whitehouse, R.W., Soulsby, R., Roberts, W., and Mitchener, H., (1997) Dynamics of Estuarine Muds. Telford, 209pp	Conventional Sedimentation Tower Method followed was that outlined in Soulsby, R., (1997) Dynamics of Marine Sands. Telford, 249pp.
Density	Volumetric Method ISO/TS 17892-3; 2004	Volumetric Method ISO/TS 17892-3; 2004
Natural Fluorescence	Standard fluorescent microscope guidance (e.g. Herman, B., and Tanke, H. J., 1998 Fluorescence Microscopy (Microscopy Handbooks) Springer, 170pp)	
Natural Magnetics	Flow-through magnetic particle separator, magnetic fraction weighed and analyzed with Coulter LS230 with PIDS or light microscopy; Reference Hillier, S., and M. E. Hodson 1997 High-gradient magnetic separation applied to sand-size particles; an example of feldspar separation from mafic minerals. Journal of Sedimentary Research; v. 67; no. 5; p. 975-977.	

5.4.1 Measurement Quality Objectives (MQO)

<u>Statistical Indices</u>:— The expected sensitivity, precision, bias and accuracy of the above methods was specified in the contractual MQO document by Ecology. Quantitative experimental data exists in relation to density measurement and for particle size distribution. However, for settling velocity single runs on single samples only were conducted, which means that an assessment of precision and bias cannot be made. Further, there are to our knowledge no certified reference materials available within sedimentology with which to ascertain the accuracy of the measurement, although the sensitivity (~0.1) is known. What can be performed is a comparison of the data (given knowledge of the size) with standard textbook representations of the size-settling velocity relationship (e.g. Soulsby, 1997, p. 137), and to do so provides a positive view that the data are reasonable. Generally, where quantitative estimates are available the analytical methods exceed the MQOs.

The MQO also prescribes limitations on derived quantities such as number of tracer particles per litre, number of tracer particles per m^2, and tracer mass per m^2. The information presented in Sections 5.2 and 5.3 encompass this. The sensitivity of the mass derivation is of the order 0.01 mg (m^{-2}). The coefficient of variation expresses the variation encountered during consecutive (duplicate) sub-sampling, and this is rather higher than specified (45% to 86%) but is to be expected within an estuary sediment sub-sampling protocol (the same would likely be true for organic content or chlorophyll content). Withdrawal of duplicate sub-samples produces no consistent directional bias. Finally, a numerical adjustment (2.207) of the tracer mass from image analysis is necessary in order to derive an accurate value for the mass in the parent sample, and gives the accuracy as presented.

A tabulation of the specified MQOs together with experimentally determined values is given in Appendix 1.

Summary of Hydraulic Similarity Analysis:— Assessment of the hydraulic similarity is the process where the hydraulic properties of the manufactured tracer sediments (which are a function of physical attributes such as size and density) are compared to those of native sediments. Table 9 summarizes the similarity comparison. The density similarity is expressed as the ratio of the specified density (1200 kg m^{-3} for silts, 2600 kg m^{-3} for sands) to that determined on a batch of the tracer and values close to unity reflect a high quality matching. In order to define required particle sizes for the tracking study, numerous bedded samples were analyzed. These tests showed that the sand fraction comprises dominantly fine sand for most samples processed, with occasional samples comprising very fine to medium sand. The silt fraction comprises fine skewed (i.e. towards the coarse end of the spectrum), poorly sorted medium to coarse silts. These data formed the basis for commissioning tracer. Inspection of the percentile indices (d_{10}, d_{50} and d_{90}) show that the sand tracer is largely within the prescribed very fine sand to fine sand range (63 to 250 μm), although a detailed inspection of the particle size distribution indicated a fine tail (with some grains <63 μm present). By mass this constituted ~7 kg (from 100 kg). For the silts, the size range is largely similar to the native estuary silts, and skewed to the coarse end of the spectrum like many of the bedded samples tested. However, a proportion of the tracer particle sizes are >63 μm. Settling velocity similarity is summarized in terms of the *range of settling velocities* measured on native sediments and that measured on the tracer batches. For sands the range of settling velocities for the sand tracer is within that for the native sand tested, indicating a good quality hydraulic matching. The silt tracer was defined by the tests as a coarse-very coarse silt (admixed with medium and fine-very fine component fractions), and although this was rather coarser than desired, nonetheless the settling velocity spectrum of the tracer was within the envelope of that characteristic of estuary silts. For an in depth description of this issue, refer to P1062.05.D001v03 - Native Sediment and Tracer Characterisation Report.

Table 9 Summary of similarity analysis of silt and sand tracers with native sediment properties. Median grain size values are highlighted in red.

		Specified/Native Sediment	**Tracer**	**SNS/Tr**
Density (gcm^{-3})	Sand	2580	2512	1.03
	Silt	1200	1210	0.99
Settling velocity (ms^{-1})	Sand	0.006 to 0.040	0.002 to 0.029	N/A
	Silt	0.00013 to 0.00024 (Region B)	0.000037 to 0.001188	N/A
Grain Size (μm)	Sand	156 (d_{50})	73 (d_{10})-128(d_{50})-248(d_{90})	
	Silt	45 (d_{50})	21(d_{10})-50(d_{50})-79(d_{90})	

5.5 Dealing with Effective Particle Size

The method used in this study uses a reduced density particle to mimic the hydraulic behaviour of silts. It is regrettable that during manufacture of the silt tracer an over-size fraction was produced which, although in hydraulic terms represents a coarse silt component (see P1062.05.D001v03 - Native

Sediment and Tracer Characterisation Report for further details), gives rise to particles which are >63 μm in size. This may appear confusing to other readers. It is possible to compute an 'equivalent' particle size for these larger (and indeed all) the silt tracer particles were they of a density of 2500 kg m^{-3} rather than 1200 kg m^{-3} using the equation of Soulsby (1997):

$$\omega = \frac{\nu}{d}\left[(10.36^2 + .049D_*^3)^{1/2} - 0.36\right] \qquad (1)$$

Where

$D_* = \left[\frac{g(s-)}{\nu}\right]^{1/3} d_{50}$, and g is the acceleration due to gravity, s is the submerged density (the density of sediment [2500 kg m^{-3}] divided by the density of seawater [1026 kg m^{-3}]), ν is the kinematic viscosity (1.36*10^{-6} m^2 s^{-1}) and d_{50} is the mean grain diameter (mm).

Figure 15 shows the results of this analysis. From the regression equation presented it is possible to convert over-size silt tracer particles to equivalent grain sizes for subsequent consideration. It is important to note that this is a theoretical approach which does not entirely reflect the true case for silt transport in the environment (as they are frequently associated with organic material and micro-biota) but is suitable for present purposes where significant tracer dispersion has occurred.

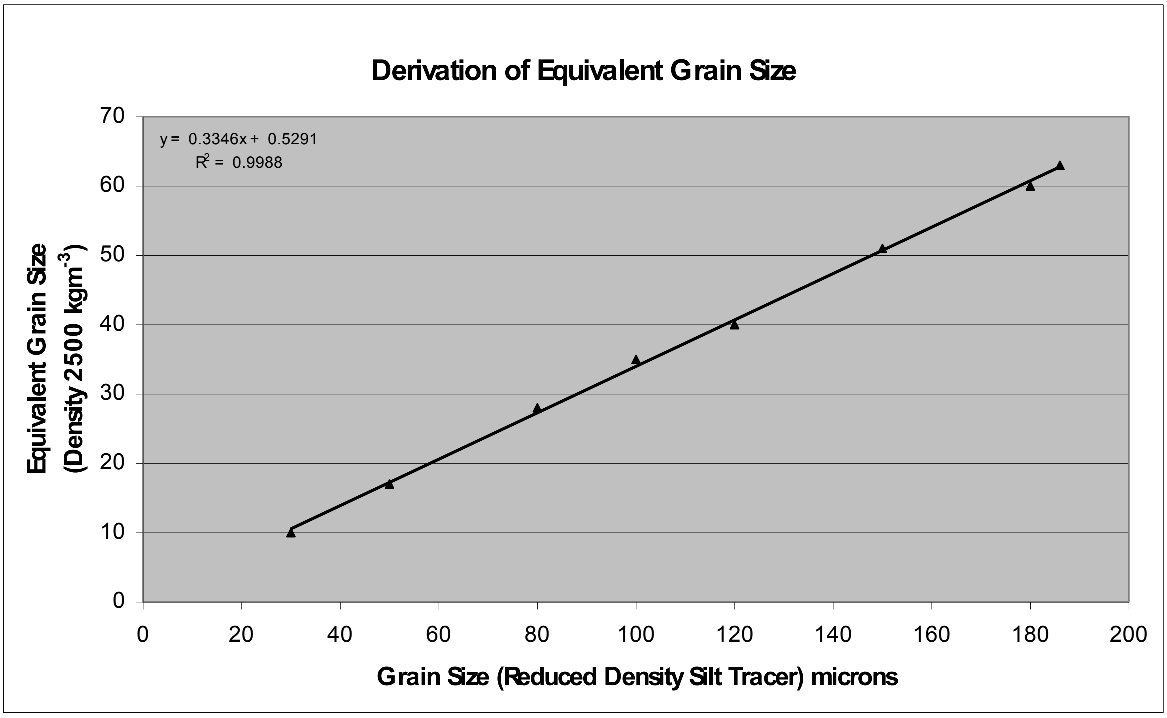

Figure 15 Graphical representation of grain size equivalence for reduced density tracer and mineral density (2500 kg m^{-3}) grains.

5.6 Dealing with Under-Size Red (Sand) Tracer

It is known that due to the omission of pre-sieving during the tracer preparation stage there was a small fraction of silt size (i.e. <63 μm) red (sand) tracer. Much of this material was likely washed away during decanting procedures during tracer pre-wetting. However, inevitably some fine material was introduced into the Lower Duwamish Waterway during tracer injection. During the image analysis of captured tracer and mass associated with this specific fraction was carried over and added to the true silt (yellow) tracer (Table 10), which resolves this issue completely.

Sample	Date	Sample	Date
LDS-04E	02/17/09	Magnet 16L	02/19/09
LDS-04W	03/11/2009	Magnet 17U	02/19/09
LDS-011W	03/12/2009	Magnet 17M	02/19/09
LDS-09W	03/12/2009	Magnet 17L	02/19/09
LDR-225	03/12/2009	Magnet 18	02/19/09
LDR-231	03/16/09	Magnet 3M	03/09/2009
Magnet 3L	02/19/09	Magnet 7	03/09/2009
Magnet 3M	02/19/09	Magnet 16M	02/19/09
Magnet 3U	02/19/09	Magnet 16M	03/09/2009
Magnet 4	02/19/09	P5504	02/13/09

The data is submitted digitally in conjunction with this report (attached Excel spreadsheet P1062.03.03.D001v05 - Results ALL (Ecology).xls). In addition to this, all particle size data have been collated into a separate file and this is P1062.03.03.D004v01 - Results (particle sizes).xls. Parent mass sample masses were also supplied as a separate file (P1062.03.03.D006v01 – Parent sample weight.xls). Finally P1062.03.03D008v01 – Formulae for Ecology.xls. For Ecology to duplicate results a value of 0.05 g must be used for the sub-sample mass (see Fig. 14).

Table 10 Summary of sand tracer samples where particles <63 μm in size were found; samples masses for these samples were transferred to the yellow (silt) tracer masses.

Magnet 5	02/19/09	P5505	02/13/09
Magnet 6	02/19/09	P5506	02/13/09
Magnet 9M	02/19/09	WM-1	02/13/09
Magnet 15U	02/19/09	WM-4	02/13/09
Magnet 15M	02/19/09	WM-5	02/13/09
Magnet 16U	02/19/09		

5.7 General Data Considerations

The following aspects should be noted with respect to the dataset (Tables 11 and 12):

Table 11 Summary of notes in relation to the provided data set.

Sample Number	Notes	Solution
LDR-41	No grab area was reported	There is no normalized mass, but raw data is reported.
LDR-20	Analyzed as two separate samples	Tracer masses and grab areas have been summed and a single value reported.
LDR-266	Analyzed as two separate samples	Tracer masses and grab areas have been summed and a single value reported.
LDR-257	Comprised two pots and these were accidentally analyzed as two different samples	Tracer masses and grab areas have been summed and a single value reported.
LDR-270	No sample	Agreed
Magnet #1 (Month 1)	Sample lost	Agreed
Magnet #8 (Week 1)	Upper/middle/lower sub-samples were combined in error and analysed as one sample.	An average submergence time (provided by Ecology) was used.
Magnet #9 (Week 1 and Month 1)	Sample was split into upper-middle-lower by mistake and analysed as three samples	Tracer masses and grab areas have been summed and a single value reported.
Samples in Table 14	Cases where two samples from repeat grab deployments were combined and analyzed as a single sample.	For these samples the grab areas for each grab deployment have been summed, and a single tracer mass value is reported.
All	Any mass associated with silt-size (< 63 μm) red (sand) tracer was transferred (added) to that of the silt (yellow) tracer.	

Table 12 Summary of samples for which two samples from repeat grab deployments were combined and analysed as a single sample. For these samples the grab areas for each grab deployment have been summed.

Sample ID	Approx RM	Date	Time	Lat	Long	Depth m	Grab1	Grab2	Grab area	RPD	Containers?	Core	Water Samp	Comments	Combined grab area (m^2)
LDR-006	0.0-2.2	10/04/2009	13:03	47.563	122.347	10.1	32	20	0.064	5	1	Y	1		0.112
LDR-006	0.0-2.2	10/04/2009	13:14	47.563	122.347	10.3	32	15	0.048	5	1	N	1		
LDR-048	0.0-2.2	10/04/2009	13:22	47.567	122.348	15.2	32	18	0.058	>30	1	N	1		0.189
LDR-048	0.0-2.2	10/04/2009	13:48	47.567	122.348	15.3	32	41	0.131	>30	1	Y	1		
LDR-063	0.0-2.2	10/04/2009	11:41	47.541	122.333	5.3	-	-	-	-	-	-	-	No sample collected	0.073
LDR-063	0.0-2.2	10/04/2009	11:45	47.541	122.333	5.2	32	11	0.035	24	1	Y	1		
LDR-063	0.0-2.2	10/04/2009	11:55	47.541	122.333	5.3	32	12	0.038	2	1	N	1		
LDR-126	0.0-2.2	11/03/2009	15:41	47.536	122.325	8	-	32.5	-	-	-	N	N	Sampler did not close	0.062
LDR-126	0.0-2.2	11/03/2009	15:49	47.536	122.325	8.2	19	32.5	0.062	20	1	N	N		
LDR-127	2.2-4.0	10/04/2009	11:08	47.535	122.324	3.3	-	-	-	-	-	-	-	No sample collected	0.090
LDR-127	2.2-4.0	10/04/2009	11:12	47.535	122.324	3.6	32	28	0.09	120	2	Y	2		
LDR-142	2.2-4.0	07/04/2009	13:32	47.537	122.319	1.8	22.5	20	0.045	4	N	1	N		0.086
LDR-142	2.2-4.0	07/04/2009	13:48	47.537	122.319	1.8	22.5	18	0.041	15	Y	1	N	Tried deploying magnet grab sampler	
LDR-143	2.2-4.0	07/04/2009	14:12	47.535	122.329	4	22.5	19	0.043	20	Y	1	N		0.090
LDR-143	2.2-4.0	07/04/2009	14:22	47.535	122.329	4.6	22.5	21	0.047	45	N	1	N		
LDR-186	2.2-4.0	10/04/2009	10:08	47.529	122.312	1.5	-	-	-	-	-	-	-	No sample collected	0.093
LDR-186	2.2-4.0	10/04/2009	10:14	47.529	122.312	1.5	32	14	0.045	>40	1	N	1		
LDR-186	2.2-4.0	10/04/2009	10:21	47.529	122.312	1.5	32	15	0.048	20	1	Y	1		
LDR-225	>4.0	12/03/2009	14:49	47.514	122.304	2.4	37	32.5	0.12	>150	1	N	N		0.149
LDR-225	>4.0	12/03/2009	14:49	47.513	122.304	2.6	9	32.5	0.029	>140	1	N	Y		
LDR-246	>4.0	07/04/2009	15:05	47.521	122.306	1.2	22.5	20	0.045	10	Y	1	Y	Collected water sample	0.092
LDR-246	>4.0	07/04/2009	15:15	47.521	122.306	1.2	22.5	21	0.047	10	N	1	N		
LDR-249	>4.0	07/04/2009	15:31	47.520	122.306	3	22.5	19	0.043	35	Y	1	N		0.086
LDR-249	>4.0	07/04/2009	15:46	47.520	122.306	2.7	22.5	19	0.043	30	N	1	Y	Collected water sample	
LDR-263	>4.0	07/04/2009	15:58	47.519	122.308	4.6	22.5	10	0.023	5	Y	1	N		0.071
LDR-263	>4.0	07/04/2009	16:09	47.519	122.308	4.6	22	22	0.048	5	N	1	N		
LDR-279	>4.0	07/04/2009	16:43	47.512	122.302	4	22.5	12	0.027	>120	Y	1	N	Magnet sampler 3X	0.079

LDR-279	>4.0	07/04/2009	16:46	47.512	122.302	4	22.5	23	0.052	>120	N	1	N		

5.8 Summary of Data

The fundamental variable in this study is tracer mass; however there are several major considerations in dealing with data of this type within sediment tracking studies generally. At the spatial length scales of interest in this project the dilution of tracer mass from the injection point is enormous, and whilst generally the data indicate a successful tracking of tracer over these distances, tracer mass values at locations downstream are very low (close to the limit of practical application of the tracking technique). With such low values it is essential to view the data in a pragmatic fashion. Firstly, isolated positive identifications with no apparent consistency are not considered important, and focus is more on samples for which multiple identifications have been found and where adjacent or nearby samples indicate the same. This approach, which attempts to provide an informal level of significance to the data, must also be considered in the framework of the sampling design; for example, whilst the fixed magnets present a fixed sampling point, successive bed sampling activities, which invariably cannot re-sample precisely the same location, can often once discover tracer and then subsequently discover none. This is almost certainly a sampling artifact (of non-Eulerian sampling) and as such must be considered during data interpretation.

The dataset should only be viewed generally within a semi-quantitative framework with some capacity for quantitative comparison of data at certain different times/places, and the particle size data collected can be used to indicate the fractions in transport at various places and times within the estuary. Potential approaches which may be based upon strict mass estimations are further complicated, especially for the silt, through the use of low density tracer particles which obviously have reduced mass. **Given these considerations the appropriate basis for representation and interpretation of the data is through an *ordinal approach*, and consequently the data have been sorted into a series of tracer mass bins**. These bins are as follows:

Table 13 Summary of bins used to sort tracer mass data.

Tracer Mass Range (g)	Qualitative Descriptor
0.000000 to 0.000001	None
0.000002 to 0.000100	Low Mass
0.000101 to 0.010000	Medium Mass
0.010010 to 1.000000	High Mass
1.000000 to 10.00000	Very High Mass

5.9 Filter Paper Samples

Table 14 summarises data from collection of water samples for filtration. Positive identifications for silt tracer were found in all samples (except the blank sample P5513), whereas sand tracer was identified only in P5502 to P5506. Appendix 2 presents photographs of examples of filter papers under fluorescent illumination.

Table 14 Summary of size and concentration data for filter paper samples. u/s=upstream sampling location, d/s=downstream sampling location. Pink shading is used to separate upstream from downstream sampling locations.

Sample Type	Sample ID	Yellow Tracer Mean EGS (µm)	Yellow Tracer Maximum EGS (µm)	Yellow Tracer Minimum EGS (µm)	Red Tracer Maximum Particle Size (µm)	Red Tracer Minimum Particle Size (µm)	Yellow Tracer Mass (g per litre)	Red Tracer Mass (g per litre)
Filtered (u/s)	P5501	28	52	4	0	0	**LOW**	0.000000
Filtered (u/s)	P5502	10	12	8	198	72	**LOW**	**LOW**
Filtered (u/s)	P5503	24	41	8	76	64	**LOW**	**LOW**
Filtered (u/s)	P5504	16	28	6	128	88	**LOW**	**LOW**
Filtered (u/s)	P5505	16	24	8	134	64	**LOW**	**LOW**
Filtered (u/s)	P5506	22	47	8	152	88	**LOW**	**LOW**
Filtered (u/s)	P5508	19	38	10	0	0	**LOW**	0.000000
Filtered (u/s)	P5509	22	47	8	0	0	**LOW**	0.000000
Filtered (u/s)	P5510	19	34	6	0	0	**LOW**	0.000000
Filtered (u/s)	P5511	21	40	6	0	0	**LOW**	0.000000
Filtered (u/s)	P5512	18	28	10	0	0	**LOW**	0.000000
Filtered (d/s)	WW02	30	43	14	0	0	**LOW**	0.000000
Filtered (d/s)	WW03	49	59	40	0	0	**LOW**	0.000000
Filtered (d/s)	WW04	25	32	22	0	0	**LOW**	0.000000
Filtered (d/s)	WW05	30	47	24	0	0	**LOW**	0.000000
Filtered (d/s)	WW06	31	47	24	0	0	**LOW**	0.000000
Filtered (d/s)	WW07	28	36	22	0	0	**LOW**	0.000000

5.10 Dipped Magnets

Table 15 summarises size and tracer mass data from the use of dipped magnets. Yellow tracer was reported for all samples all at low concentration, whereas sand tracer was reported only for WM-6 and WM-7 (also in low concentrations).

Table 15 Summary of size and concentration data for dipped magnet samples.

SampleID	Date	Yellow Tracer Mean EGS (µm)	Yellow Tracer Maximum EGS (µm)	Yellow Tracer Minimum EGS (µm)	Red Tracer Mean Particle Size (µm)	Red Tracer Maximum Particle Size (µm)	Red Tracer Minimum Particle Size (µm)	Yellow tracer mass (g/hr)	Red tracer mass (g/hr)
WM-1	13/02/2009	27	47	10	0	0	0	LOW	0
WM-2	13/02/2009	43	57	38	0	0	0	LOW	0
WM-3	13/02/2009	32	47	18	0	0	0	LOW	0
WM-4	13/02/2009	31	48	14	0	0	0	LOW	0
WM-5	13/02/2009	37	53	14	0	0	0	LOW	0
WM-6	13/02/2009	45	60	32	72	76	68	LOW	LOW
WM-7	13/02/2009	22	38	16	74	74	74	LOW	LOW

***Undersize sand tracer reported for these locations (mass added to yellow tracer)**

5.11 Bedded Samples and Fixed Magnets

Figures 16 and 17 present ordinal tracer concentration data for Week 1, Month 1 and Month 2 sampling campaigns. Each map considers the bedded sample and fixed (permanent) magnet data together in order to afford an inter-comparison of suspended sediment transport and within-estuary sedimentation. The maps are shaded to represent the River Mile sections used. Table 16 summarises the time- and space average quantities for silt and sand tracer in terms of the three river sections.

Table 16 Summary statistics of the size (equivalent grain size for silts) and concentration of silt and sand tracer for bedded and magnet samples for the River Mile sections during the three sampling campaigns.

	River Mile	**Bedded Samples**		**Suspended Sediments (Fixed Magnets)**	
		Size*	**Mass (gm^{-2})**	**Size***	**Mass (g)**
Silt (yellow EGS)					
Week 1	0 to 2.2	26, 51, 6	HIGH	26, 61, 4	MEDIUM
	2.2 to 4	25, 54, 10	HIGH	27, 51, 4	MEDIUM
	> 4	24, 57, 10	HIGH	26, 59, 6	MEDIUM
Month 1	0 to 2.2	25, 49, 4	HIGH	27, 47, 10	MEDIUM
	2.2 to 4	26, 53, 6	V. HIGH	31, 61, 10	MEDIUM
	> 4	24, 53, 6	HIGH	32, 59, 16,	HIGH
Month 2	0 to 2.2	29, 61, 22	HIGH	26, 36, 29	MEDIUM
	2.2 to 4	30, 49, 12	HIGH	N/S	N/S
	> 4	30, 52, 14	HIGH	N/S	N/S
Sand (red)					
Week 1	0 to 2.2	95, 134, 82	HIGH	76, 76, 76	LOW
	2.2 to 4	0, 0, 0	0.000000	67,70, 65	LOW
	> 4	94, 134, 82	HIGH	96, 216, 64	HIGH
Month 1	0 to 2.2	55, 175, 0	LOW	0, 0, 0	0.000000
	2.2 to 4	70, 70, 70	MEDIUM	76, 76, 76	MEDIUM
	> 4	129, 315, 64	HIGH	0, 0, 0	N/S
Month 2	0 to 2.2	0, 0, 0	None	No Tracer	
	2.2 to 4	88, 88, 88	HIGH		
	> 4	0, 0, 0	None		

*Average of the Mean, Max of the max, Min of the min. N/S=no samples.

Figure 16 Silt tracer distribution within the Lower Duwamish Waterway (bed samples and fixed magnets).

Figure 17 Sand tracer distribution within the Lower Duwamish Waterway (bed samples and fixed magnets).

Sand Tracer:— In general terms sand tracer was *not* identified in the majority of samples (bedded and water column) through the three sampling campaigns. Of the filter paper samples, low concentrations were found on five upstream samples in the region of the tracer injection zone (PP5502 to PP5506). None of the water filter samples collected downstream contained any sand tracer (Table 13), although two dipped magnets did collect very fine sand size tracer at the Western Gateway region (Table 14). Further, if the data from the three sampling campaigns is considered together, then 80% of positive sand tracer identifications were reported from River Miles 2.2-4+, and 20% from River Miles 0-2.2.

Sampling close to the tracer injection location revealed the most frequent positive identifications for sand. Sand tracer was found in magnet#1 in high concentrations, and in medium concentrations for magnets #3 and #5 which were also in the region of the tracer injection location. That magnet #3 intercepted tracer only on the upper magnet indicates that tracer transport is heterogeneous on the scale of dm to m. Tracer sand was also found in the bedded samples LDR-225 (very high), and LDS-10M (high) both of which were located in the same region of the estuary (RM>~3.8) to magnet #1. Sand tracer was detected at a high level in LDS-09M at RM 3.4, and also at the nearby fixed magnet location magnet #5. The downstream mass gradient of tracer sand (and silt) is most striking for the fixed magnets (Fig. 18 & 19).

The size range of sand tracer collected at magnet #1 was 64 to 216 microns, and that for LDR-225 was 146 to 245 μm. These reflect an appreciable spread of size within the tracer size distribution but indicate first suspension then deposition of the coarsest tracer particles. The presence of such large particles in suspension is also indicated by the filter paper data (e.g. for PP5502, 5505, 5506; Table 13). A similar situation is found for location LDR-225 where tracer grain sizes were of the order 180 to 245 μm. Grain size is 93 μm for LDS-010M indicative of prior loss of the very coarser grains, and farther downstream at LDS-09M at RM 3.4 particle size is 70 μm, and for magnet #5 grain sizes range 65 to 70 μm. These data indicate directly that the fine sand fraction and the coarser end of the very fine sand fraction have both settled i.e. evidence of a downstream fining. The bedded sample data (LDS-09M) and magnet #5 show tracer both in suspension and sedimenting to the bed at or around RM 3.4. However, sand tracer in high mass concentration at bedded sample LDS 06E and at LDR-124 after two months potentially indicates tracer transport to ~RM 2.4. It is interesting to note that (isolated) positive tracer identifications are available for fixed magnets #14[U] and #16L closer to Western Gateway region, and for dipped magnets WM-6 and WM-7 (Table 14) perhaps indicating some tracer transport to the downstream reaches. Rather consistently, size analysis from these samples shows a narrow range of 68 to 76 μm.

Table 17 summarises the size-concentration trends which indicate the downstream gradients observed.

Table 17 Summary of key particle size and concentration data which show downstream fining and dilution of sand tracer (for locations see Figures 2, 3, 4 and 5).

Sample Type		Date	Red Tracer Mass ($g\ m^{-2}$)	Mean Particle Size (µm)	Max. Particle Size (µm)	Min. Particle Size (µm)
Magnet #1		19/02/2009	0.018454 gT^{-1}	124	216	64
LDR-225		12/03/2009	1.695410 $g\ m^{-2}$	180	245	146
LDS-010M	**Upstream**	18/02/2009	0.038434 $g\ m^{-2}$	93	93	93
PP5502 u/str		13/02/2009	0.000017 gl^{-1}	108	198	72
PP5505 u/str		13/02/2009	0.000008 gl^{-1}	95	134	64
PP5507 u/str		13/02/2009	0.000013 gl^{-1}	125	152	88
LDS-090M		12/02/2009	0.013300 $g\ m^{-2}$	70	70	70
Magnet #5		19/02/2009	0.00048 gT^{-1}	67	70	65
LDS 06E		07/04/2009	0.786421 $g\ m^{-2}$	110	175	70
LDR-124	↓	11/03/2009	0.025372 $g\ m^{-2}$	88	88	88
Fixed magnet#14U		19/02/2009	0.0000730 gT^{-1}	76	76	76
Fixed magnet#16L		09/03/2009	0.0000800 gT^{-1}	76	76	76
Dipped magnet WM-6	**Downstream**	13/02/2009	0.0000018 ghr^{-1}	72	68	72
Dipped magnet WM-7		13/02/2009	0.0.000008 ghr^{-1}	74	74	74

With a single exception, fixed magnets did not record sand tracer in suspension during the Month 1 and Month 2 sampling periods.

Silt Tracer:—In contrast to the sand tracer, silt tracer was found on most fixed magnets and for many bed samples throughout the Lower Duwamish Waterway recurrently through the three sampling campaigns. This indicates advection of the silt tracer certainly through the mid-section of the estuary and just about to the West Waterway region during the tidal excursion(s). Tracer presence in the lower estuary water was indicated and supported late in the ebb tidal excursion (mid-afternoon) through the use of dipped magnets (Table 14), and silt tracer was detected in the vicinity of RM 0 to 2.2. Visual observations made during the data collection activity indicated tracer on all the dipped magnets, and this was the case for all magnets following image analysis. Silt tracer was also found on all filtered water samples (Table 13). Together, both the data types support the view that tracer was present, albeit in low concentrations, in the lower estuary water following injection. Interestingly, during the Week 1 sampling campaign bed sampling detected high concentration silt tracer *upstream* of the injection point.

Using the ordinal approach to describe the data, during Week 1 fixed magnets generally show medium tracer mass concentrations for RM>2.2, reducing to low values in the downstream region RM 0 to 2.2. This indicates a downstream concentration gradient (Fig. 18). Closer inspection of the data confirm this (Fig 17) to around magnet #9. Magnet #9 exhibits tracer mass of 2.58 x 10^{-3} g (≡ medium on the ordinal scale) which is arguably a sufficiently high number to warrant significance. The bedded samples show a similar spatial pattern, with many samples upstream of, and within, the upper river region from RM 3 to RM4.4+ indicating high tracer mass. Within the lower half of RM 2 to 4.4 there are many zero tracer mass values within samples and for the region RM 0 to 2.2 there are a relatively greater number of medium mass concentration values. This gradient, however, is not as pronounced as for the fixed magnet samples.

After one month, tracer is still detectable within the estuary at medium to high mass concentrations. The general pattern comprising:

- greater numbers of higher tracer concentration, certainly for bedded samples, upstream of ~RM 3.2 (LDR 104),
- generally more frequent samples showing medium tracer mass values, and
- low values for fixed magnets and zero tracer finds for bedded samples at ~RM 0,

This is similar to the general distribution reported for Week 1 sampling.

After two months only the bottom sediments in the estuary were sampled (mostly the above RM 2.2). The data indicate high values for tracer mass concentrations, some of which (e.g. LDR-246, LDR 006) are 10^{-1} g m^{-2}; although the sampling was biased to the central and eastern river sections (>RM 2.2) tracer was present in all samples collected within this region, whereas 4 out of 7 samples collected within the lower river (RM <2.2) displayed zero tracer mass. This indicates that the same weak gradient in concentration is possibly persistent within the estuary bedded samples. What is important is that many of these samples comprising positive tracer mass values were those for which the overlying water was retained during sampling (see Table 1), and for which there is a greater level of confidence that the tracer mass data are trustworthy.

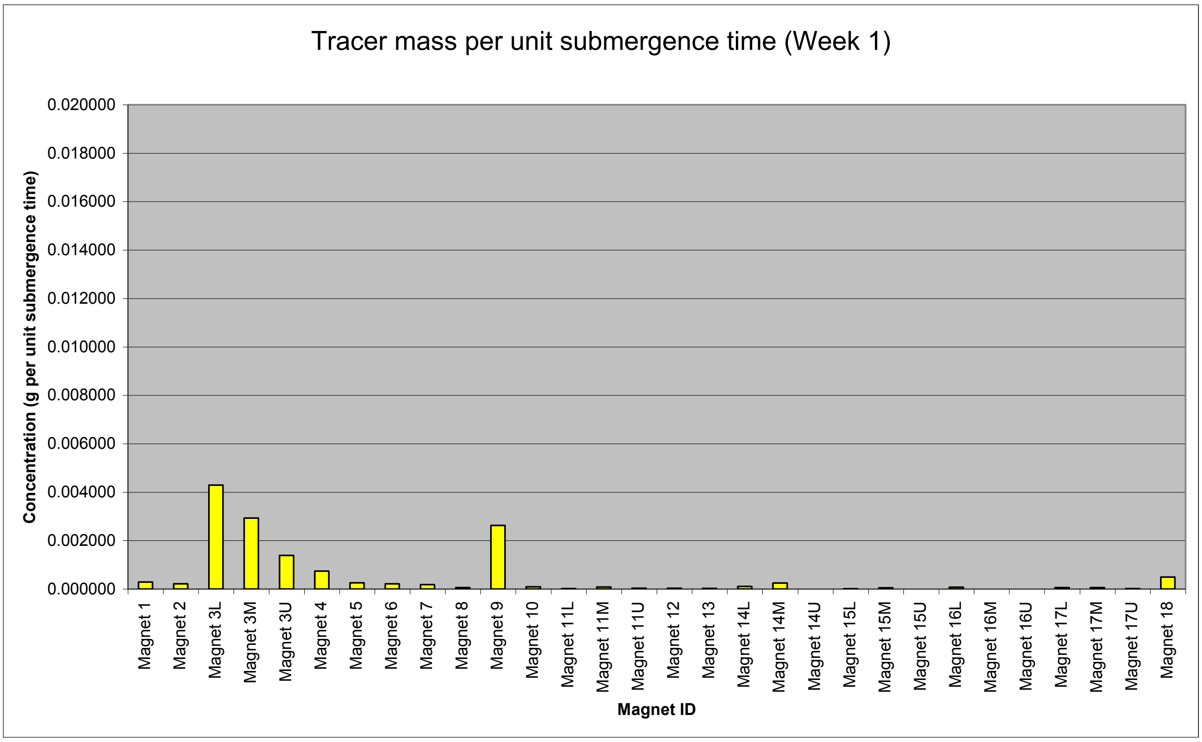

Figure 18 Tracer mass per unit submergence time (fixed magnets, week 1)

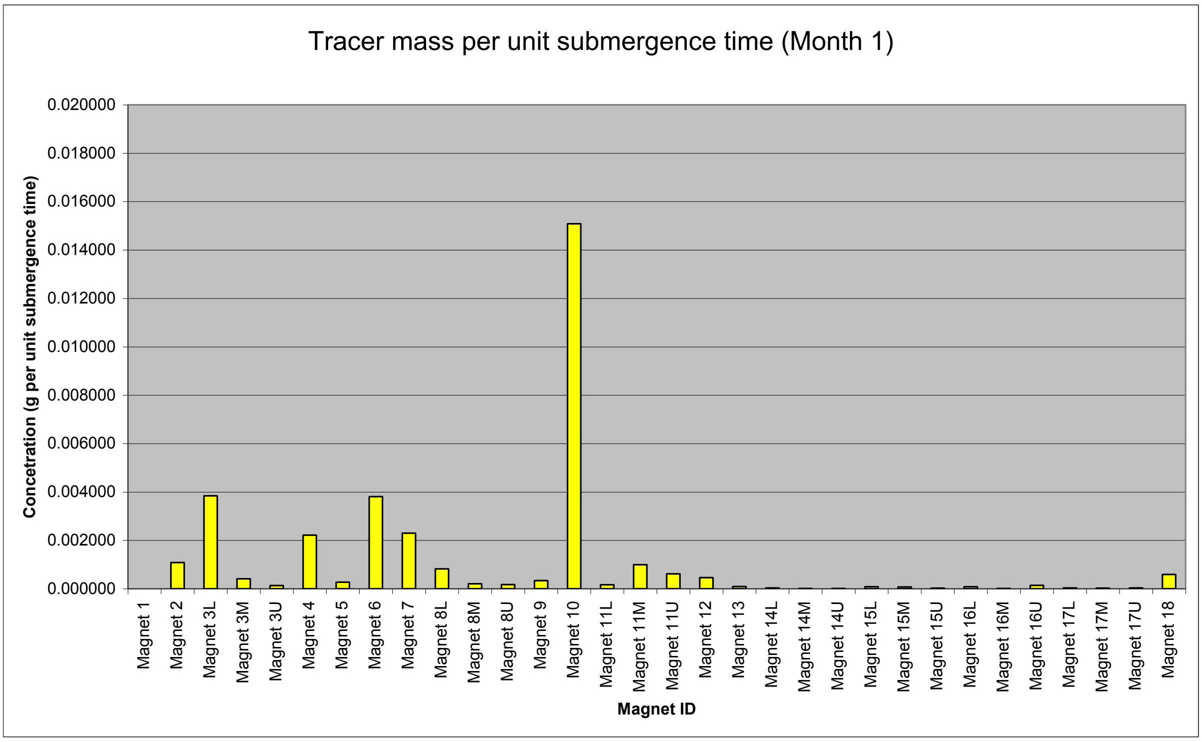

Figure 19 Tracer mass per unit submergence time (fixed magnets, Month 1)

In terms of particle size, an overview of the entire datasets for silt by river region, by type (bedded, suspended) and by time (Week1, Month 1, Month 2) does not indicate significant gradients (Table 15). Summary maximum (50 to 60 μm), mean (~25 to 30 μm) and minimum (5-12 μm) equivalent grain sizes appear highly similar. Moreover, these data are consistent with that from dipped magnets, and from filter paper samples. Figure 20 shows mean particle size for Week 1 and Month 1 magnets, and the variability is clear.

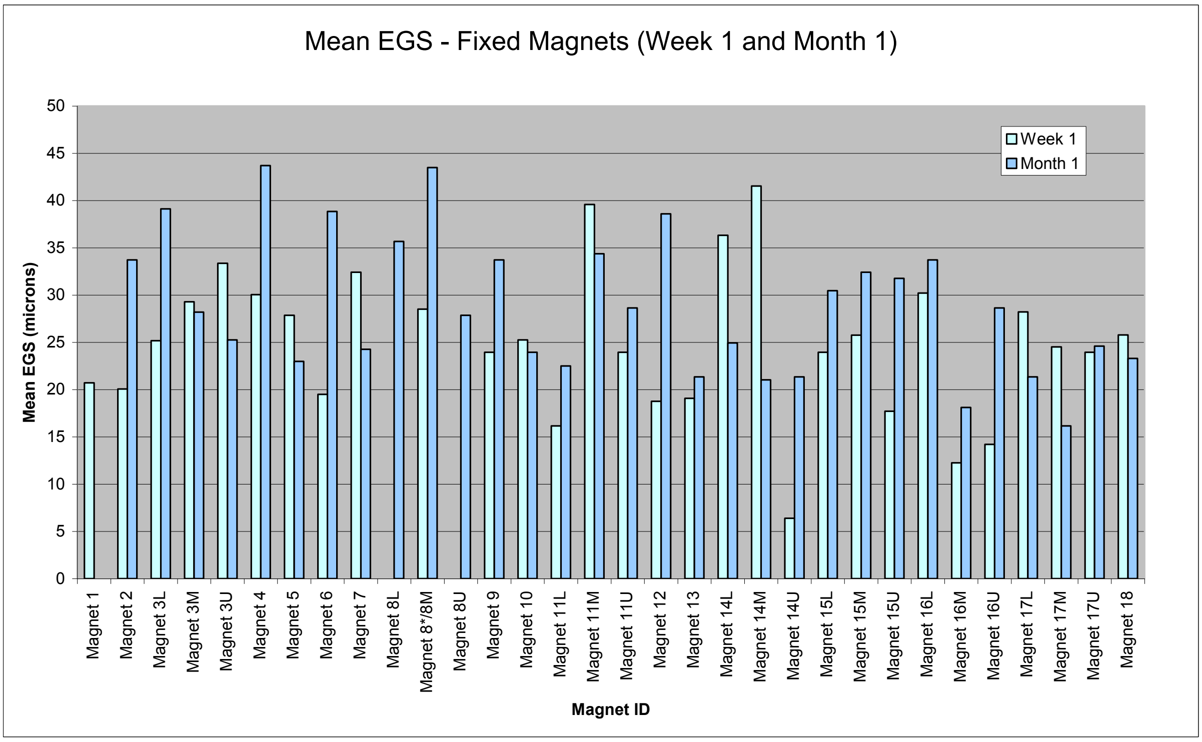

Figure 20 Mean equivalent grain size (EGS), fixed magnets (Week 1 and Month 1) *Magnet 8, Week 1 is reported as a single sample (see Table 3, Section 5.1).

However, a closer inspection of individual (bedded) samples shows that those which have the highest numerical mass concentrations typically have higher maximum equivalent grain size values >~40-60 μm. These data are summarized in Table 18. Figure 21 shows maximum grain size for bedded and suspended (fixed magnet) samples plotted as histograms for each sampling period. From this it is possible to compare the range of grain sizes in the water column and at the estuary bed for each river section and for each sampling period.

Table 18 Summary of silt tracer size data for samples with high/very high mass concentration values (arbitrarily defined here as concentration >0.05 g m^{-2}).

Sample Type	Date	Yellow Tracer Mean EGS (μm)	Yellow Tracer Maximum EGS (μm)	Yellow Tracer Minimum EGS (μm)	Yellow Tracer Mass (g m^{-2})
LDS-04E	17/02/2009	24	38	16	0.053207
LDR-137	18/02/2009	37	51	10	0.156667
LDS-012E	18/02/2009	27	45	12	0.063215
LDS-08M	18/02/2009	40	54	16	0.231216
LDS-09W	18/02/2009	37	40	32	0.107281
LDS-013M	19/02/2009	22	40	10	0.066722
LDR-178	11/03/2009	36	38	34	0.095317
LDS-04W	11/03/2009	26	49	4	0.251394
LDS-011M	12/03/2009	27	43	18	0.056404
LDS-09W	12/03/2009	25	51	6	0.603254
LDR-231	16/03/2009	19	47	6	0.103522
LDS-12W	16/03/2009	34	53	18	0.237935
LDR-010	07/04/2009	25	26	24	0.044918

Sample Type	Date	Yellow Tracer Mean EGS (μm)	Yellow Tracer Maximum EGS (μm)	Yellow Tracer Minimum EGS (μm)	Yellow Tracer Mass (g m^{-2})
LDR-124	07/04/2009	31	40	22	0.062862
LDR-249	07/04/2009	41	49	32	0.104400
LDR-263	07/04/2009	29	49	18	0.099899
LDR-143	07/04/2009	31	43	18	0.090565
LDR-246	07/04/2009	39	49	26	0.159401
LDR-006	10/04/2009	39	61	30	0.221189
LDR-172	10/04/2009	38	38	38	0.045619
LDR-127	10/04/2009	32	45	12	0.088134
LDR-186	10/04/2009	18	18	18	0.011594

Comparison of the histograms between the various river reaches is of interest. The Week 1 data are most closely related to the silt transport on injection day and for about 10 of tides thereafter. Within RM 2.2-4 and RM4+ it is interesting to note that both the bedded samples and fixed magnets collect coarse silts but some finer silt tracer is found in the bedded samples only. Farther downstream in RM 0 to 2.2 the histograms for the bed and water column are highly similar, which would indicate a well mixed environment.

After 1 month, a similar pattern to that after 1 week exists through the estuary, with finer silt particles evident in bed samples for the middle and upper river sections, but in the lower estuarine reaches the range of particle sizes is similar for both bed and suspended tracer (20 to 50 μm EGS).

For month 2 sampling only data are available for bedded samples. The histogram indicate that silt tracer from 20 to 65 μm is found in each of the three river sections, with no discernible strong spatial gradients or trends.

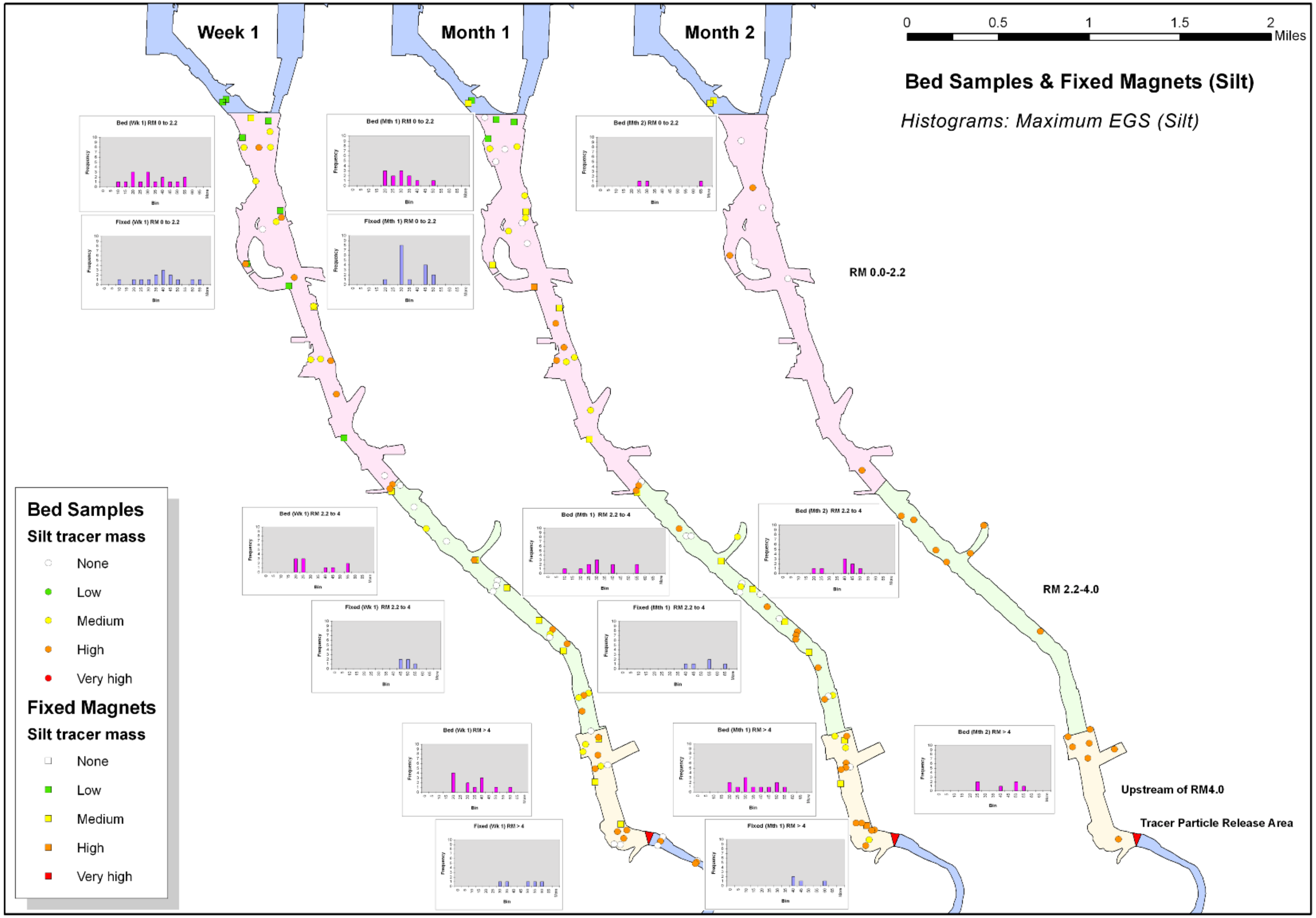

Figure 21 Bed samples and fixed magnets. Histograms show the reach-averaged maximum EGS for bedded and magnet samples (silt tracer).

6. DISCUSSION

The primary goals of the sediment tracking project were:

- to assist the Ecology in the direct assessment of *transport and fate of suspended solids that enter the Lower Duwamish Waterway* from the Duwamish/Green River system;
- to show *how far into or beyond* the cleanup site fluorescent sediment particles that mimic those found in the Duwamish/Green river can be transported when released into the water column under various conditions, and
- to *trace the movement* of these particles *into, and possibly through, the waterway*; and, in particular,
- to *trace where they can settle to the bottom*.

It is within the framework provided by these project objectives that a discussion of the findings can be set. In the following discussion these major themes will be addresses:

- General overview of the study;
- Tracer commissioning and manufacture, including the 'equivalent grain size' concept;
- Sampling and analytical methods;
- A discussion of the transportation of silt and sand tracers within the Lower Duwamish Waterway;

Tracer data will be discussed mostly in terms of the semi-quantitative (ordinal) approach justified in Section 6.2. With such powerful dilution gradients within the estuary, inspection of the individual sample mass values is not appropriate in general terms. It is, however, pertinent to note that during tracer injection tracer concentrations were ~2,000-3,000 g l^{-1} (rapidly decreasing within several hundred metres of the injection zone metres downstream to ~0.0030 gl^{-1}; Gries *pers. comm.*) whilst at RM0 tracer concentrations approach 10^{-6} gl^{-1}. In addition, size data for the silt tracer are quoted in terms of their equivalent grain size (EGS; refer to Section 5.5), rather than in terms of measured values on the low density tracer.

6.1 General Overview

Although there are limitations on a full quantitative analysis of the data (due principally to issues associated with sampling surface sediments and the generally low/very low tracer mass values due to natural dilution/dispersion processes) the data collected have demonstrated tracer transport *into the waterway* as well as *how far into/beyond* the cleanup site particles have travelled (for the hydrodynamic conditions present during the 2 month study period), and in this respect the study is considered successful in meeting the project objectives.

- Sand tracer transport is largely confined to the upper river reaches (~RM3+), although there is indication of very fine sand tracer in suspension to the lower river reaches.
- High to medium (silt) tracer levels were positively identified at the downstream extent (in the vicinity of RM 0) through various methods (dipped magnets, fixed magnets, bedded samples) and positive tracer identifications were made at the fringes of the estuary in the vicinity of RM 0 where fixed magnets were located. Thus, the conclusion is that (silt) tracer was not only transported to the downstream estuary reaches, but also dispersed laterally within the lower estuary waters.

This information is of importance to assessment of the longitudinal and lateral length scales of transport. The study is a 'one-off' study which relates to the hydrodynamic conditions prevalent during the two month study duration (i.e. different flow regimes would potentially produce different data). If there are hydrodynamic data available for the tracking study duration, then the observations can be placed within the context of the range (frequency) of hydrodynamic conditions that are encountered in the Lower Duwamish Estuary.

6.2 Tracer Commissioning, Manufacture and Similarity Analysis

The use of particulate analogues to track the movement of sediments in aquatic systems is based upon a logical set of events and processes (Black et al., 2007). In the first instance testing of native sediments, using standard (international) methods which are prescribed and verified through the Measurement Quality Objective (MQO) table (see Appendix 1), is required in order to establish the physical-hydraulic (and fluorescent-magnetic) nature of these sediments. In some studies only settling velocity is determined on native sediments, as this is the chief attribute which governs the behaviour of particles in geophysical flows. However, more frequently a range of physical-hydraulic indices are measured as this provides a wider platform upon which to design a tracer analogue.

In this study samples of bedded and suspended sediments were tested for their physical-hydraulic characteristics. These tests showed that the sand fraction on the seafloor of the Lower Duwamish Waterway comprises dominantly fine sand for most samples processed, with occasional samples comprising very fine to medium sand. The silt comprises fine skewed (i.e. towards the coarse end of the spectrum), poorly sorted medium to coarse silts. A bulk value for the density of a bedded sample is 2580±400 kgm^{-3}. Settling velocity data are consistent for the sands tested, whereas a range of discrete median settling velocity corresponding to textural sub-fractions within the bedded silts (e.g. coarse fraction, medium silt fraction etc.) are found for the silts. These data were used as the basis for designing tracer specifications, but specific instructions were in addition issued by Ecology on the basis of wider project objectives to:

- manufacture a sand tracer of size range 60 to 250 μm (i.e. very fine to fine sand); and
- manufacture a reduced density silt tracer which reflected the intermediate settling velocity fraction (nominally 30 to 60 μm) fraction.

Tracer batches were manufactured using these criteria, both of which were highly paramagnetic and fluorescent in colour.

Sand Tracer:— 93 kg of a dual-signature sand tracer with density, size and settling velocity attributes highly similar to native sand was manufactured (see Table 9). The tracer material resembled in a macroscopic sense mineral sand (it became naturally slightly compact, there was observable moisture redistribution upon disturbance, there was temporary clumping when troweled into the injection funnel). 93% of the manufactured tracer was within the specified size range. The ratio of tracer to native sand density was 1.03 (Table 19), which is within the tolerance specified by Black et al., (2007) as acceptable for tracking studies. The mean settling velocity ($\bar{w}_s$) was 0.022 ms^{-1} which is centrally located within the range of settling velocity values for native sediments ($0.006 < \bar{w}_s < 0.040$ ms^{-1}). The similarity of the tracer sand to the native sand is therefore judged as good.

The sand tracer included a small silt fraction due simply to the absence of a sieving stage during production due to time constraints. Although some of this fine material was lost during tracer the pre-wetting stage, some was inevitably introduced into the surface waters during tracer injection. In such instances the mass associated with the silt-sized sand tracer has been added to any corresponding silt tracer mass which removes any issue with this fraction entirely.

Silt Tracer:— A different approach is used to manufacture the silt tracer. A like-for-like process in which tracer sediment particles equal in size and density are manufactured cannot be achieved for silts. This is in part because silts exhibit mass sedimentation properties in nature and thus their settling behaviour is not directly related to individual grain properties such as size and density. Second, inclusion of a para-magnetic signature within every particle limits the minimum size achievable in manufacturing terms. Given these considerations, a tracer particle population is manufactured using density-adjusted particles. In this method, the mass sedimentation character of the native silts is first measured, and using this data a tracer particle batch is designed so that the mass sedimentation character (i.e. the median or mean settling velocity) is highly similar. For this study a density of 1200 kgm^{-3} was selected as an appropriate density for a size range of 30 to 60 μm to produce similarity of settling velocity.

Following manufacture the silt tracer was tested for both settling velocity and size; each test indicated that the batch was rather coarser than specified, with particles up to ~120 μm in size, and with elevated settling velocities. However, the tracer settling velocity was *within the range of values of the native silts and non-overlapping with the sand tracer settling velocity*, and therefore - in hydraulic terms - the tracer batch was a true silt. Moreover, the skewness in the settling velocity data is in the same direction as that for native silts, which White (1998) observes should ensure that the transport behaviour will be largely similar. Preferably, the over-size particles would have been removed through pre-sieving but, as for the sand tracer, there was insufficient time in the study programme to do this. It is judged that a silt tracer with settling velocity attributes highly similar to native very coarse silts was available for introduction into the surface waters of the Lower Duwamish Waterway. In addition, the tracer resembled in macroscopic terms and behaved like an estuary silt/mud (with elastic-plastic properties and discernible vertical consolidation gradients inside enclosed vessels; Fig. 7).

It was fortuitous that a greater quantity of silt tracer was manufactured than specified (160 kg versus 100 kg), and this was due to over-estimation of source material quantities by Partrac. In actuality 84.8 kg of hydraulically acceptable tracer material within the specified size range was manufactured and introduced into the estuary, and 75.2 kg of over-size but hydraulically acceptable tracer was manufactured and introduced into the estuary. This situation, although unwarranted, is considered a positive benefit to the tracking study.

Over-Size Silt Tracer Particles and 'Effective' Grain Size:— The existence of over-size silt tracer introduces a complexity, especially since data on particle size was collected during the sample analysis stage. For example, sample location LDS-09W contains particles of up to 152 μm in diameter, and although it should be understood that this is a reduced density particle and therefore hydraulically a silt, clearly in a conventional sense this would not ordinarily be described as a 'silt'. In view of this, it is possible to establish an 'equivalent' particle size for each silt tracer particle size. This can be defined as: *the equivalent size a particle of a given size would be were it of a density of 2500 kgm*$^{-3}$. The size equivalence relationship between the silt tracer and normal density particles is given in Figure 15, and the dataset contains a column of equivalent particle size for tracer mean, minimum and maximum silt tracer size values. This approach is suitable, in the first instance, for tracer particles which have been advected away from the injection point and have become diluted through transport and dispersion within the main body of the estuary (i.e. particle-particle interactions are minimal) (Soulsby, 1997).

6.3 Sampling and Analytical Methods

Issues associated with the sampling and analytical procedures need consideration in order to establish a context for interpretation of the data. Sampling issues can be examined first as this represents the point of collection of samples from the estuary.

6.3.1 Field Sampling

A field sampling strategy was implemented which comprised:

- Arrays of fixed magnet stations;
- Day-of-release water column sampling using dipped magnets;
- Day-of-release water column sampling (pumped filtration) stations/transects;
- Bedded (deposited) sediment stations, comprising randomly selected locations and subjectively selected locations.

In terms of both utility and successful implementation, the use of powerful (11,000 gauss) time-integrating magnets fixed onto various [permanent] frames throughout the estuary proved a successful, simple *in situ* tool to capture tracer (an equivalent sampling programme simply could not be achieved with hand-held water samplers). The magnets are sufficiently powerful to capture both naturally suspended magnetic material and tracer (Fig. 11a). In some instances tracer was visible to the eye upon collection, and for this and future studies such observations could be used to drive a sampling programme in real-time. The key issue with setup of the fixed magnets was that in most cases the magnets were fixed to permanent structures at different datums relative to the lowest astronomical tide; the proportion of time that each was submerged was therefore different. For each magnet, tracer masses have been adjusted by the ratio $\frac{T_{\max}}{T_i}$ where T_{max} is the maximum submergence duration of any magnet during a specific sampling period (e.g. 1 week, 1 month), and T_i is the submergence period for a specific magnet for the same sampling period (i.e. T_i is always less than T_{max}). This normalization, which assumes that there is an equal chance of interception of tracer for different height magnets at different stages of the tide which may not hold true for different tidal stage (although it is likely insignificant over the two month duration of the project), was agreed with Ecology during the analysis stage. *Note, however, that since* T_{max} *is different for the sampling campaigns (1 Week, 1 Month, 2 Months) it is correct to compare tracer mass values within each period but not strictly correct to compare tracer mass values between campaigns.* This is discussed more fully in Section 7.5.

The dipped magnets sampled the surface waters effectively, and field experience and experience with the magnets more generally suggest that any captured tracer was not subsequently washed off during recovery.

Mobile filtration of pumped surface water samples also proved a successful means of collecting tracer, and in some instances (e.g. P5510, see Appendix 2) provide a direct indication of tracer presence in the water. Quantitative use of filtration data is problematic since the method accumulates mineral particles on the filter which contribute mass, and this mass cannot be readily separated from mass due to tracer. A particle counting approach based upon scanning the filter paper surface (see Section 5.2.4) in a statistically sound manner was devised and agreed between Ecology and Partrac. This methodology is judged to be semi-quantitative. Although it proved only possible to photograph the four filter paper samples (see Appendix 2) as these display high number concentrations of tracer particles, it was possible to see with the eye tracer on filters with lower tracer number concentrations; positive tracer identifications were made on all filtration samples. These visual observations constitute a powerful, semi-quantitative and direct indication of tracer transport/presence at various locations within the estuary water body. Table 13 indicates that in this instance use of filter paper mass is perhaps not the best method of deducing tracer presence, likely because the silt tracer particles are of reduced density; in addition, as noted without e.g. dissolvable filters, it is not currently possible to separate mineral mass from tracer mass effectively. This is an issue that is worthy of future attention.

Bedded samples proved the most problematic, or error vulnerable, sample types to collect. Largely this was due to bow wave effects as the grab approached the seabed, which potentially washes away surface sediments, and if these sediments contain tracer the information will be lost. This is a characteristic of grab sampling which is difficult to avoid or overcome, especially for fine-grained sediments, but which is especially relevant to bedded samples. Moreover, it rises in importance for samples where the tracer mass values are already very low. For the majority of bedded samples, *interpretation is therefore approached in a semi-quantitative basis only*. To address this issue a procedure which involved sampling the retrieved overlying water for some samples (see Table 3 for sample locations) was swept with one of the permanent pole magnets; magnetic particles were removed from the water using the magnet sequentially until no further magnetic particles were recovered. These samples were then quantitatively examined for the presence of tracer particles, and the magnet sample then added back to their corresponding sediment sample (Table 1).

The tracer mass values observed in these samples indicates that the additional effort expended in the field to improve upon the sampling *was* fruitful. Table 19 presents the normalised silt tracer mass values (gm^{-2}) for these samples. The tracer mass values are comparatively high, particularly for LDR-246, LDR-249, and LDR-238. These three sample are, in comparison to the other sample locations, closer to the tracer release point and it might be expected that they might be higher if the distribution of tracer reflects deposition during or shortly following the tracer release day (see Section 6.4.2). Generally, however, these tracer mass values are higher than a great many other samples for other (earlier) sampling periods, which typically are 10^{-4} to 10^{-6} gm^{-2}. Together these observations suggest that an appreciation of the sampling issues for fine sediments within tracer studies, together with a more meticulous approach to field sampling procedures can give rise to improvements in tracer detection.

Table 19 Normalised tracer mass values for Month 2 bedded samples for which an improved sampling method was employed.

Collection Date	Overlaying water collected, concentrated and added to sediment samples	Silt Tracer Mass (gm^{-2})
April 7th, 2009	LDR-246	0.159401
	LDR-249	0.104400
April 10th, 2009	LDR-186	0.011594
	LDR-238	0.126920
	LDR-127	0.088134
	LDR-172	0.045619
	LDR-048	0.000000

6.3.2 Laboratory Analytical Methodology

The laboratory analytical methodology was based upon an image analysis method, in which individual grain are visually counted and sized. Whereas the use of *in situ* magnets in the field, and different but

equally powerful magnets within the magnetic particle separator (MPS) in the laboratory, utilises successfully the magnetic character of tracer particles in order to separate tracer from other sedimentary material, the presence of a natural magnetic fraction within the estuary water and bottom sediments means that a direct visual inspection using the fluorescent characteristics of the tracer becomes necessary to assess quantitatively the abundance of tracer within a sample.

Within the methodology used (see Section 5.2.3), a standardized approach was developed and applied to all sample types except the filter papers. Thus, for the fixed magnets, dipped magnets and bedded samples a sub-sample of ~0.05 g (dry weight) was taken from the parent sample and dispersed onto a microscope counting slide. This mass of course is relatively greater for samples from fixed magnets (which were consequently easier to process) than for bedded samples. Bedded samples, in particular, proved to contain a significant natural magnetic fraction which interfered with sample analysis, and in relative terms confidence is greater for the image analysis procedure for fixed magnet (where parent masses were generally <10 g and mostly <4 g) and filtered samples than for bedded samples. From the prior background study (i.e. before tracer release) a mean mass concentration (*n*=4 bedded samples) for the extracted material from the 4 samples was 0.09 mgg^{-1} which, in comparison to the quantity of tracer subsequently found in bedded samples, is high. Particles varied from 100 μm - 1.5 mm in size from the prior analysis, although during analysis of the bedded samples for tracer far finer natural magnetic material was found.

The image analysis procedure involved counting of 300 random particles. This number was established on the basis of previous experience and the time taken for individual sample analysis[4]. Counting of a fixed number constitutes a standardized, consistent approach which permits inter-comparison between samples. There is scope for different approaches to the adopted methodology, including automated enumeration (e.g. see Forsyth, 2000), but the key point is that whatever the method employed it must be standardized between samples e.g. per unit time for slide examination, or per unit (sub-sample) mass, in order that inter-comparisons between samples can be made. Automated approaches perhaps require consideration, as the analytical method used is rather time-consuming.

The necessity for sub-sampling potentially introduces errors associated with a) variability if the parent sample is not thoroughly homogenized and b) the ability of the sub-sample to scale with the total tracer mass present within the parent sample. Moreover, these issues rise in importance where for samples where the tracer mass values are already very low (although this is not known *a priori*). Several investigations were undertaken to address these issues.

The coefficient of variation (CV) expresses the variation encountered during consecutive (duplicate) sub-sampling, and this is rather higher than specified (45% to 86% with no consistent bias) in the QAPP/MQO (see Appendix 1) but is to be expected within an estuary sediment sub-sampling protocol (the same would likely be true for organic content, bacterial biomass or chlorophyll content e.g. van Duyl, 2000; Galois et al., 2000; Paterson et al., 2000). The range of CV values can be considered as error bars on the fundamental assessment of tracer mass within sub-samples, and therefore within the parent sample. It is interesting to note that a mean CV for those sub-samples from internal (Partrac) QC testing (Table 4) using spiked sediment is ~10%; it is possible that the difference reflects the use of a reference mud versus the use of natural samples, or is related to differences in mud composition between the internal and the Ecology QC samples. A lower CV suggests a sample which is more homogeneous, and this may be a factor since the reference mud used was acid-washed (with

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[4] In the original project scope collection of information on tracer size was not present, and a subsequent request to collect this influenced the scale of the analysis possible.

hydrogen peroxide) whereas the Ecology spikes comprised natural mud from Lower Duwamish Waterway. Acid-washed sediments contain no micro-biota, amorphous organic material and organic mucus and in general are less prone to clumping and aggregation (a phenomenon for muddy sediments which can be appreciated by rubbing a sample between the fingers) than the natural mud.

The ability of the image analysis methodology to derive accurate estimates of total tracer mass present within the parent sample was also examined using spiked reference mud samples. This was achieved by consecutive sub-sampling of the parent sample and consideration of individual and mean values to derive tracer mass (Table 4). This investigation showed that, for a sample with a known mass within a reference mud, the estimate from image analysis under-estimated the dry mass of tracer within the sample by ~45%; this investigation resulted in tracer mass estimates for all bedded samples to be multiplied by 2.207.

The inter-comparison of analytical results with QC blanks for bedded samples, fixed magnets, and filtration samples is presented in Table 5. In an exercise similar to that above, QC samples containing either known a known tracer mass plus Lower Duwamish Waterway estuary mud, or a known tracer particle number concentration plus Lower Duwamish Waterway estuary mud were tested. Data from the former indicated that the image analysis method under-estimated tracer content by between 1.6 to 3.2, a range which embodies the value found above for a spiked (rather than natural) reference sediment. However, it is interesting to note that analysis of samples prepared by adding a known number (as opposed to mass) of tracer particles to native Lower Duwamish Waterway mud did not report any tracer. Whilst this is of concern to the methodology used, assessment of the sampling variability for duplicate sub-sampling shows that the probability of detecting tracer within a sub-sample is not 100% but ~81% i.e. on average 2 attempts for every 10 will give non-positive tracer identifications. This situation arises from the non-homogenous nature of natural samples but also must be related to the size of the size sample (~0.05 g) in relation to that of the parent sample (typically 30 to 60 g for bedded samples). Only a small fraction of the parent sample is inspected under the microscope.

Clearly, improvements to the method to a) reduce heterogeneity within samples e.g. by increasing homogenization energy, b) increase the minimum number of particles counted and c) either increase the mass of the sub-sample or decrease the mass of the parent sample (or both) would be beneficial. It is also possible to scale the image analysis process to the parent sample mass, but this would entail time considerations for larger samples. Initially it was hoped that sieving might be used to reduce the mass of the natural magnetic (NM) fraction, but this was not possible with the size distribution of the NM fraction. This perhaps leaves approaches which are able to examine a larger sub-sample, or even process the entire parent sample (e.g. using the FlowCam technology). This is specifically discussed in the Section 9. This issue was less acute for fixed magnet and dipped magnet samples due to lower parent sample masses, and therefore any future studies might wish to use these sampling types relatively more, or to devise a means of sampling with magnets at the sediment-water interface.

Sample types for which no tracer was added and none was found indicate that there were no false positive results.

The chief conclusions following both field sampling and laboratory analytical methods is that there is an under-estimation of tracer mass in retrieved samples, particularly within bedded samples. The loss of potential tracer due to the method of sampling using the grab[s] cannot be quantified, but if the view is taken that the laboratory analytical methodology is consistent (i.e. precise if not accurate) the QC data collected indicate tracer mass under-estimation of factor of 1.6 to 3.2.

6.4 Silt and Sand Tracer Transport

6.4.1 Sand Tracer Transport

93 kg of red tracer sand was released into the surface waters of the Lower Duwamish Waterway, and a sub-surface plume was observed to be advected downstream and to disperse and spread in three dimensions.

Transport of sand tracer was limited within the estuary. It was nominally considered that the tracer sand would deposit in the near-field i.e. within a footprint region downstream of the injection location, and thus give rise to a marked longitudinal concentration and particle size gradient within the estuary. Although this region was not extensively sampled (as the project focus was more towards understanding silt tracer transport), the data collected largely support this. The data which can be used to assess sand tracer transport was presented in Table 16. This shows, in general terms, that the tracer plume was advected downstream following injection. Data from fixed magnet #1 indicate particles within a wide range (60 to 250 μm) traveled in suspension, and this was evidenced visually by the filter paper sample P5506 collected at 10:40am on the injection day (see Appendix 2). It is interesting to note that particles of this size have successfully traveled the distance from the injection point to Magnet#1, a distance ≈150 m, and this provides an indication that the current flows at the moment of tracer injection were capable of carrying virtually all fine and very fine sand tracer over a considerable distance.

Data from bed samples LDR-225 and LDS-010M both of which are in the near-field (~500 m distance) of the tracer injection zone, show that the coarsest particles settled to the bed. Sampling locations farther downstream to RM 3.4 (LDS-09M and fixed magnet #5) indicate transport (confirmed suspension, confirmed deposition), although tracer particle sizes are considerably lower (~60 to 70 μm); although the data density is not high these observations indicate downstream transport of the *finer* tracer sand only, which may extend as far as the Western Gateway region on the basis of observations from two dipped magnets (WM-6, WM-7). With such disparate sampling intervals, it is problematic to interpret whether this downstream transport of very fine sand is real and significant. If it is, then it indicates that whilst the majority of the sand settles out upstream, the estuarine/rivers flows during the study are capable of maintaining such particles in suspension. This may have implications for the transportation of silt within the estuary.

With a single exception, fixed magnets did not record sand tracer in suspension during the 1 and 2 month sampling periods, which indicates that the tracer sand was likely an immobile sediment pool, most of which was on the seabed within the upper estuary.

6.4.2 Silt Tracer Transport

In an effort to understand the transportation of silt tracer within the Lower Duwamish Waterway, it is most useful to examine the data that exists in relation to the tracer release day, then at the end of the respective sampling periods (Week 1, Month 1, Month 2). In addition, the data can be separated into suspended sediment transport and deposition to the bed.

Silt Tracer Transport (Day-of-Release, Day 0)
Upon injection of 160 kg of yellow-green silt tracers, a sub-surface plume was observed (Fig. 9) to be advected downstream and to disperse and spread in three dimensions. Filter paper samples collected as injection was in progress (Table 14) confirm tracer presence (low mass) about 100-50 m downstream of the tracer. Tracer presence in the water immediately downstream of the injection

location and during the injection was quantified by pumped water sampling (see the photograph corresponding to samples PPs 10/11/12 Appendix 2). The equivalent size of the tracer estimated from image analysis indicated a range of (equivalent) grain sizes (EGS) during injection from ~4 to 60 μm in suspension. Towards the end of the ebb tide during the injection day, filter paper samples were also taken from the downstream end of the estuary (Transect 4 ~RM0; Fig. 2; Table 14), and these showed positive, low mass value silt tracer identifications in all (six) sampling events. In addition, red tracer bordering on the sand-silt boundary was also detected in dipped magnet samples WM-6 and WM-7 collected at Transect 4 (~RM1.5) during the late ebb phase (Table 15). These observations collectively confirm longitudinal (and lateral, through transect-based sampling) tracer transport down the waterway and to the vicinity of RM 0. Tracer mass values were universally low (10^{-4} to 10^{-6} g), nonetheless these observations *directly confirm* advective transport (and lateral turbulent mixing and diffusion) of tracer over these distances. The equivalent grain size of the tracer in suspension from both dipped magnets and pumped samples (Tables 14 and 15) measured using the image analysis methodology reveals particles in the range 10 to 60 μm and 14 to 59 μm, respectively i.e. broadly the entire range of tracer particle sizes, including the coarse silt fraction. This indicates that the river and estuary flows during the ebb-tide injection were sufficiently powerful to maintain all these particles in suspension[5]. Were this not the case then it would be expected that the spectrum of particle sizes in suspension sampled towards the end of the ebb tide would be skewed towards the fine fraction.

Although sampling continued for a further nine weeks, these specific data demonstrate tracer transport *into the waterway* as well as *how far into or beyond* the cleanup site particles have travelled (for the hydrodynamic conditions present during the 2 month study period), and in this respect the study is considered successful in meeting the principal project objectives (see Section 1.2.2).

The pool of suspended silt tracer present in the water column at the end of the ebb tide of the day of release represents tracer which is available for continued transport in suspension by ensuing tides. The size range of particles indicates that the entire silt fraction is present and able to be transported by the tidal currents. The tracer detected by pumped water sampling (WW 01/02/03 on Transect 1) is considered to be the 'leading edge' of the plume, and therefore it is not unreasonable to assume tracer is distributed in three dimensions within the estuary waters upstream of ~RM0 at the moment when the ebb tide turned. This provides a conceptual model of a low tracer mass distributed throughout the tidal waters at the end of the ebb tide, characterized by a full range of silt particles in terms of suspended tracer size. This material is potentially available to be intercepted by the array of fixed magnets during subsequent tides, and is available for deposition to the estuary bed if or when the hydrodynamic conditions permit.

Week 1 Suspended Silt Tracer Transport

Unlike for the sand tracer, silt tracer was found on most fixed magnets throughout the Lower Duwamish Waterway when sampled after 1 week (including upstream of the injection location; Fig 16)). It is important to note that whereas the preceding discussion summarized the evidence for silt tracer transport during the day of release, description of patterns of silt tracer transport for Week 1, Month1, and Month 2 sampling periods is necessarily different; these time periods are comparatively long with regard to the sampling frequency and therefore only a time-averaged view of tracer (re-)distribution can be made. It cannot be known, for example, *when* the tracer arrived at locations where it was sampled (although the evidence exists for transport to RM0 on the tracer release day and this is a useful guide).

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[5] Observations of the distance traveled by tracer sand following injection indicate that the ebb estuarine-river flow was reasonably energetic.

Sampling after 1 week showed that tracer was distributed throughout the estuary both on fixed magnet samples and within bedded samples, confirming the processes of both advective transport of the suspended fraction and deposition to the estuary bed. Since the length scale of tracer transport is known to be to RM0 during the day of release, the distribution of mass on fixed magnets and within bedded samples potentially may reflect transport processes on this day alone. A plot of the tracer mass normalized to a unit submergence timescale for Week 1 (Fig. 18) shows higher tracer mass values for magnet #3[6] (RM 4), a monotonic decrease in mass by magnet #5 (~RM 3.5) and thereafter low values (~10^{-5} to 10^{-6} gT^{-1}); this pattern is also evident visually from the map in Figure 16. The lower river section (RM 0 to 2.2), northwest of fixed magnet #7 all display low mass values (Fig. 16). The existence of a longitudinal concentration gradient within the estuary, caused by progressive dilution of silt tracer down the estuary axis, suggests that the pattern of tracer distribution is dominantly due to processes occurring during Day 0, rather than to processes occurring subsequently.

The plot of mean EGS for the silt tracer for each of the fixed magnets down the estuary (Fig. 20) indicates no significant trend in grain size and hence supports the inference from both upstream and downstream filtration samples (Table 14) and dipped magnets (Table 1) of negligible or zero changes to the suspended tracer size spectrum. The same conclusion is provided by treating the data on a reach averaged basis (Table 16), and in fact this appears to be the case during Month 1 sampling also (Fig. 19).

Silt Tracer Deposition

The appearance of tracer within collected bedded samples indicates deposition within the estuary during Week 1. As noted, it is not possible to know when this deposition occurred. It is tempting to conclude that deposition during the day of tracer release was minimal since the spectrum of particle sizes in suspension and the end of Day 0 was not significantly different from at the start, but this cannot be substantiated. Nonetheless, high tracer mass values are found the length of the estuary, and the frequency of medium tracer mass values increases in the vicinity of RM 0 to 1, and this suggests a weak longitudinal gradient in terms of mass deposition that may be due to processes which occurred on Day 0. In addition, there is evidence of deposition of larger silt particles in locations where deposition appears to be greater (Table 17). Regardless of when deposition may have occurred during Week 1, what must be investigated is the inference within the data of highly similar particle size spectra for both suspended and deposited tracer the length of the estuary (Table 16), particularly in the lower estuary region (Fig 21). This situation initially appears anomalous as it indicates concurrent suspension transport and deposition.

In order to understand processes influencing the transport and deposition of silt tracer the data were presented as a series of histograms representative of a) bedded sediments and b) suspended sediments for each river reach (RM 0 to 2.2, 2.2-4, 4+) (Fig. 21). The objective was to investigate whether any systematic trends in suspended tracer deposition were apparent down the estuary.

The results for Week 1 sampling are interesting. For RM4+ comparison of the two histograms shows that tracer particles of 30 to 60 μm EGS (coarse silts) are found both in suspension and on the bed; the same is the case for RM 2.2-4, although there is an indication that medium silts are found in the bed

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[6] Fixed magnet #3 is ~500 m from the tracer injection location, and the presence of medium-high tracer mass values here provides a length scale of relevance to future studies; although tracer can be tracked to far lower number concentration levels using powerful magnets, for the river/estuary flow and the mass of tracer used in the study, useful data of a sufficient data density and therefore quality was collected at this distance from the release point.

but not in suspension. The data is counter-intuitive in that one might expect the finer fraction where it is evident to be found in suspension, and coarser grains to be settled onto the bed. This is likely either a sampling artefact or an artefact of compositing the data, as it is not evident if the data are examined in other ways (e.g. Table 16).

For RM 0 to 2.2, the reach-averaged particle size histograms indicate a wider range of particles in suspension and on the bed. Critically, the histograms for the bed samples and water column samples are highly similar (although for some individual samples there is a suggestion of larger silt tracer particles where bedded mass values are higher; see Table 18). The only means of explaining these observations is through the existence of velocity gradients, including the existence of a bottom boundary layer, within the water column. It is not unreasonable to assume that the tracer is well-mixed through the water column in the lower estuarine reaches, and evidence of very fine tracer sand in suspension in the downstream reaches as noted indicates a moderately energetic water flow. This means that tracer grains may experience differing flow velocities according to their position in the water column, in particular those closer to the bed will experience reduced flow velocities due to bed friction. If this is the case, then deposition from suspension may occur for tracer within low velocity regions concurrently with persistent suspension of tracer material in higher velocity regions. This observation of a similar situation from the Month 1 sampling indicates that this is a real phenomenon. Moreover, deposition is recorded the length of the Lower Duwamish Waterway, and advection/diffusion of tracer into low velocity regions is the only physical mechanisms available to explain this. Although it was not undertaken, and although it would be only an indirect indication of deposition at the seabed, fixed magnets deployed onto small bed-frames would have provided insight into whether tracer was being transported close to the seabed.

These observations may have implications for the management of suspended contaminated sediments in the Lower Duwamish Waterway, in particular approaches to dealing with sources of ongoing (legacy) contamination. The classic notion of part of the silt fraction remaining permanently in suspension whilst the coarser component settles is not clear for the present study. Clearly, on a time-averaged and space-averaged basis the entire silt fraction can both remain in suspension and settle to the bed. In order to clarify further the physical processes which may be responsible for the observations, it would be useful to conduct a flow velocity measurement programme using ADCPs to map the vertical velocity structure at key locations within the estuary. A series of lateral transects from RM0 up to and including the tracer injection location (e.g. every 0.5 miles) through a full tidal cycle would be useful. Use of the numerical sediment transport model as well as contemporary data should be used to direct ADCP data collection to those transects where there is vertical structure in the water column, or to explore regions of lower velocity.

Month 1
Following sampling of the array of fixed magnets at the end of Week 1, a clean set of magnets were re-affixed to the sampling locations throughout the estuary. In terms of suspended tracer dynamics, there appears to be a downstream mass gradient (Figs. 16, 20), with magnets in the upper estuary (broadly from magnet #3 to magnet #8-9) exhibiting tracer mass values similar to Week 1 values, and values in the lower estuary reaches approximating very low values or zero. The presence of a tracer mass gradient is not simply explained during this sampling campaign, except potentially by tidal resuspension of tracer which may have settled in upstream areas following injection. As for Week 1 sampling, the size of the silt tracer in suspension during Month 1 the length of the estuary is very similar (Table 16), and largely unchanging from that after Week 1 sampling, and there are no strong longitudinal gradients in tracer EGS (Fig. 20).

Bedded samples show that deposition has occurred in all river reaches with mass values generally similar to those reported within Week 1. However, it is important to understand that there is no basis to indicate that these bedded sample tracer mass values arise from deposition of suspended silt during the Month 1 sampling interval; because sampling of bedded sediments using grabs and corers never returns to precisely the same seabed location, it is entirely possible that the distribution of tracer within the bottom sediment down the estuary was produced sometime during Week 1 (and in fact the similarity between the two sampling events, the similarity of the data in the size distribution histograms, and the similarity of Month 2 bed sampling data all tend to support this view). This can never be known, and yet it is an important consideration for sediment tracking studies. In contrast, sampling using arrays of fixed magnets is a true Eulerian method in which time-series data can be examined more objectively because they *do* sample exactly the same location.

Month 2
Very few fixed magnets were sampled during the Month 2 sampling campaign (only magnets #15 and #16) (Fig. 21). Tracer mass values at these locations were medium. Tracer EGS values ranged 16 to 36 μm; the maximum value of 36 μm suggests a slightly finer pool of suspended tracer in comparison to the Month 1 and Week 1 sampling intervals. Such a result is not surprising given the longevity of the sampling (see Table 16). The distribution of silt tracer within bedded samples is given in Figures 16 and 21. As for the Month 1 sampling campaign, it is not possible to discern whether the distribution of tracer within seabed samples represents accumulation during the second month, or is a pre-existing distribution created at some earlier time period. Tracer mass values are generally either high (for RM>2.2), with zero values occasionally reported from RM 0 to 2.2. As noted above, the general similarity in spatial extent and tracer mass to both Week 1 and Month 2 suggests that this may be the case. Additional care was taken for many of the bedded samples during sample retrieved during Month 2 (see Table 1), wherein the overlying water was successfully captured and re-combined with the sediment sample, and there is every reason to believe that these data (in particular) are reliable.

6.5 Inter-comparison of Different Sampling Campaigns

The fixed magnet data presented in this report have been normalized and presented through the use of a unit submergence time (see Section 5.2.6). This was chosen on the basis of discussions with Ecology. The rationale behind this approach, rather than a tracer (accumulation) mass per day normalization, is that results based upon the latter tend to suggest that *a fixed mass of tracer is intercepted/captured by the magnets each day*, and this is not true in reality. In reality, the probability of tracer capture decreases due to mixing, dispersion and dilution in the tidal waters, and this can be complicated by usual circulation patterns of factors such as wind drift which may transport water (and hence tracer) to specific regions. The presentation of tracer mass normalized to the maximum submergence period of the sampling interval (T_{max}) is *to represent the data as though each magnet was submerged for an equal time through the sampling campaign*. This makes the data inter-comparable within each sampling campaign, however since T_{max} is different for the 1 Week, 1 Month and 2 Month campaigns it makes the inter-comparison between these campaigns difficult.

In order to compare fixed magnet data between the Month 1 and Week 1 (and Month 2 and Month 1) sampling periods, the data have been transformed to discrete accumulation rates (g.day^{-1}). In order to achieve this, the Week 1 magnet data have been adjusted using blank magnet data (using Equation 1; Table 7) to account for the fact that they were not cleaned prior to deployment on Day 0. Figure 22 shows this data for all three sampling campaigns.

It is clear that accumulation rates for suspended tracer appear to be visibly greater in the central and upper estuary region (upstream of magnet #10). The reason for this is not obvious, but it is interesting to note that other evidence indicating weak longitudinal concentration gradients provides evidence for greater silt tracer mass in the central and upstream areas (see above). The conceptual model described suggests the formation of a longitudinal concentration gradient during tracer injection and maintenance during the Week 1 sampling. A pool of mobile suspended tracer (of a relatively broad size spectrum) is available for transport up and down the estuary by the tidal (and river) flows. However, once magnet sheaths were renewed at the start of both Month 1 and Month 2 sampling, any concentration gradients associated with tracer release should have disappeared. Consistently higher accumulation rates in the middle-upper estuary can only be attributed to a source of tracer, and resuspension of bedded sediments was previously suggested as a potential candidate. However, without any data on the bed material erodibility within the estuary, and on the magnitude of bed friction due to tidal currents, it is difficult to establish this as a causative process with any confidence. Deployment of bed-frames with ADCP instruments and turbidity sensors at locations upstream of ~RM1 would be useful as they would indicate directly if there is localized resuspension of bottom sediments within the estuary.

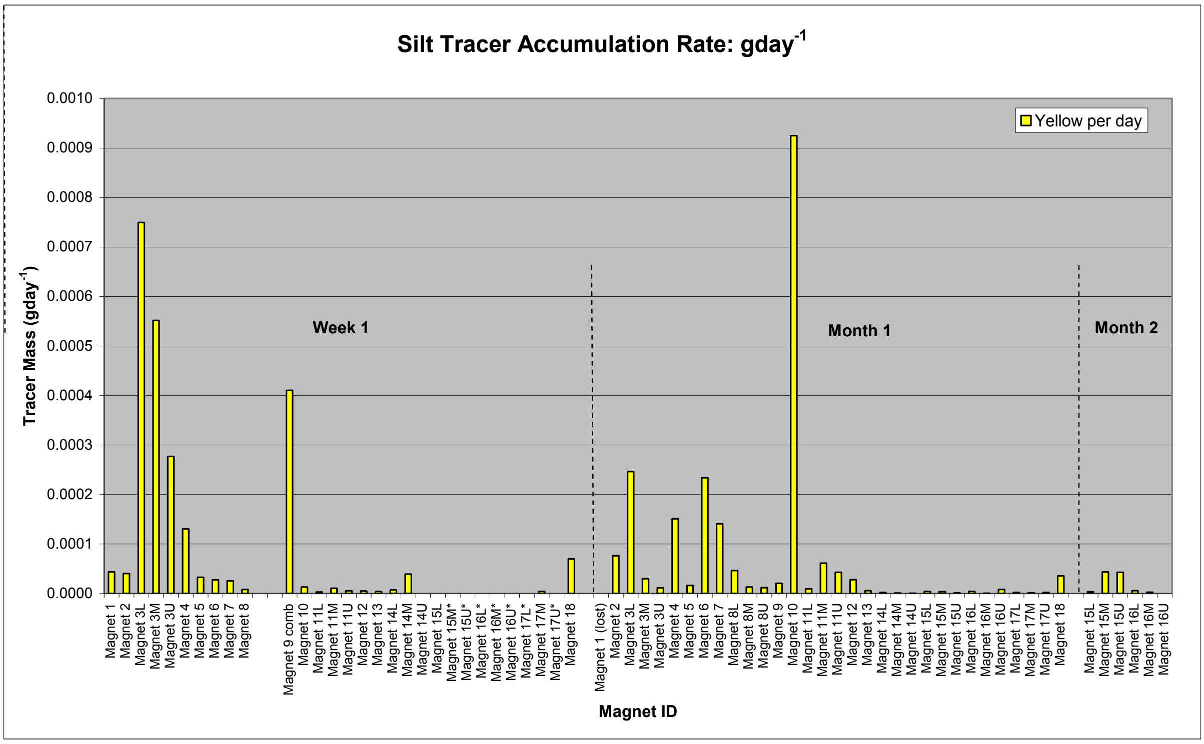

Figure 22 Comparison of silt tracer data (expressed as accumulation rate in gday^{-1}) between Week 1, Month 1 and Month 2 sampling periods. The * for Week 1 magnets indicate no data as blank values>data values.

Figure 23 shows a subtraction (comparison) plot of the accumulation rate data for Month 1 versus Week 1. The mass accumulation rates for Week 1 were subtracted from corresponding Month 1 values (this is valid since the sampling location in space is the same between the sampling intervals). The graph shows the relative (and direction of) change in accumulation rate between these two sampling campaigns. With the exception of fixed magnet #10, which shows a significant increase in accumulation rate, there is no consistent pattern. In the estuary region to fixed magnet #9 two of twelve locations experience an increase in tracer mass, whilst the rest constitute decreases in mass from one sampling interval to the next else negligible change. In the lower estuary region (i.e. west of magnet #11) the differences are entirely negligible. With the exception of fixed magnet #10, generally the trend through time is largely as expected with tracer mass values at fixed (in space) sampling locations largely decreasing or unchanging. A mobile pool of tracer which is simply advected up and down the estuary by the tidal currents and which has reached a stable dilution would give these results (based upon the gday^{-1} normalisation). The reason behind the large difference in accumulation rate for magnet #10 is not known. Figure 24 shows the same analysis for the Month 2 versus Month 1 data; there are only six samples in this sampling interval four of which indicate negligible change, and two of which indicate an increase in mass, albeit at very low mass values. It is interesting to note the size data from this time period indicate a somewhat finer tracer spectrum in suspension, which is not surprising given the elapsed time from the tracking study start.

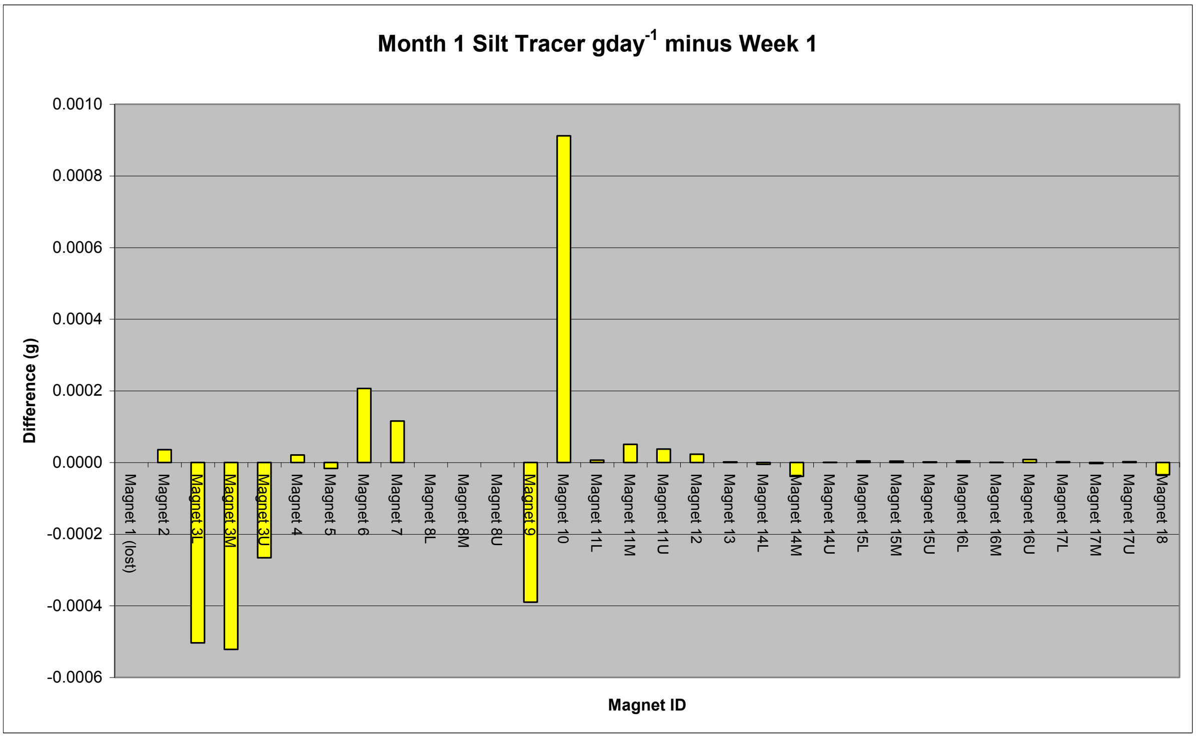

Figure 23 Difference bar chart plot showing the tracer mass accumulation rate for Week 1 substracted from that for Month 1.

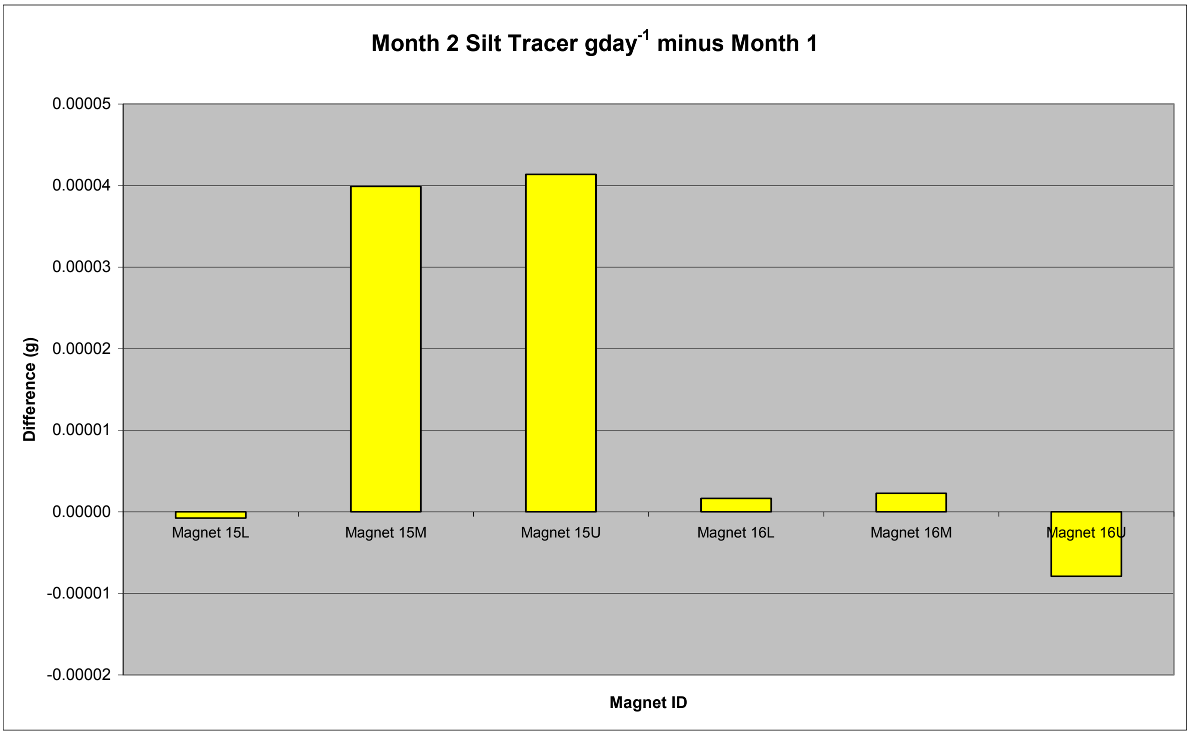

Figure 24 Difference bar chart plot showing the tracer mass accumulation rate for Month 1 substracted from that for Month 2.

7. CONCLUSIONS

The study formed part of a wider study to examine the patterns of contaminated particulate material within the Lower Duwamish Waterway. This study has involved manufacture of differing tracers to mimic the hydraulic behaviour of silts and sand sediments which may be delivered to the waterway by the river.

The conclusions can be summarized in relation to a) tracer design, manufacture and testing, b) tracer injection and field sampling activities, and c) analysis of data and results.

7.1 Tracer Design, Manufacture and Testing

Samples of the native silts and sands within the Lower Duwamish Waterway were tested for their physical-hydraulic properties, and design criteria established by Ecology to inform manufacture of two sediment analogues (tracers): a very fine-to-fine mineral density sand, and a silt tracer hydraulically matched to the medium silts found within the estuary. Two fluorescent-magnetic, dual signature tracers were ordered and made according to the specifications. Each proved to be highly para-magnetic and highly fluorescent. However, the sand tracer satisfied the specification but artefactually contained a minor textural fraction within the very coarse silt range (an issue which was subsequently resolved completely during the sample analysis stage); the silt tracer was hydraulically a silt typical of bedded silts within the waterway, but slightly coarser than specified (it contained coarse to very coarse silt fractions). Tests revealed that the tracer did not overlap in an hydraulic sense with the sand tracer, and it was certified for use in the tracking study.

Generally the tests, analyses and analytical methods used met specified measurement quality objectives.

7.2 Tracer Injection and Field Sampling Activities

A method which involved gentle flushing of tracer down a sub-surface pipe, was designed to introduce ('inject') each tracer into the surface waters of the Lower Duwamish Waterway, and this proved highly successful. Plumes of submerged tracer were observed adverting downstream during this activity. A 2 month sampling strategy combining an array of fixed (11000 gauss) magnets, bed sampling, and filtration of pumped water samples and dipped (towed) field portable magnets was designed and successfully implemented within the waterway from RM4+ to RM0. In particular the benefits of using a magnetic tracer with submerged fixed magnets (i.e. a Eulerian approach) throughout the waterway as a means of intercepting tracer was evident. Bed sampling was undertaken to support fixed magnet data and to monitor deposition, but limitations on this method for sampling deposited tracer were evident (although improvements to the approach were implemented at nine sampling locations with some success). The pump sampling and dipped magnets also provided useful (and unequivocal) information on tracer presence-absence, some of it in real-time and this guided field sampling activities.

7.3 Analysis of Data and Results

The study demonstrated the ability to recover magnetic tracers from a relatively large, diluting system using limited tracer mass and with different sampling methods. It is considered that the data collected contribute directly to fulfilling the project objectives. However, issues associated with sampling fine bedded sediments in an un-biased manner, coupled with the frequent very low tracer mass values in

samples (due to dilution and dispersion within the waterway) indicate the appropriate manner in which to present and interpret data is through an ordinal (low-medium-high) rather than direct, quantitative approach.

Although the particle tracking methodology is based on mass, an image analysis method was used to determine the tracer mass in collected samples due to the presence of native magnetic material. Whilst this provided quantitative data, the method under-estimated tracer mass within samples by a factor between 1.6 and 3.2. Further, the probability of detecting tracer was only 81%, and there was also measurable variability during sample processing. Modifications to this method e.g. removal of a human operator, a different approach to scanning the sample etc., can be made to improve the results.

Sand Tracer:— It was nominally considered that the tracer sand would deposit in the near-field of the tracer injection location i.e. within a footprint region immediately downstream of the injection location, and the number of samples collected were sufficient to detect this pattern. There was evidence of initial suspended transport of sand over a distance of ~150 m, and deposition of large tracer sand grains (~100-250 μm) within 500 m of the injection location. Sampling locations farther downstream at ~RM 3.4 indicate transport of very fine sand (particles ~60 to 70 μm) in suspension. This represents a size fractionation, and indicates the flow conditions at that time were able to transport particles of this size some distance through the waterway. Isolated samples at very low concentrations, indicate tracer particles of this size in the region of the Western Gateway area (RM0).

With a single exception, fixed magnets did not record sand tracer in suspension during the 1 and 2 month sampling periods, which indicates that the tracer sand was likely an immobile sediment pool, most of which was on the seabed within the upper estuary.

Silt Tracer:— Unlike for the sand tracer, silt tracer was found on most fixed magnets throughout the Lower Duwamish Waterway. Sampling using dipped magnets and pumped water sampling on the day of tracer injection confirmed longitudinal (and lateral) tracer transport to the vicinity of RM 0. Concentrations were universally low (10^{-4} to 10^{-6} g), with perhaps the study operating very close to the limits of the tracking methodology. Nonetheless these observations *directly confirm* advective transport (and lateral turbulent mixing and diffusion) of tracer over these distances during a single tidal ebb duration. Whilst this project arguably is ambitious in its approach, the study has demonstrated the ability to recover magnetic tracers from a relatively large, diluting system using limited tracer mass and with different sampling methods. It is considered that the data collected contribute directly to fulfilling the project objectives.

A distinctive longitudinal concentration gradient developed during Day 1. There is weak evidence that areas of higher deposition are characterized by the coarser silt fractions which might be associated with a longitudinal gradient in particle size. However, largely, this is not the case and the size range of particles in suspension (~10 to 60 μm) is highly similar down the estuary length. While this might suggest non-deposition, examination of tracer in bedded samples indicates that deposition has occurred down the length of the estuary. Of interest, the distribution of silt tracer particles size within bedded sediments is highly similar to those in suspension. Concurrent transport in suspension and deposition along the estuary length is explained by widely dispersed tracer encountering regions of lower flow velocity (e.g. the bottom boundary layer, backwater regions) where deposition is possible. These observations may have implications for the management of suspended contaminated sediments in the Lower Duwamish Waterway, in particular approaches to dealing with sources of ongoing (legacy) contamination). The classic notion of part of the silt fraction remaining permanently in suspension whilst the coarser component settles is not clear for the present study, likely due to the prevalent hydrodynamic conditions through the study.

The pool of suspended tracer at the end of Day 1 provides a mobile pool of material available for transport through Months 1 and 2. An inter-comparison of the fixed magnet data for Week 1 and Month1 is not yet possible and will be reported subsequently. The distribution of tracer in bedded samples through Months 1 and 2 is highly similar to that observed for Week 1, which indicates that the pattern may have arisen due to deposition during the early phase of the study and changes little during time.

8. RECOMMENDATIONS

This study is the first use of the fluorescent-magnetic sediment tracking methodology over such wide spatial scales and over such timescales. Consequently some experience has been gained during the study which points towards a number of recommendations. These are summarized in Table 20.

Table 20 Summary of recommendations arising from the tracking study.

Basis of comment	Issue	Approach/Benefit
Financial resource	Purchase of greater quantities of tracer and use of multiple injection vessels to establish a greater cross-stream input	Increases the probability of finding tracer downstream; improves mass transport estimations.
Financial resource	Use of a greater number of survey vessels downstream for sampling	Will permit greater spatial (and temporal coverage) thereby improving data collection/tracer recovery.
Technology	Sampling	For **a background value** aim to deploy magnets at all subsequent sampling locations; always pre-cleaned magnets prior to tracer injection. Use of magnets at a fixed datum (e.g. relative lowest tide or MSL) in order that issues regarding submergence time and the probability of tracer capture are minimized/removed. Development of a calibrated 'magnetic sampler' for bedded sediments and other alternative sampling methods e.g. diver-deployed suction sampler, box core, will improve confidence in tracer recovery and detection. Use of interval pump sampling at **fixed** sites within the LDW; this constitutes Eulerian time-series sampling as done in dye tracking studies and as performed by the fixed magnet samples.
Technology	Field data acquisition of flow etc	Collection of concurrently flow velocity data would be a considerable advantage; use of vessel-mounted ADCP attached to one of the small vessels would provide a hydrodynamic backdrop/context to future studies.
Laboratory methodology	Improvements to image analysis	Automation of the tracer image analysis component to remove a human component would be significant; or use of entirely human-independent technology e.g. FlowCam (www.planet-ocean.co.uk). This is a machine similar to laser diffraction instruments which can count and analyse for shape and fluorescence signature millions of particles over a wide dynamic range

		of size very quickly. This would reduce the uncertainties associated with image analysis and sample processing can be applied to the whole (parent) sample without need for sub-sampling
Laboratory methodology	Improvement to filter methodology	Use of dissolvable (e.g. cellulose acetate) filter papers; this would facilitate recovery of tracer for enumeration.

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10. APPENDIX 1 QUALITY ASSURANCE PROJECT PLAN: COMPARISON OF MQ OBJECTIVES WITH DATA (INCLUDING HYDRAULIC SIMILARITY DATA)

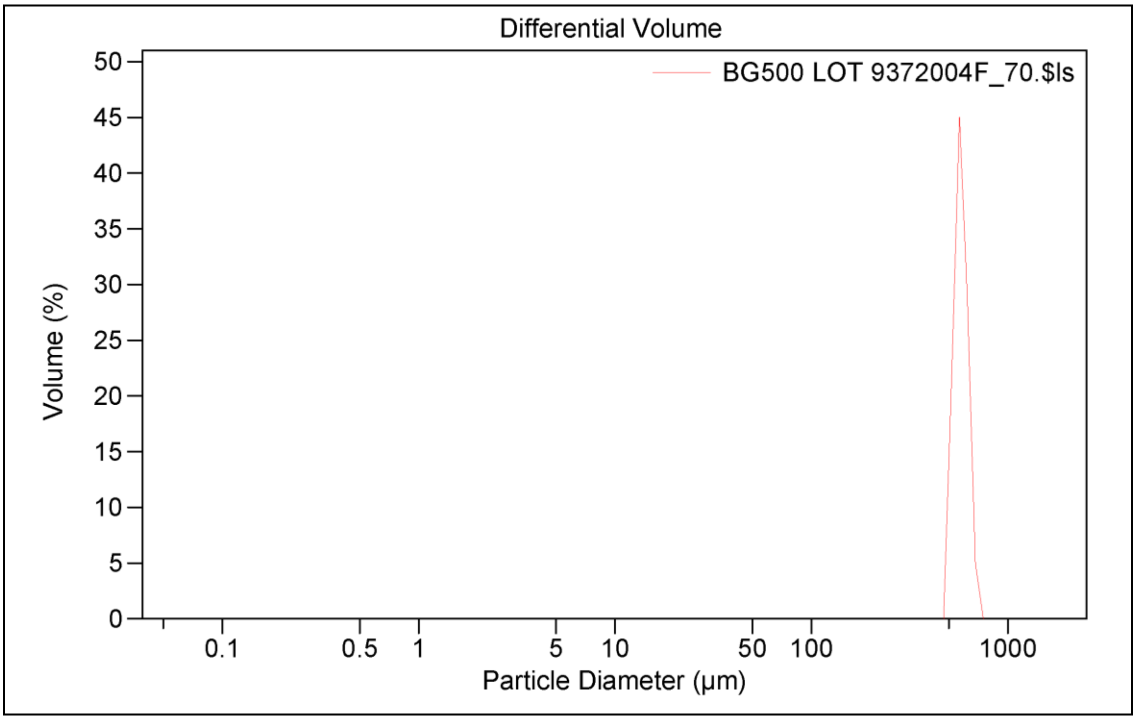
Table 7 Comparison of MQ objectives with data

Parameter		**Sensitivity DL/RL**	**Tracer**	**Precision RPD/RSD**	**Tracer**	**Bias**	**Tracer**	**Accuracy**	**Tracer**
Analytical QA									
Specific gravity or density (g/cm^3)		0.1	✓	± 5%	±3.7%	± 5%	+2.1%	± 6%	±5.5% (CRM)
Settling velocity (min, mode, max) (cm sec^{-1})		0.2	0.1	± 20%	Single sample only run	± 20%	Single sample only run	± 20%	**N/A**
Tracer PSD (min, mode, max) (microns)		0.2	±1% of d50	± 20%	<1% (3 triplicates)	± 20%	0 (3 triplicates)	± 20%	± 5% (CRM)
Release (compared to targets or field conditions)									
Location (m)		± 10	~~± 3~~To be calculated by Ecology ~~± 20%~~ ~~± 20%~~ ~~± 20%~~						
TSS (mg/l) EPA Method 2540D		0.5							
Tracer Analysis									
Tracer particles	Number counted	1 in 300 magnetic particles examined		N/A		N/A		N/A	
Tracer concentration	Number / liter	0.5 (assumes 2L filtered)	✓	± 25%	Coefficient of variation (45 to 86%)	± 25%	Variable (not directionally consistent)	± 25%	
	Number / m$^{2)}$	5 (assumes 1/0.2 m^2)	✓	± 25%	Coefficient of variation (45 to 86%)	± 25%	Variable (not directionally consistent)	± 25%	
Tracer mass (dry mg)	Instrument	0.1		± 20%		± 30%		N/A	

Parameter		**Sensitivity DL/RL**	**Tracer**	**Precision RPD/RSD**	**Tracer**	**Bias**	**Tracer**	**Accuracy**	**Tracer**
	Sample mg/m^2	0.5	0 1	± 25%		± 25%	Variable (not directionally consistent)	± 25%	220%

<u>HYDRAULIC SIMILARITY</u>		**Specified/Native Sediment**	**Tracer**	**SNS/Tr**	**Notes**
Density (gcm-^{3})	Sand	2580	2512	1.03	
	Silt	1200	1210	0.99	
Settling velocity (ms^{-1})	Sand	0.006 to 0.040	0.002 to 0.029	N/A	
	Silt	0 .00013 to 0.00024	0 .00037 to 0.001188	N/A	Note: reduced density particles
Grain Size (µm)	Sand	156 (d50)	73 (d10)-128(d50)-248(d90)		Native range partially specified verbally
	Silt	30 (d50)	21(d10)-50(d50)-79(d90)		Native range partially specified verbally

Laser Particle Size Analysis



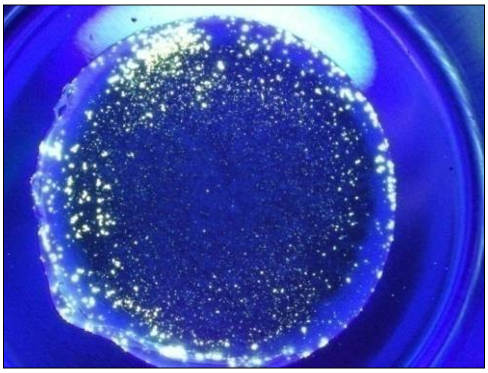
Certified Reference Material (CRM) for laser particle size analysis

Uniform Glass Beads

Reference Material Size 570 µm
File name: \Partrac\BG500 LOT BG500 LOT 9372004F_70.$ls
File ID: BG500 LOT 9372004F
Operator: B Hume
Run number: 70
Comment 1: EXP 13/11/10
Calculations from 0.040 µm to 2000 µm
Volume: 100%
Mean: 577.0 µm
Median: 575.6 µm
Mean/Median ratio: 1.002
Mode: 567.8 µm
S.D.: 1.079
Variance: 1.165

11. APPENDIX 2 FILTER PAPER PHOTOGRAPHS

Fluorescence macro-photographs of small filter paper surfaces at various times during tracer release (02/13/09). The silt (yellow) tracer was injected first, followed by the sand (red) tracer.



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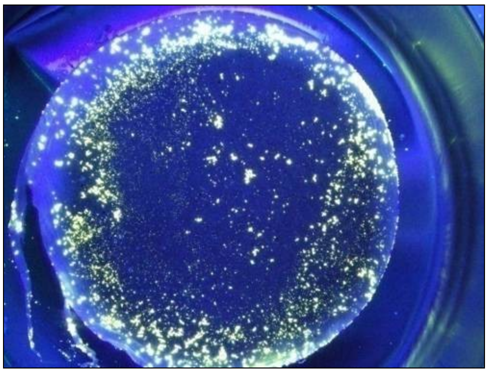
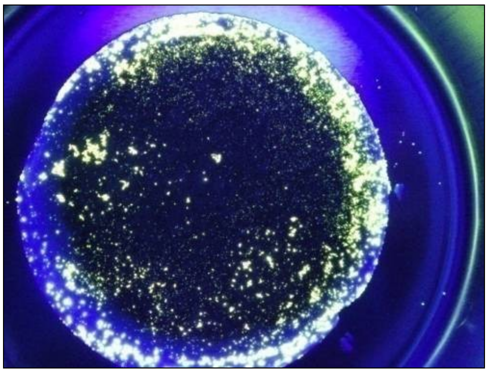
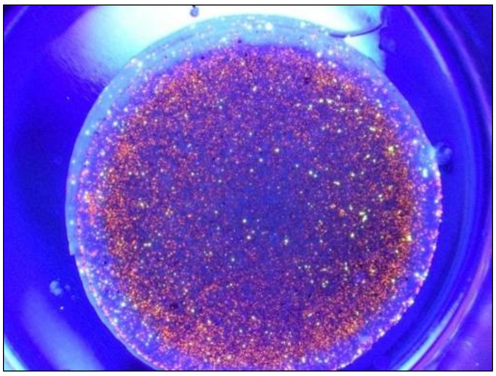


P5511 Time 09:25



P5510 Time 09:43



P5506 Time 10:40

12. APPENDIX 3 SAMPLE CHAIN OF CUSTODY FILES

Partrac sample Chain of Custody sheet

Log-in Date:	11/03/2009, 19/03/2009
Laboratory:	Gatty Marine Research Institute
Project Name:	Tracer - Washington
Project Number:	P1062
Reference:	P1062

Partrac Contact Name:	Niall Turnbull & Barbara Hume		
Phone:	0141 303 8255	Email:	nturnbull@partrac.com bhume@partrac.com

Date(s) Samples Taken	17/02/2009 18/02/2009 12/03/2009	
Location(s) Samples Taken	Lower Duwamish, Washington	
Sample Reference No.(s)	LDS – 04W	02/17/09
	LDS – 04W(2)	02/17/09
	LDS – 04M	02/17/09
	LDS – 06E	02/17/09
	LDS – 06E(2)	02/17/09
	LDS – 06W	02/17/09
	LDS – 06M	02/17/09
	LDS – 08E	02/18/09
	LDS – 08E(2)	02/18/09
	LDS – 08W	02/18/09
	LDS – 08W(2)	02/18/09
	LDS – 08M	02/18/09
	LDS – 08M(2)	02/18/09
	LDS – 09E	02/18/09
	LDS – 09W	02/18/09
	LDS – 09W(2)	02/18/09
	LDS – 09M	02/18/09
	LDS – 09M(2)	02/18/09
	LDS – 10E	02/18/09
	LDS – 10E(2)	02/18/09
	LDS – 10W	02/18/09
	LDS – 10W(2)	02/18/09
	LDS – 10W(3)	02/18/09
	LDS – 10M	02/18/09
	LDS – 10M(2)	02/18/09
	LDS – 11E	02/18/09
	LDS – 11E(2)	02/18/09
	LDS – 11W	02/18/09

	LDS – 11W(2)	02/18/09
	LDS – 11M	02/18/09
	LDS – 11M(2)	02/18/09
	LDS – 12E	02/18/09
	LDS – 12W	02/18/09
	LDS – 12W(2)	02/18/09
	LDS – 12M	02/18/09
	LDS – 12M(2)	02/18/09
	LDS – 08E	03/12/09
	LDS – 08E(2)	03/12/09
	LDS – 08W	03/12/09
	LDS – 08W(2)	03/12/09
	LDS – 08M	03/12/09
	LDS – 08M(2)	03/12/09
	LDS – 08M(3)	03/12/09
	LDS – 09E	03/12/09
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	LDS – 09W(2)	03/12/09
	LDS – 09M	03/12/09
	LDS – 09M(2)	03/12/09
	LDS – 10E	03/12/09
	LDS – 10E(2)	03/12/09
	LDS – 10W	03/12/09
	LDS – 10W(2)	03/12/09
	LDS – 10W(3)	03/12/09
	LDS – 10M	03/12/09
	LDS – 10M(2)	03/12/09
	LDS – 11E	03/12/09
	LDS – 11E(2)	03/12/09
	LDS – 11W	03/12/09
	LDS – 11M	03/12/09
	LDS – 11M(2)	03/12/09
	LDS – 11M(3)	03/12/09
	LDS – 12M	03/12/09
	LDS – 12M(2)	03/12/09
Sample Description	Natural magnetic material and fluorescent magnetic material.	
Type(s) of analysis to be performed	% of fluorescence particles using fluorescence micro-photography (Please e-mail several images) (Bulk %)	

Agreed Costs per Sample	
Special Comments	Return to Partrac after testing. Some dates are written; month-day-year and others are day-month-year
Storage Requirements	
SIGNED (Partrac)	
SIGNED (Laboratory)	

Partrac Sample Analysis Sheet

Log-in Date:	11/03/2009, 19/03/2009
Laboratory:	Gatty Marine Research Institute
Project Name:	Tracer - Washington
Project Number:	P1062
Reference:	P1062

Partrac Contact Name:	Niall Turnbull & Barbara Hume		
Phone:	0141 303 8255	Email:	nturnbull@partrac.com bhume@partrac.com

Date(s) Samples Taken	17/02/2009 19/02/2009 11/03/2009	
Location(s) Samples Taken	Lower Duwamish, Washington	
Sample Reference No.(s)	LDS – 01E	02/17/09
	LDS – 01E(2)	02/17/09
	LDS – 01W	02/17/09
	LDS – 01W(2)	02/17/09
	LDS – 02E	02/17/09
	LDS – 02E(2)	02/17/09
	LDS – 02W	02/17/09
	LDS – 02W(2)	02/17/09
	LDS – 02M	02/17/09
	LDS – 02M(2)	02/17/09
	LDS – 04E	02/17/09
	LDS – 04E(2)	02/17/09
	LDS – 13E	02/19/09
	LDS – 13W	02/19/09
	LDS –13M	02/19/09
	LDS – 14E	02/19/09
	LDS – 14M	02/19/09

	LDS – 14W	02/19/09
	LDS – 14W(2)	02/19/09
	LDS – 01E	03/11/09
	LDS – 01E(2)	03/11/09
	LDS – 01W	03/11/09
	LDS – 01W(2)	03/11/09
	LDS – 01M	03/11/09
	LDS – 01M(2)	03/11/09
	LDS – 02E	03/11/09
	LDS – 02E(2)	03/11/09
	LDS – 02W	03/11/09
	LDS – 02W(2)	03/11/09
	LDS – 02M	03/11/09
	LDS – 02M(2)	03/11/09
	LDS – 04E	03/11/09
	LDS – 04E(2)	03/11/09
	LDS – 04W	03/11/09
	LDS – 04W(2)	03/11/09
	LDS – 04M	03/11/09
	LDS – 04M(2)	03/11/09
	LDS – 06E	03/11/09
	LDS – 06E(2)	03/11/09
	LDS – 06W	03/11/09
	LDS – 06M	03/11/09
Sample Description	Natural magnetic material and fluorescent magnetic material.	
Type(s) of analysis to be performed	% of fluorescence particles using fluorescence micro-photography (Please e-mail several images) (Bulk %)	
Agreed Costs per Sample		
Special Comments	Return to Partrac after testing. Some dates are written; month-day-year and others are day-month-year	
Storage Requirements		
SIGNED (Partrac)		
SIGNED (Laboratory)		

Partrac Sample Analysis Sheet

Log-in Date:	11/03/2009,
Laboratory:	Gatty Marine Research Institute
Project Name:	Tracer - Washington
Project Number:	P1062
Reference:	P1062

Partrac Contact Name:	Niall Turnbull & Barbara Hume		
Phone:	0141 303 8255	Email:	nturnbull@partrac.om bhume@partrac.com

Date(s) Samples Taken	12/02/2009 19/02/2009	
Location(s) Samples Taken	Lower Duwamish, Washington	
Sample Reference No.(s)	**Magnet:**	
	Magnet # 1	
	Magnet # 2	
	Magnet # 3U	
	Magnet # 3M	
	Magnet # 3L	
	Magnet # 4	
	Magnet # 5	
	Magnet # 6	
	Magnet# 7	**Sample ID:**
	Magnet # 8U	84471
	Magnet # 8M	15011
	Magnet #8L	96269
	Magnet # 9	18696
	Magnet # 10	11133
	Magnet # 11U	92045
	Magnet # 11M	13352
	Magnet # 11L	81751
	Magnet # 12	15153
	Magnet # 13	76822
	Magnet #14 U	26010
	Magnet #14 M	70077
	Magnet #14 L	90843
	Magnet #15 U	56304
	Magnet #15 M	52630
	Magnet #15 L	25202
	Magnet #16 U	35946
	Magnet #16 M	31377
	Magnet #16 L	40758
Sample Description	Natural magnetic material and fluorescent magnetic material.	
Type(s) of analysis to be performed	% of fluorescence particles using fluorescence micro-photography (Please e-mail several images) (Bulk %)	
Agreed Costs per Sample		
Special Comments	Return to Partrac after testing. Some dates are written; month-day-year and others are day-month-year	
Storage Requirements		

SIGNED (Partrac)	
SIGNED (Laboratory)	

Partrac Sample Analysis Sheet

Log-in Date:	11/03/2009,
Laboratory:	Gatty Marine Research Institute
Project Name:	Tracer - Washington
Project Number:	P1062
Reference:	P1062

Partrac Contact Name:	Niall Turnbull & Barbara Hume		
Phone:	0141 303 8255	Email:	nturnbull@partrac.com bhume@partrac.com

Date(s) Samples Taken	12/02/2009 19/02/2009	
Location(s) Samples Taken	Lower Duwamish, Washington	
Sample Reference No.(s)	**Magnet:**	**Sample ID:**
	Magnet # 14T	87357
	Magnet # 14M	23540
	Magnet # 14B	86821
	Magnet # 15T	46556
	Magnet # 15M	30434
	Magnet # 15B	85413
	Magnet # 16T	63478
	Magnet # 16M	65142
	Magnet # 16B	30922
	Magnet # 17T	33826
	Magnet # 17M	52702
	Magnet # 17B	17101
	Magnet # 18	43058
	Magnet # 1 Blank 1/2	72375
	Magnet # 1 Blank 2/2	97897
	Magnet # 5 Blank 1/2	51861
	Magnet # 5 Blank 2/2	55985
	Magnet # 9 Blank	32313
	Magnet # 15 Blank 1/2	50177
	Magnet # 15 Blank 2/2	89418
Sample Description	Natural magnetic material and fluorescent magnetic material.	
Type(s) of analysis to be performed	% of fluorescence particles using fluorescence micro-photography (Please e-mail several images) (Bulk %)	
Agreed Costs per Sample		
Special Comments	Return to Partrac after testing. Some dates are written; month-day-year and others are day-month-year	
Storage Requirements		

SIGNED (Partrac)	
SIGNED (Laboratory)	

Partrac Sample Analysis Sheet

Log-in Date:	11/03/2009,
Laboratory:	Gatty Marine Research Institute
Project Name:	Tracer - Washington
Project Number:	P1062
Reference:	P1062

Partrac Contact Name:	Niall Turnbull & Barbara Hume		
Phone:	0141 303 8255	Email:	nturnbull@partrac.om bhume@partrac.com

Date(s) Samples Taken	09/03/2009	
Location(s) Samples Taken	Washington	
Sample Reference No.(s)	**Magnet:**	**Sample ID:**
	Magnet # 1	43691
	Magnet # 2	92129
	Magnet # 3U	58877
	Magnet # 3M	92772
	Magnet # 3L	68248
	Magnet # 4	40702
	Magnet # 5	95455
	Magnet # 6	38660
	Magnet# 7	90687
	Magnet # 8U	73724
	Magnet # 8M	47472
	Magnet #8L	14630
	Magnet # 9	21433
	Magnet # 10	72045
	Magnet # 11U	83995
	Magnet # 11M	83853
	Magnet # 11L	77600
Sample Description	Natural magnetic material and fluorescent magnetic material.	
Type(s) of analysis to be performed	% of fluorescence particles using fluorescence micro-photography (Please e-mail several images) (Bulk %)	
Agreed Costs per Sample		
Special Comments	Return to Partrac after testing. Some dates are written; month-day-year and others are day-month-year	
Storage Requirements		
SIGNED (Partrac)		

SIGNED (Laboratory)	

Partrac Sample Analysis Sheet

Log-in Date:	11/03/2009,
Laboratory:	Gatty Marine Research Institute
Project Name:	Tracer - Washington
Project Number:	P1062
Reference:	P1062

Partrac Contact Name:	Niall Turnbull & Barbara Hume		
Phone:	0141 303 8255	Email:	nturnbull@partrac.om bhume@partrac.com

Date(s) Samples Taken	09/03/2009 & 07/04/09	
Location(s) Samples Taken	Washington	
Sample Reference No.(s)	**Magnet:**	**Sample ID:**
	09/03/09	
	Magnet # 13	57252
	Magnet #14 U	54838
	Magnet #14 M	12146
	Magnet #14 L	10971
	Magnet #15 U	33757
	Magnet #15 M	42155
	Magnet #15 L	31423
	Magnet #16 U	66310
	Magnet #16 M	87555
	Magnet #16 L	17616
	Magnet #17 U	65911
	Magnet #17 M	79039
	Magnet #17 L	36732
	Magnet #18	81210
	07/04/09	
	Magnet #15 U	45934
	Magnet #15 M	14000
	Magnet #15 L	43055
	Magnet #16 U	45758
	Magnet #16 M	72834
	Magnet #16 L	24735
Sample Description	Natural magnetic material and fluorescent magnetic material.	
Type(s) of analysis to be performed	% of fluorescence particles using fluorescence micro-photography (Please e-mail several images) (Bulk %)	
Agreed Costs per Sample		
Special Comments	Return to Partrac after testing. Some dates are written; month-day-year and others are day-month-year	
Storage Requirements		

SIGNED (Partrac)	
SIGNED (Laboratory)	

Partrac Sample Analysis Sheet

Log-in Date:	11/03/2009, 19/03/2009
Laboratory:	Gatty Marine Research Institute
Project Name:	Tracer - Washington
Project Number:	P1062
Reference:	P1062

Partrac Contact Name:	Niall Turnbull & Barbara Hume		
Phone:	0141 303 8255	Email:	nturnbull@partrac.com bhume@partrac.com

Date(s) Samples Taken	07/04/2009 10/04/2009 12/03/2009	
Location(s) Samples Taken	Lower Duwamish, Washington	
Sample Reference No.(s)	**12/03/09**	**12/03/09**
	LDR – 104	88396
	LDR – 104 (2)	70387
	LDR – 171	47445
	LDR – 171 (2)	67443
	LDR – 174	30744
	LDR – 174 (2)	26773
	LDR – 225	37055
	LDR – 225	49055
	07/04/09	
	LDR – 10	94204
	LDR – 10	75140
	LDR – 9	31998
	LDR – 43	97183
	LDR – 43 (2)	80577
	LDR – 124	73598
	LDR – 124 (2)	78771
	LDR – 192	93961
	LDR – 192 (2)	75900
	LDR – 195	87218
	LDR – 130	96908
	LDR – 279	81516
	LDR – 279 (2)	41705
	LDR – 249	20321
	LDR – 249 (2)	75054
	LDR – 249 (3)	54031
	LDR – 300	90933
	LDR – 142	40612
	LDR – 142 (2)	74336
	LDR – 263	96184
	LDR – 263 (2)	14506
	LDR – 201	59495
	LDR – 201 (2)	10910
	LDR – 201 (3)	48559
	LDR – 143	33569

	LDR – 143 (2)	47761
	LDR – 246	34629
	LDR – 246 (2)	58359
	LDR – 246 (3)	61735
	10/04/09	
	LDR – 6	92451
	LDR – 6 (2)	48815
	LDR – 48	32601
	LDR - 48 (2)	10420
	LDR – 48 (3)	70425
	LDR – 63	74897
	LDR – 63 (2)	90357
	LDR – 34	57666
	LDR - 34 (2)	33618
	LDR – 55	37112
	LDR – 55 (2)	39065
	LDR – 172	31393
	LDR – 172 (2)	63820
	LRD – 172 (3)	18054
	LDR – 127	84045
	LRD – 127 (2)	95083
	LDR – 238	42338
	LDR – 238 (2)	23078
	LDR - 238 (3)	24166
	LDR – 186	36368
	LDR – 186 (2)	73800
	LDR – 186 (3)	19463
Sample Description	Natural magnetic material and fluorescent magnetic material.	
Type(s) of analysis to be performed	% of fluorescence particles using fluorescence micro-photography (Please e-mail several images) (Bulk %)	
Agreed Costs per Sample		
Special Comments	Return to Partrac after testing. Some dates are written; month-day-year and others are day-month-year	
Storage Requirements		
SIGNED (Partrac)		
SIGNED (Laboratory)		

Partrac Sample Analysis Sheet

Log-in Date:	11/03/2009, 19/03/2009
Laboratory:	Gatty Marine Research Institute
Project Name:	Tracer - Washington
Project Number:	P1062
Reference:	P1062

Partrac Contact Name:	Niall Turnbull & Barbara Hume

Phone:	0141 303 8255	Email:	nturnbull@partrac.com bhume@partrac.com

Date(s) Samples Taken	11/03/2009 16/03/2009 18/02/2009	
Location(s) Samples Taken	Washington	
Sample Reference No.(s)	**11/03/09**	**12/03/09**
	LDR – 3	13439
	LDR – 3 (2)	73098
	LDR – 19	25276
	LDR – 19 (2)	43531
	LDR – 27	82407
	LDR – 27 (2)	96674
	LDR – 44	70712
	LDR – 44 (2)	63687
	LDR – 69	62580
	LDR – 69 (2)	13500
	LDR – 79	28692
	LDR – 79 (2)	51880
	LDR – 92	69840
	LDR – 92 (2)	21530
	LDR – 126	38242
	LDR – 173	83358
	LDR – 173 (2)	85359
	LDR – 178	23984
	LDR – 185	16664
	LDR – 185 (2)	51680
	16/03/09	
	LDR – 20	
	LDR - 257	
	LDR – 56	60204
	LDR – 129	39002
	LDR – 129 (2)	94160
	LDR – 208	46894
	LDR – 208 (2)	72365
	LDR – 231	80218
	LDR – 231 (2)	53103
	LDR – 264	82406
	LDR – 282	93092
	18/02/09	
	LDR – 133	79334
	LDR – 137	21169
	LDR – 177	77672
	LDR – 177 (2)	92076
	LDR – 182	99456
	LDR – 182 (2)	58684
	LDR – 199	16138
	LDR – 199 (2)	59761
	LDR – 203	64472
	LDR - 203 (2)	67833
	LDR – 233	13043
	LDR – 257	12580
	LDR – 261	62981
	LDR – 261 (2)	74251
	LDR – 268	22556
	LDR – 268 (2)	49115
	LDR – 294	63388
	LDR – 294 (2)	77832
	16/03/09 LDS	
	LDS – 12 W	54035

	LDS – 12W (2) **LDS – 12E**	67035 67404
Sample Description	Natural magnetic material and fluorescent magnetic material.	
Type(s) of analysis to be performed	% of fluorescence particles using fluorescence micro-photography (Please e-mail several images) (Bulk %)	
Agreed Costs per Sample		
Special Comments	Return to Partrac after testing. Some dates are written; month-day-year and others are day-month-year	
Storage Requirements		
SIGNED (Partrac)		
SIGNED (Laboratory)		

Partrac Sample Analysis Sheet

Log-in Date:	11/03/2009, 19/03/2009
Laboratory:	Gatty Marine Research Institute
Project Name:	Tracer - Washington
Project Number:	P1062
Reference:	P1062

Partrac Contact Name:	Niall Turnbull & Barbara Hume		
Phone:	0141 303 8255	Email:	nturnbull@partrac.com bhume@partrac.com

Date(s) Samples Taken	12/03/2009 17/02/2009
Location(s) Samples Taken	Washington

Sample Reference No.(s)	**12/03/09**	**12/03/09**
	LDR – 220	39944
	LDR – 220 (2)	94106
	LDR – 227	48292
	LDR – 227 (2)	70004
	LDR – 260	64076
	LDR – 260 (2)	59968
	LDR – 266	56651
	LDR – 266 (2)	64448
	17/02/09	
	LDR – 5	71906
	LDR – 5 (2)	30464
	LDR – 8	48859
	LDR – 11	23556
	LDR – 11 (2)	22474
	LDR – 20	55072
	LDR – 29	33057
	LDR – 29 (2)	15243
	LDR – 41	17163
	LDR – 41 (2)	91652
	LDR – 82	66659
	LDR – 82 (2)	29115
	LDR – 12	12363
	LDR – 102 (2)	62113
	LDR – 134	30986
	LDR – 134 (2)	32240
	17/02/2009	
	LDS – 01M	66233
	LDS – 01M (2)	42550
Sample Description	Natural magnetic material and fluorescent magnetic material.	
Type(s) of analysis to be performed	% of fluorescence particles using fluorescence micro-photography (Please e-mail several images) (Bulk %)	
Agreed Costs per Sample		
Special Comments	Return to Partrac after testing. Some dates are written; month-day-year and others are day-month-year	
Storage Requirements		
SIGNED (Partrac)		
SIGNED (Laboratory)		

Partrac Sample Analysis Sheet

Log-in Date:	11/03/2009,
Laboratory:	Gatty Marine Research Institute
Project Name:	Tracer – Washington & ADAS
Project Number:	P1062
Reference:	P1062

Partrac Contact Name:	Niall Turnbull & Barbara Hume		
Phone:	0141 303 8255	Email:	nturnbull@partrac.com bhume@partrac.com

Date(s) Samples Taken	13/02/2009	
Location(s) Samples Taken	Washington	
Sample Reference No.(s)	**MW-01** **MW-02** **MW-03** **MW-04** **MW-05** **MW-06** **MW-07**	17832 60660 83289 21139 88734 67146 22857
Sample Description	Natural magnetic material and fluorescent magnetic material.	
Type(s) of analysis to be performed	% of fluorescence particles using fluorescence micro-photography (Please e-mail several images) (Bulk %)	
Agreed Costs per Sample		
Special Comments	Return to Partrac after testing. Some dates are written; month-day-year and others are day-month-year	
Storage Requirements		
SIGNED (Partrac)		
SIGNED (Laboratory)		

Partrac Sample Analysis Sheet

Log-in Date:	11/03/2009,
Laboratory:	Gatty Marine Research Institute
Project Name:	Tracer – Washington & ADAS
Project Number:	P1062
Reference:	P1062

Partrac Contact Name:	Niall Turnbull & Barbara Hume		
Phone:	0141 303 8255	Email:	nturnbull@partrac.com bhume@partrac.com

Date(s) Samples Taken	13/02/2009, 19/02/2009	
Location(s) Samples Taken	Washington	
Sample Reference No.(s)	**PP5501**	81473
	PP5502	58678
	PP5503	51964
	PP5504	60174
	PP5505	14230
	PP5506	30843
	PP5508	14752
	PP5509	96108
	PP5510	55316
	PP5511	72770
	PP5512	12947
	PP5513	77724
	WW-01	59535
	WW-02	24070
	WW-03	92720
	WW-04	20657
	WW-05	54025
	WW-06	31452
	WW-07	10060
Sample Description	Natural magnetic material and fluorescent magnetic material.	
Type(s) of analysis to be performed	% of fluorescence particles using fluorescence micro-photography (Please e-mail several images) (Bulk %)	
Agreed Costs per Sample		
Special Comments	Return to Partrac after testing. Some dates are written; month-day-year and others are day-month-year	
Storage Requirements		
SIGNED (Partrac)		
SIGNED (Laboratory)		

13. APPENDIX 4 STANDARD OPERATING PROCEDURES (SEDIMENT CHARACTERISATION)

13.1 Particle Density

Following the international standard: **ISO/TS 17892-3 (2004)**

13.1.1 Preparation

1. Label foil dish and place sub-sample (5 to 10 g) from main sample into foil dish.

2. Place foil dish into oven (80°C) for a minimum of 24 hours.

3. Print particle density datasheet :

   <u>P0007.04.D0003v02 – Determination of particle density</u>

   Rename document as appropriate, saving file into project folder.

13.1.2 Pycnometer Calibration

1. Weigh pycnometer (Figure 21) when dry.

2. Pour distilled water to the neck of pycnometer, replace capillary lid. Water should emerge from capillary lid. Ensure there are no air spaces or bubbles in pycnometer and leave at room temperature (20°C ± 5°C) for at least 30 minutes.

3. Dry the outside of pycnometer and record the weight on particle density datasheet.

4. Remove distilled water from pycnometer, rinse out with acetone to speed the drying process.

Figure 25 A volume pycnometer bottle.

Oven-dried Specimens

1. Remove sub-samples from oven and place in desiccator for a minimum of 15 minutes.

2. Ensure that pycnometer is completely dry.

ENSURE SCALES HAVE BEEN CALIBRATED BEFORE USE (SEE SECTION)

3. Weigh dry pycnometer and record value. Use the value from the calibration for "Mass of Pycnometer + liquid (g)."

4. Weigh the oven-dried samples and record value. DO NOT INCLUDE THE WEIGHT OF FOIL DISH. Samples should weigh > 5 g.

5. Carefully transfer the sample into mortar. Ensure ALL of the sample is in the mortar. Grind with pestle until fine sediment is the result or at least particles small enough to fit into pycnometer.

6. Prepare a small paper funnel to transfer sediment from mortar to pycnometer. Use a small brush to gently encourage the sediment into the funnel. Ensure ALL of the sediment is in the pycnometer.

7. Gently pour distilled water into pycnometer until water is 1 to 2 cm above the sediment. Ensure the water saturates into the sediment.

8. Place pycnometer bottle in a water bath and slowly heat for 10 minutes. This heating process agitates the sediment and aids with the removal of air from the pycnometer.

9. After 10 minutes, remove the pycnometer from the water bath and leave to cool to ambient temperature (approximately 1 hour).

10. To check temperature of contents, remove pycnometer capillary lid, and carefully insert thermometer.

11. Once the contents in the pycnometer have cooled (between 10°C and 30°C), gently fill the pycnometer with distilled water past the neck line. This ensures that there is no air in the pycnometer.

12. Weigh the pycnometer and record result.

13. Empty the pycnometer, and thoroughly rinse out contents. Rinse with a small volume of acetone and dispose.

13.2 Grain Size Analysis

Following the international standard: **ISO 11277 (1998)**

13.2.1 Dry sieving (material > 2 mm)

1. Weigh the sample (nearest 0.5 g) and record. Table 1 shows the recommended maximum weight (g) of sand for sieves indicated.

Table 8 Maximum load for 8 inch-diameter sieves using British Standards sieves (McManus, 1965), nominal aperture was converted from phi (Φ) to mm.

British Standard Sieves No.	Nominal aperture in mm	Recommended maximum weight of sand for sieve indicated (g)
7	2.37	150
14	1.18	100
25	0.59	70
52	0.29	50
100	0.14	35
200	0.07	25

2. Stack sieves of relevant sizes (generally 63 µm, 125 µm, 250 µm, 1 mm and 2mm for standard analysis, this may vary) onto the Ro-Tap shaker (Figure 22). Ensure that the solid pan is at the bottom of the stack, to catch the smallest particles.

3. Pour sample in the top sieve, gently brush material over sieve apertures with stiff sieve brush and cover with lid.

4. Secure sieve stack with lid and clamp onto shaker.

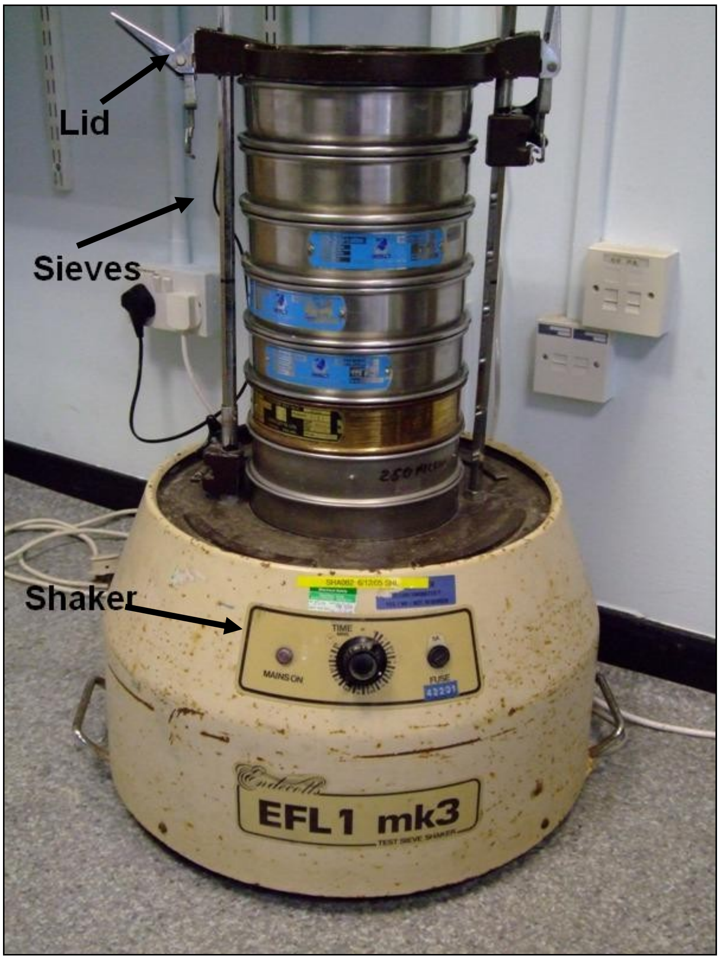

Figure 26 Ro-Tap Sieve shaker.

5. Run the shaker for approximately 15 minutes. Be aware that the shaker may move across the room.

6. Remove sieves from shaker. Remove top sieve and lid. Take a piece of A3 paper and make a crease down the middle. Carefully tip the sieve onto the paper. With the sieve upside down on the paper, use a sieve brush to dislodge any trapped sediment (see section 2.2 for brush technique).

7. Tip the sediment into a large foil dish (that has been weighed previously). Record amount retained to nearest 0.5 g.

8. Repeat for each sieve and bottom pan.

9. Clean sieves for next analysis.

10. Transfer weights recorded from each sieve into Gradistat (section 2.3.2)

13.2.2 Gradistat

1. Open GRADISTATv6.
2. Enter weight from each mesh size (are changeable) into single/multiply sample data input.
3. Calculate statistics.

Gradistat will produce grain size statistics about the sample.

Further instructions are on the first tab of the Excel document.

13.2.3 Wet sieving (material <2 mm)

NOTE: Removal of organic substances with reagents maybe performed prior to analysis but must be performed in a fume cupboard.

1. Set up a large container with a large funnel inside (make sure the funnel is large enough for sieve to comfortable fit inside.)
2. If sample contains > 2 mm particles, it may be advisable to stack a 63 and a 2mm sieve inside the funnel and rinse. Remove the 2mm sieve when all < 2mm has passed through.
3. Place sample on 63 μm sieve, and rinse with a small volume of water until the water that enters the container is clear.
4. Record weight of large foil dish and label.
5. Empty contents > 63 μm into large foil dish and place in oven (80°C) until dry.
6. Once dry, allow cooling in oven (switch off), weigh and record. Dry sieving into smaller size classes can now occur.

   If total percentage is required:

7. Allow sediment from container (< 63 μm) to settle. Once sediment has settled, remove excess water via siphon.
8. Record weight of large foil dish and label, empty contents into dish and place in oven (80°C) for a few days.
9. Once dry, allow cooling in oven (switch off), weigh and record until dry.
10. Calculate sand and silts as percentage of the total.

Table 9 Size scale Wentworth (1922).

Grain size	Descriptive term

phi (Φ)	**mm**		
-10	1024	Very Large	
-9	512	Large	**BOULDER**
-8	256	Medium	
-7	128	Small	
-6	64	Very Small	
-5	32	Very Coarse	**GRAVEL**
-4	16	Coarse	
-3	8	Medium	
-2	4	Fine	
-1	2	Very Fine	
0	1	Very Coarse	**SAND**
	µm		
1	500	Coarse	
2	250	Medium	
3	125	Fine	
4	63	Very Fine	
5	31	Very Coarse	**SILT**
6	16	Coarse	
7	8	Medium	
8	4	Fine	
9	2	Very Fine	
		Clay	

13.2.4 Sub-sampling

Sieving large quantities of sediment takes a long period of time. A solution to reducing sieving time is to take a sub-sample from main sample by the cone and quarter method.

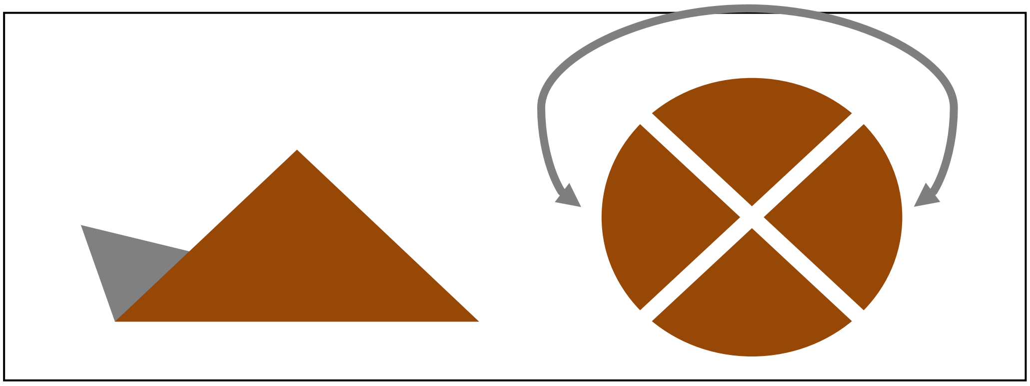

Figure 27 Pile of sediment (side view), and pile (aerial view) sectioned into quarters, indicating opposing quarters.

1. On a piece of A3 paper, make a neat pile of sediment.
2. Press down on the pile with something flat i.e. bottom of a tray.
3. With a ruler cut the pile into quarters (Fig. 23).
4. Take the two opposing quarters into one container, and remaining sediment into another container.
5. Mix sediment from opposing quarters together and repeating steps 1 to 4.
6. Repeat this process until the quantity required has been attained.

13.3 Settling Velocity

13.3.1 Silts

1. Prepare a number of filter papers for TSS the day before and charge Dataron.

2. Take a sub-sample and wet sieve <63 μm, empty approximately 50 ml into vial.

3. Fill 2 l glass beaker with 1.5 l of tap water.

4. Print out spreadsheet:

   P0007.04.D016v01 - Silts Settling Velocity TSS

5. Switch the Dataron on, synchronise time and date with a computer, use Data Bank GUI to do so. Then ensure it is on setting #13 (NTU) shown by Figure 10. Note the reading on tap water (0.50 – 1.00 NTU).

6. Attach OBS (optical backscatter sensor) to Dataron. Then attach the OBS to clamp and position OBS to the middle of the beaker, with the sensor window facing inwards. Set up shown by Figure 9.

Figure 9. Silts settling velocity set-up.

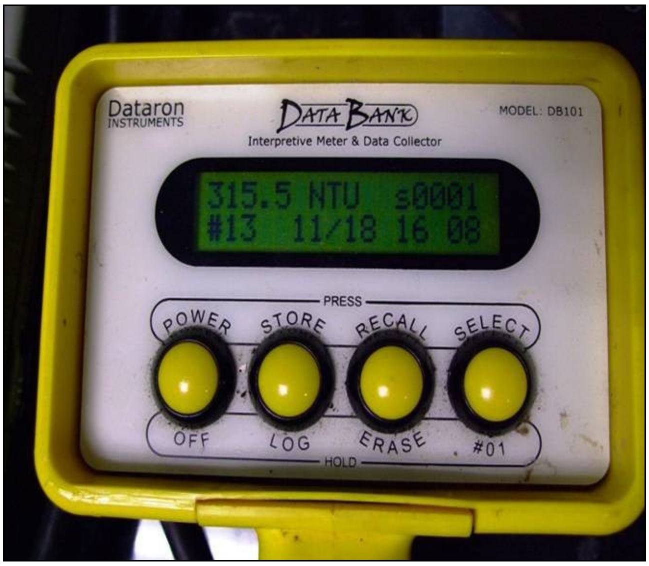

Figure 10. Dataron screen.

7. Fully homogenise the sample, and pour 25 ml into the glass beaker. Carefully stir the liquid and start logging on the Dataron by holding down STORE/LOG button. This will record a reading every 5 seconds.

8. Record the time and NTU value from the Dataron then with a syringe, remove 50 ml from the glass beaker. Perform TSS (section 3). Repeat this every 30 minutes for approximately 2 hours, gaining five TSS values.

9. Connect Dataron to computer. Run Data Bank GUI, switch on Dataron (programme will show communication with instrument). Click the second tab

and download Dataron data. Once data has been downloaded and saved, delete Dataron memory, this function is also located on the second tab of GUI.

NOTE: If Dataron has been left to run over night, it is more than likely that the instrument will have no power and will need to be charged prior to downloading data.

13.3.2 Sands

1. Take a sample of approximately 10 g and remove fine-grained sediment (<63 µm) from sample by sieving.
2. Inside the settling tower there are four yellow fishing lines. Hook one of the yellow lines up onto one of the hooks underneath the shelf that the scale sits on. This will tilt the scale plate.
3. Attach hose to tap and insert other end inside the settling tower. Secure the hose and turn on tap. Fill the tower ¼ full, switch off the tap and allow the water to settle for approximately 30 minutes to an hour. Repeat until tower is full.
4. Unhook yellow line. Unhook the cross-frame, moving the scale plate to the correct position.

13.3.2.1 Scale and computer set-up

1. Turn on computer and turn on scale (Scout® Pro)
2. After initial full screen display, hold down ON/ZERO button for approximately 3 seconds.
3. When SETUP appear page through to PRINT menu and down to A-Print and then CONT.
4. Come out of SETUP menu
5. Press PRINT **twice** to ensure printer function is ON.
6. Steps 5 and 6 contradict each other; however it is the only way to ensure that the printer function is ON.
7. Open up a HyperTerminal interface on laptop.
    a) Start.
    b) All programs
    c) Accessories
    d) Communication
    e) HyperTerminal

   f) User name – project number and run

   g) Select com3/com8

   h) Select **bits per sec**: 2400, **data bits**: 7, **Parity**: none, **Stop bits**: 2, **Flow control**: hardware.

   i) Click apply then OK.

8. Click on TRANSFER and the CAPTURE TEXT, select the file storage location and name.

9. Clicking OK will start the test. DO NOT START YET.

10. Thoroughly mix sediment. Equally spread sample (approximately 5 g) onto the sediment release mechanism (Figure 11) avoiding the hole in the centre.

11. Carefully submerge the sediment release mechanism. Immediately click OK (or use a second person) on HyperTerminal, open the mechanism (Figure 12) and start a stop watch.

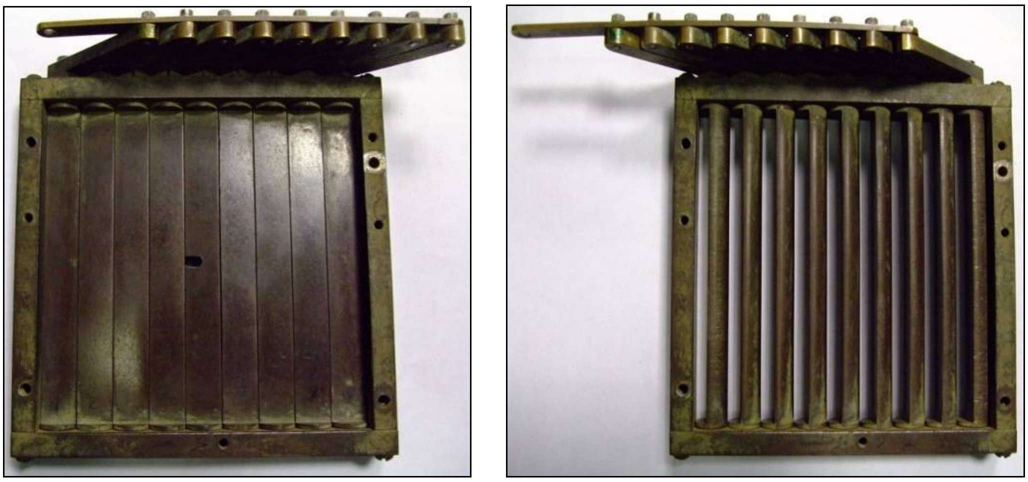

Figure 28 Sediment release mechanism closed and open.

Avoid leaving the sediment on the mechanism for a long period of time before starting the test, as the sediment will clump together. This will not give a true measurement of settling velocity.

12. Values should appear on the computer screen, gradually increasing. The data captured will be recorded.

13. Once complete, record time from stop watch and stop. Copy data from laptop and back up onto server.

14. Transfer the data on to an Excel spreadsheet, add a column (time). The balance records five readings per minute. Calculate the average weight per minute.