TWO PROTOTYPE FLUVIAL SUSPENDED SEDIMENT SAMPLERS EVALUATED IN AN INSTREAM FLUME

by

BRUCE HARRISON RODDAN
B.Sc., The University of British Columbia, 1980

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ABSTRACT

Fluvial suspended sediment (FSS) is a measured physical component of hydrologic and environmental watershed studies. A variety of tools and strategies are employed to collect a FSS sample that is representative of the source water FSS. The discrete point-in-time automatic fixed speed pump sampler (DPS) is a commonly used tool in FSS studies. During May-October 2006, two prototype FSS samplers, a time integrated passive sampler (TIPS) and a continuous flow proportional variable speed pump sampler (CPS), were evaluated using an instream flume and a DPS sampler, placed in a small, low energy, second order stream in the Southern Interior of British Columbia, Canada. The time integrated passive sampler consisted of a passive instream sampler, and collected FSS continuously over a 24-hour period from a point in the stream cross-section. The CPS consisted of a combined instream suction pipe, pressure differentially controlled variable speed peristaltic pump, removable inclined pipe expansion, and filter bed system. The CPS pumped and filtered water for FSS continuously over a 24-hour period from a point in the stream cross-section. The instream flume consisted of an immersed 1 m diameter by 5 m long half pipe section on adjustable legs.

Results indicated that all three samplers were correlated in the assessment of FSS silt/clay (mineral particle size fractions < 53 μm), sand (mineral particle size fractions > 53 μm), and organic matter based on weight, concentration, and percent proportions. Regression results demonstrated that there was disagreement between the DPS and the other two samplers for the assessment of organic fractions. The CPS- and TIPS-measured blend of percent organic and percent mineral fractions were in agreement, particularly if the TIPS measured percent sand was less than 35%. The TIPS collected FSS variables were most responsive to changes in flume flow velocity (log-log relationship), particularly the measurement of FSS total weight. The TIPS weight variables were predictors of flume FSS load values when calibrated to CPS or DPS load values.

The study of the TIPS operational characteristics revealed that the inlet velocity was less than the ambient flume velocity of 400 mm s^{-1} by a factor of 3.9. The proportion

of inlet FSS retained in the TIPS body was determined by studying the ratio of expelled to retained FSS proportions (E:R). The E:R ratio was stable at 1:1 for flume velocities between 300 mm s^{-1} and 400 mm s^{-1}. The E:R ratio varied predictably (linearly) according to the flume velocity, but less predictably according to changing proportions of organic matter, mineral particle size < 53 µm, and mineral particle size > 53 µm .

The TIPS and CPS were capable of collecting enough FSS to assess a mineral particle size < 53 µm and > 53 µm. DPS assessment was restricted by the collected sample size to the assessment of organic matter and total mineral fractions only. The DPS was capable of partitioning the 24-hour hydrograph into 2-hour segments, whereas the CPS and TIPS collected a time integrated composite sample over the 24-hour period. The DPS pump speed was fixed, whereas the CPS pump speed was variable, according to the pressure differential readings on a venturi at the TIPS sampler outlet that responded to flume flow velocity. The instream flume provided a stable 24-hour sediment supply, linearized flow and isolated the FSS supply from streambed sediments. The flume was also a convenient, adjustable working platform above the watercourse.

The CPS and TIPS prototypes represent successful initial steps toward designing an alternative sampling device to the automatic pump sampler.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

CPS – Continuous pump sampler, (1) or (2)
DPS – Discrete pump sampler
E:R – Ratio of expelled sediment to retained sediment
FSS – Fluvial suspended sediment
SSC – Suspended sediment concentration
TIPS – Time integrated passive sampler, (1) or (2)

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DEDICATION

For Marie

CHAPTER 1
GENERAL INTRODUCTION

Fluvial suspended sediment (FSS) is a measured physical component of hydrologic and environmental watershed studies. A variety of tools and strategies are employed to collect a FSS sample that is representative of the source water FSS. The discrete point-in-time automatic fixed speed pump sampler (DPS) is a commonly used tool in FSS studies. Suspended sediment researchers such as Walling and Woodward (1993), Mason and Cuttle (1988), Gracyck et al. (2000), Pathak (1991), and Phillips et al. (2000) have created effective alternatives to the discrete automatic pump (fixed speed) sampler. Moody and Meade (1994) and Eads and Thomas (1983) made adaptations to the automatic pump sampler to improve the performance and range of applications. These authors demonstrated that there is room for innovation and invention in the field of fluvial suspended sediment (FSS) sampling technology. This study introduces two prototype FSS samplers to the field of FSS sampling technology: a time integrated passive sampler (TIPS) and a continuous (variable speed) pump sampler (CPS).

1.1 Fluvial Suspended Sediment

Annual fluvial suspended sediment discharge can benefit channel morphology, benthic habitat and the fertility of a watershed riparian environment, but it can also degrade reservoirs, shipping channels, bridge stability and drinking water quality. Recognizing the mixed economic, environmental and social impacts of FSS, the Canadian government has made efforts to improve sampling devices to accurately measure FSS dynamics in small and large watersheds (Engel and Zrymiac,1989)

Suspended sediment measurements are used to quantify the transport of eroded materials from the land to the ocean, and to determine the chemical, physical, and biological properties of suspended sediment concentrations (SSC). Fluvial suspended sediment is the composite of mineral and organic fragments entrained in a moving body of water. Suspended sediments are flocculated and have colloidal properties that attract and concentrate contaminants depending on the proportion of surface electrical charges

(Droppo, 2000). Flocs are porous, irregular in shape, and water saturated. They are composed of heterogeneous aggregates of bacteria, algae, diatoms, organic components (e.g., fibrils and detritus) and inorganic minerals (e.g., silt and clay). Fibrils (extracellular polymeric materials) and electrochemical bonds hold the flocs together. Droppo (2000) described flocs as cohesive sediments and micro-ecosystems. Floc settling velocities are greater than those of primary mineral particles because of their size, shape, and porosity.

Categories of entrained sediment include suspended bed material and wash load; the distinction is determined by the amount of time in suspension and the balance between sediment settling velocities and water turbulent shear forces. Suspended bed material sediments are temporarily elevated above the stream bed, generally comprised of particles between the sizes of 63 μm and 250 μm (fine sand to coarse sand), and dispersed in vertical and lateral concentration gradients. Wash load sediments are continuously elevated above the stream bed, not found in the stream bed, dispersed evenly throughout the water profile by turbulence, and are generally smaller than 63 μm (silt to clay sized particles).

The supply of FSS is limited to the amounts of material available from the stream bed and the erosion delivery rate from soils to streams. The supply also depends on the limb of a hydrograph and the continuity of discharge at the beginning and end of a stream reach. Typically, the suspended load cycles in a hysteresis fashion, with the supply being greatest at a given discharge on a rising stage versus a falling stage of the same discharge value.

Fluvial suspended sediment is reported as total solids (evaporation residue) or total suspended solids (2.0 μm glass filtered residue). Both methods are also reported as suspended sediment concentration if the whole collected sample is processed (not an aliquot) (Standard Methods, 1998). Stream concentrations of FSS are calculated as the weight of dry sediment in a water sediment mixture (mg L^{-1}). Suspended sediment discharge, or load (tonnes day^{-1}), is the quantity of FSS per unit of time passing through a stream cross-section. Sediment concentration is related to stream discharge by measuring stream discharge and sediment concentration at a stream cross-section.

The most common FSS rating curve model is the power function:

$$L = aQ^h \tag{2.1}$$

where L=load (mg L^{-1}), Q=streamflow ($m^3 s^{-1}$), and the curve parameters a and h are unique to each stream load monitoring site (Crawford, 1991). The statistical reliability of these suspended sediment rating curves is questioned by Crawford (1991) and Holtschlag (2000), who attempted to statistically improve the estimation of a and h coefficients and the interpolation of discrete measurement data. Crawford (1991) concluded that parameter estimates are determined most accurately by using a log-log linear transformation, ordinary least squares, and a correction for transformation bias. Regression models of SSC versus stream flow rate can also be refined by stratifying discrete instantaneous data, based on time and stage of hydrographs (Thomas and Lewis, 1995), or by using continuous surrogate data collected from readings of turbidity (Pfannkuche and Schmidt, 2003). Although flow rate is difficult to estimate and is often prone to errors in measurement, measuring SSC is the most time consuming, expensive, and error prone aspect of suspended sediment rating estimates. Therefore, interpolation is used to fill in the data gaps, or make predictions based on current flow rate readings. The measurement of FSS discharge is stratified according to dimensions within time and space. Spatial stratification includes the equal-width increment and equal-discharge increment methods. Time stratification is based on hydrographic and weather events.

Collected FSS samples are usually analyzed for physical, chemical, and biological factors, including bacterial and chemical contaminants. Physical characteristics include: particle size distribution (PSD), settling velocities, and fractal dimensions.

1.2 Fluvial Suspended Sediment Sampling Devices

Ultimately, a FSS sampling device that collects continuously over all time and all cross-sectional space of a water course would be the ideal, but as yet, there is no such tool. The probability of collecting and measuring a representative FSS sample is very dependent on the design of the sampling device, the sampling frequency, and the proportion of the stream cross-section and length that is sampled. The sampler design should be responsive to the stream flow rate, because flow rate is strongly related to FSS concentration. It should also be reliable and robust enough to withstand weather and stream conditions, economical in cost and maintenance, and able to collect a representative FSS sample. The choice of sampling device is dependent on scientific objectives and budget.

There is a wide variety of FSS samplers that have been scientifically tested in a laboratory flume, or by comparison with other FSS sampling tools under field conditions (Federal Inter-Agency Sedimentation Project, 2001). The laboratory flume testing reveals some of the operating characteristics of each design, while the comparative studies evaluate the ability to collect a representative FSS sample relative to other designs.

The FSS sampler can be divided into two categories: discrete point-in-time collection and continuous in time collection. Within these categories the samplers can be further divided into depth integrated, time integrated, isokinetic, and flow proportional.

1.2.1 Discrete Fluvial Suspended Sediment Samplers

The simplest type of FSS sampler is an open mouthed bottle. This is a point-in-time, discrete, non-isokinetic collection device. The operator can sample FSS by scooping the water from one point near the surface, or though a profile of depths. The U.S. Federal Interagency Sediment Project (FISP) invented the US WBH-96 weighted bottle sampler that is attached to a rope to be dangled into a stream from overhead (Wilde et al., 1998). It is used to collect discrete samples instantaneously from a point within the stream cross-section. Closures at the bottom and top of the sampler are operated remotely with a rope that opens and seals the container at the depth of collection, protecting the sample as it is withdrawn from the water. Experiments or monitoring programs that are interested in point-in-time FSS concentrations use bottle samplers when stream velocities are less than the minimum for isokinetic depth integrated samplers (0.4 to 0.6 m s^{-1}), or during times of high velocity and large debris where open bottle samplers may be the only choice available (Edwards and Glysson, 1999). Statistical analysis of this type of discrete data is difficult to report because of large variability. Edwards and Glysson (1999) recommended duplicating some of the discrete bottle samples by collecting isokinetic depth integrated samples and correlating the two results to verify accuracy. Another strategy is to collect sub-sample duplicates that may add confidence to the results.

The FISP™ isokinetic depth integrated samplers are used to determine accurate FSS discharge within streams and rivers. Isokinetics are an important characteristic of discrete depth integrated samplers. A discrete isokinetic depth integrated sampler can only collect a representative FSS sample if the inlet is close to being isokinetic, that is, if the inlet velocity (V_i) is equal to ambient stream velocity (V_s) (Federal Inter-Agency Sedimentation Project, 2001). The sampler will undersample FSS concentration if $V_i > V_s$, and oversample if $V_i < V_s$. Since particle size is a function of flow velocity, then the collected particle size distribution is affected by the $V_i{:}V_s$ ratio, particularly in the sand size (> 63 μm) fraction. Suspended sediment is drawn through an engineered orifice into a collection bottle in the body of the sampler at a velocity equal to the ambient stream velocity. Nozzle velocity is calculated based on the time elapsed to collect a volume of water through the cross-sectional nozzle area. Each sampler design is rigorously tested to collect a representative suspended sediment sample over a set vertical transit rate from the surface to a set stream depth and back to the surface (continuous round-trip depth integration). Air purging is bathymetrically controlled by an air orifice, pressure equalizing chamber, and the rate of descent and ascent. An electronically controlled valve enables the samplers to be used for discrete samples at measured depths. A bag sampling device, US-D96, was designed to sample at depths as great as 30 m and overcomes limitations of a rigid bottle by filling a 3 L collapsible plastic bag. The sampler weighs 60 kg and is 1 m in length (Federal Inter-Agency Sedimentation Project, April 2001). Hand held and cable-reel FISP™ samplers are flume and tow tested to assess the performance of each sediment sampler and inlet nozzle. Inflow efficiency graphs are used to relate the ratio of nozzle velocity to stream ambient velocity, and to determine the maximum and minimum stream or towing velocities. Each sampler is hydro-dynamically tested to determine submersed positional attitude. The filling characteristics and the transit rate are determined for each sampler nozzle configuration. Operational limits, including velocity, depth, and transit rate limitations are published for each sampler along with calibration tables for bathometric pressure and temperature. Laboratory testing is used to meet United States Geologic Survey Office of Water-Quality criteria for trace-element sampling (Edwards and Glysson, 1999). Crawford (1991) and Holtschlag (2000) both noted that, even with the performance standards and calibration there are still reliability problems regarding the temporal and spatial sampling intervals. The sampler, when used according to operational limits, is capable of giving accurate discharge weighted (flow proportional) FSS concentrations for one transit pass of a vertical in a stream cross-section at the time of sampling. However, the reliability breaks down with successive vertical passes through other intervals in the stream cross-section, and furthermore, with successive sampling dates within a stream's hydrometric stages. Thus, even with this reliable FSS sampling device, the statistical sampling methodology used to estimate FSS is important because of temporal and spatial variability (Edwards, and Glysson, 1999).

Automatic pump samplers are portable, battery operated, computerized water samplers that use a peristaltic pump to lift stream water through a suction hose to fill a carousel of sample bottles. Automated pumping samplers are a preferred method of collecting discrete FSS samples because the onboard computers can be programmed to statistically sample according to random events, such as precipitation, temperature, and water discharge (Thomas and Lewis, 1995; Wren et al., 2000). Automated samplers are programmed to collect a specified volume of water from a point-in-time (instantaneous) and point in the cross-section of a stream.

To overcome the labour and timing constraints of FSS sampling, Walling and Teed (1971) developed an automatic pump sampler for use in small watersheds. Storm events are an important part of a stream hydrograph and are difficult to characterize because of the sudden onset after a rainfall or snowmelt events. Automatic pump samplers can be programmed to sample on an event basis using a rainfall tipping bucket, rising stream gauge, or turbidity readings. The Walling and Teed (1971) prototype was triggered by a float switch installed in a stilling well to detect rising storm water events. As noted by Walling and Teed (1971), the primary limitation of automatic pump samplers was that they are discrete and obtain samples from just one point in the cross-section of a watercourse. The samples are not temporally or spatially integrated or flow proportional. Field testing was performed by Walling and Teed (1971) to compare the automatic pump sampler with a discrete, depth integrated, isokinetic US DH-48 Wading Rod Sampler. There was agreement within 10% error variability between the two sampling methods using linear regression. The authors speculated that the clay sized suspended sediments were responsible for the good linear fit, as these particles are uniformly distributed within the water column. Although the field testing was not rigorous, the researchers proceeded with the use of the sampler in field experiments in larger watersheds to characterize the FSS loads of stream hydrographs during storm events. A stepwise regression analysis failed to define a confident relationship (r^2=0.39) between the suspended sediment load and stream discharge. The authors did conclude that the automated pump sampler would enable them to collect more intensive data during all stages of stream flow and could eventually lead to an equation, which could be used to predict suspended sediment values from corresponding discharge values. Another benefit of the automated sampler was in illustrating the critical initial moments of a storm hydrograph during which the concentrations of FSS peak and then fall, indicating that the availability of suspended sediment supply is exhausted and immobilized after the initial surge.

Edwards and Glysson (1999) recommended the use of automatic pump samplers for ephemeral or fast rising flashy streams to capture rare hydrologic stages. They did note the shortcomings in the ISCO™ brand of sampler pumping lift capacity. In some cases, the lift is beyond the capacity of the pump and vulnerable to sample cross contamination. The intake is prone to trash accumulation if it is not directed downstream. The choice of sampling position in the stream is critical to achieve a representative sample. To protect the sampler from washing away, it must be placed away from the stream bank. Battery power must be maintained. Security from theft and vandalism is a concern.

Siphon samplers are single stage non-isokinetic FSS samplers that are used to collect discrete water samples during rising or falling water levels (Edwards and Glysson, 1999; Wilde et al., 1998). FISP™ developed this as an affordable and portable alternative to automated pump samplers. FISP™ designed siphon samplers to obtain FSS samples from streams at remote sites or at streams where rapid changes in stage make it impractical to use a conventional isokinetic depth integrating sampler. Single stage samplers can be mounted above each other to collect samples from different elevations or times as stream flow increases and stream stage rises. When the water level reaches the sampler inlet a siphon is created that draws stream water through a 6 mm tube into a

750 mL plastic wide mouthed bottle. The outlet exhaust tube is positioned above the intake. When the water level reaches the exhaust the flow is blocked by an air lock; thus, the bottle fills with water near the surface of a rising stream. The FISP™ US U73 design can be used to collect water in a rising and waning stream, and has trash deflectors to avoid blockages. These samplers are vulnerable to freezing and dislocation by large trash objects. The collected sample is exposed to ambient temperatures; thus, biological and temperature sensitive gases are vulnerable to change with time (Wilde et al., 1998).

The FISP laboratory tested and developed several versions of this sampler such as the US U-59 and US U-73. Laboratory results of the Federal Inter-Agency Sedimentation Project (1961), determined that the design was valid to collect representative samples for distinct ranges of stream velocity, water surface surge, water temperature, and suspended sediment.

Graczyk et al. (2000) field tested the siphon sampler in comparison to the ISCO™ automatic pump sampler. Forty-seven paired water samples were collected using both samplers. Suspended sediment, ammonia nitrogen, and total phosphorus concentrations were determined using standard methods. Pairs were compared using a non-parametric Wilcoxon signed-rank test. At α=0.05 significance level, none of the comparisons was different. The study concluded that siphon samplers are useful when suspended sediment concentrations near the water surface are needed and sampling by other, possibly more accurate samplers, is not practical. The study also concluded that the siphon sampler is an affordable automatic way of collecting FSS and chemical contaminants in a riparian zone prone to flash flooding, and that the concentrations can be weighted with the hydrometric stage to produce a discrete suspended sediment discharge.

1.2.2 Continuous Time Integrated Fluvial Suspended Sediment Samplers

Moody and Meade (1994) investigated the use of discharge weighted pumping combined with a continuous flow centrifuge. The objective was to achieve sample sizes large enough to conduct a full array of chemical and physical analysis, and also, to pump a discharge weighted volume of water that was representative of FSS loads. The pumping rate was constant at 4 L min^{-1} using a double diaphragm pump. The pumping time was based on the calculated discharge weighted volume. The method was compared to the particle size distribution results of an isokinetic depth integrated sampler. The results indicated that the pumped samples were representative of the silt and clay particles (< 63 μm) but undersampled the sand sized fractions. Also, the centrifuge process was less than 74% efficient at trapping the fluvial suspended sediment samples. Up to 10% was lost in the intake, and 9% was expelled in the discharge.

A depth and time integrated, continuous flow, passive sampler was created by Pathak (1991) to study the hydrology of small streams. According to the author, there is a lack of suspended sediment sampling tools designed specifically for small agricultural watersheds (400 ha) with a small controlled stream channel. The study watershed was monitored to test different soil erosion control measures. Pathak (1991) used a time and depth sampling strategy in which FSS, at a point in the cross-section of the stream, were sampled continuously through suction tubes located at several depths concurrently. Time and depth were integrated by collecting on a continuous basis into collection vessels for each depth. Sample sizes for each depth varied according to the stream velocity and stage. Depth integration using this sampler allowed the author to partition the hydrograph into average suspended sediment concentration over time by depth. The experimenter could determine the concentration of suspended sediment collected from near the water surface by the highest elevation collecting tube immersed during a storm. Laboratory evaluation of the sampler was performed by controlling the water flow using a Parshall flume, and by controlling the suspended sediment concentration and particle size distribution using a sediment mixing chamber. The objective was to determine the efficacy of the sampler to collect FSS during different flows, a range of suspended sediment concentrations, and varying particle size distribution. Experimental results proved that the sampler was best adapted to measure fine to medium textured sediments, and at shallow water depths (9 to 25 cm). Turbulence was blamed for a reduction in sampler efficiency with increasing flow. Pathak (1991) suspected that turbulence affected the even distribution of sand sized particles within the water profile. The clay and silt sized particles were collected within a range of 90% to 96%. This proved adequate for Pathak's (1991) research needs because the percentage of sand sized particles in the studied eroded soils ranged between 1% and 6%. Field evaluation of the sampler was performed by comparing the sampler results with frequent grab samples taken during the several storm events within several segments of the runoff hydrograph. There was good agreement between the data obtained with the field sampler and the bottle sampler. Pathak (1991) noted several advantages to using this sampler as well as the limitations. It is inexpensive, and has no moving parts except for the accompanying stage recorder, which may or may not be automated. It is appropriate for small streams or ditches with water depths of less than 30 cm, having suspended sediment concentrations consisting principally of clay and silt particles (< 63 μm), for which the sampler is up to 96% accurate. The sampler does not appear to be robust enough to withstand trash or freezing conditions. By design, it is precluded from measuring more than one hydrograph peak, but is advantageous for measuring FSS concentrations within hydrograph segments. Sample collection contents are bulked precluding the measurement of flow weighted FSS concentration in time. Furthermore, the collection vessels are below stream grade, which may not be present in natural stream settings. No attempt was made to install isokinetic nozzles.

Time integrated passive samplers are a proven alternative to other fluvial suspended sediment samplers, such as the automatic pump sampler (Phillips et al., 2000; McDowell and Wilcock, 2004). The TIPS sampler collects fluvial suspended sediment from points in a stream cross-section. It can operate continuously, utilizing only the ambient stream flow energy. The TIPS consists of an inlet, a storage body, and outlet. The TIPS diverts ambient stream water into the inlet, through the settling chamber that retains a portion of the suspended sediments, and returns the expelled portion to the stream through the outlet. The net effect is to collect an averaged composite FSS over time.

Phillips et al. (2000) created a time integrated passive composite sampler. The purpose of their sampling device was to collect fine textured sediments from smaller streams in bulked quantities large enough to conduct a full range of laboratory analysis. The authors noted that sediment sample sizes greater than 10 g are needed to conduct a range of geo-chemical analyses and that suction pump samplers are limited in this regard to FSS concentrations greater than 2 g L^{-1}. Furthermore, the authors emphasized that much of the suspended sediment is flocculated and, therefore, the finer silt and clay size particles will settle fast enough to be trapped by their design. Phillips et al. (2000)

postulated that the flocculated nature of stream sediments with increased mass compared to dispersed particles would favour a better recovery distribution within their sampler. This is supported by the research of other authors (Walling and Woodward, 1993; deBoer and Stone, 1998; Droppo, 2000; Droppo et al., 2005). The sampler body consisted of a 1 m long by 98 mm diameter plastic pipe, with a cone cap on the upstream end and a flat plug on the downstream end. A plastic 150 mm long by 4 mm inside diameter tube was fitted through both the caps to provide an inlet and an outlet. The sampler was mounted in the stream horizontally on two poles at the desired height above the stream bed, allowing the water to flow through the body. The device was deployed for two weeks, then emptied and redeployed.

Laboratory flume tests conducted on the sampler characterized the hydro-dynamics and collection efficiency. Dye was pumped through the sampler to reveal the inner dynamics of the sampler in ambient stream flows of 0.6 m s^{-1}, and proved that passive fluid zones in the body are responsible for the efficient sedimentation principles of the tool. Hydro-dynamically, the sampler inlet is not isokinetic, in that the inlet velocity is less than the ambient flow. At velocities greater than 0.6 m s^{-1} the inlet velocity could not be determined due to flume turbulence. The sampler efficiency was tested by introducing a known quantity of chemically dispersed coarse and fine textured sediment at two velocities, 0.3 m s^{-1} and 0.6 m s^{-1}. Overall, recovery efficiency was between 31% and 71% of the inflowing suspended sediment and was biased in favour of the coarser sediment fractions. Phillips et al. (2000) suspected that the non-isokinetic properties might cause an over sampling of sand particles (> 63 μm). These concerns were discarded when the sampler was used in smaller streams devoid of suspended sand. In general, the greater the ambient stream velocity, the lower the recovery efficiency, especially with smaller particle sizes. A Kolmogorov-Smirnov statistical test confirmed that unless the flow velocity is low (< 0.6 m s^{-1}), the inflowing sediment is not in the same proportions as that retained in the sampler.

Field evaluation of the sampler proved that it collected a representative fluvial suspended sediment sample from a stream according to a Kolmogorov-Smirnov statistical comparison with discrete samples collected by an automatic pumping sampler. Comparisons of weighted mean particle size diameters and total carbon concentration between the automatic pump samples and the continuous time integrated sampler were accomplished by running the collection period during winter storm events in three streams near Leicestershire, England. The study concluded that the sampler was inexpensive, easily fabricated, and appropriate for collecting an accurate distribution of particle sizes from small streams with fine textured sediments. Constraints, such as ambient flows less than 0.6 m s^{-1}, and a vulnerability to trash accumulation interference, limited the use of this sampler to small streams during above freezing conditions.

1.3 STUDY OBJECTIVES

Existing FSS samplers are limited to specific field applications by the advantages and disadvantages of each design. The most common limitations of samplers include the inability to collect a representative FSS sample, insufficient sample size to conduct particle size distribution, trash accumulation, and expense and labour intensiveness. In response to these limitations alternative sampling tools have been invented, and, as each design is introduced, it has been tested and compared to existing technologies to prove that it is an effective alternative.

This thesis introduces two prototype sampling devices: a continuous variable speed pump sampler (CPS), and a time integrated passive sampler (TIPS). The CPS addresses the issues of sample size and flow proportionality while retaining the ability to be controlled by automated programmed systems. The TIPS addresses the issues of sample size, flow proportionality, and is an inexpensive, passive sampler that can operate continuously, utilizing only the ambient stream flow energy. The overall objective of this study was to evaluate the ability of these two prototype samplers to collect a representative FSS sample and to cross evaluate them with a commercial grade discrete automatic pump sampler (DPS). The testing was conducted in an innovative instream flume design placed in a small, low energy, second order stream.

This thesis study was comprised of four experiments, and was conducted to achieve four objectives.

Experiment #1: The objective was to compare a prototype time integrated passive sampler, a prototype continuous pump sampler, and a discrete pump sampler, based on the assessment of flume FSS properties (suspended sediment concentration, particle size distribution and organic matter). The hypothesis tested was that all three samplers were correlated in the ability to assess flume FSS, and that the assessments were linearly related between samplers.

Experiment #2: The objective was to relate each sampler individually (TIPS, CPS and DPS) to flume flow rate. The hypothesis tested was that the all three samplers were related by a common non-linear response to flume flow rate, and that based on this relationship, the samplers could be ranked according to their suitability for the assessment of flume FSS properties.

Experiment #3: The objective was to examine the following operating characteristics of the TIPS prototype in an instream flume: the inlet flow velocity in relation to ambient flume velocity, the expelled FSS to retained FSS ratio in relation to flume flow velocity and flume FSS concentration, and the use of pressure differentials, measured at the TIPS outlet, to regulate a variable speed peristaltic pump. The hypothesis tested was that the characteristics of the TIPS sampler were linearly related to flume, velocity, and FSS concentration.

Experiment #4: The objective was to predict flume FSS load using the TIPS sampler FSS weight measurements calibrated to the CPS and DPS flume FSS load measurements. The hypothesis tested was that TIPS sampler FSS weight measurements could be used as a predictor of FSS load based on simple linear regression models.

CHAPTER 2
MATERIALS AND METHODS

2.1 Study Period

Four experiments were run concurrently and repeatedly in an instream flume set in Campbell Creek (21 km East Kamloops, B.C.). An experiment run (observation) consisted of one 24-hour period of measurements. During this interval all three samplers (TIPS, CPS and DPS) were operated in an instream flume concurrently. Thus, the experimental conditions that affect sediment settling velocities were the same within each observation for each sampler and each experiment. A total of 61 observations at various dates were obtained (Table 2.1). The first 15 observations were conducted as preliminary

Table 2.1. List of observations and their associated dates.

Observation	Date	Observation	Date	Observation	Date
1	9/21/05	21	6/05/06	41	8/01/06
2	9/22/05	22	6/07/06	42	8/08/06
3	9/23/05	23	6/11/06	43	8/10/06
4	9/25/05	24	6/13/06	44	8/13/06
5	9/26/05	25	6/15/06	45	8/15/06
6	9/27/05	26	6/18/06	46	8/17/06
7	9/29/05	27	6/20/06	47	8/18/06
8	9/30/05	28	6/22/06	48	8/27/06
9	10/05/05	29	6/25/06	49	8/29/06
10	10/06/05	30	6/29/06	50	8/31/06
11	10/07/05	31	7/02/06	51	9/03/06
12	10/12/05	32	7/04/06	52	9/05/06
13	10/13/05	33	7/06/06	53	9/07/06
14	10/14/05	34	7/11/06	54	9/12/06
15	10/15/05	35	7/13/06	55	9/14/06
16	5/18/06	36	7/20/06	56	9/17/06
17	5/20/06	37	7/23/06	57	9/19/06
18	5/24/06	38	7/25/06	58	9/26/06
19	5/26/06	39	7/27/06	59	9/28/06
20	6/01/06	40	7/30/06	60	10/02/06
				61	10/04/06

work in September to October of 2005, and are not included in the experimental results. The observation number increment was a reflection of the progress through the sampling period.

2.2 Experimental Conditions

2.2.1 Campbell Creek Study Site

The study site was located at 120°11'12" W and 50°36'1"N within Campbell Creek, at an elevation of 620 m (Figure 2.1 and 2.2). Campbell Creek is a second order tributary to the South Thompson River, approximately 25 km East of Kamloops, British

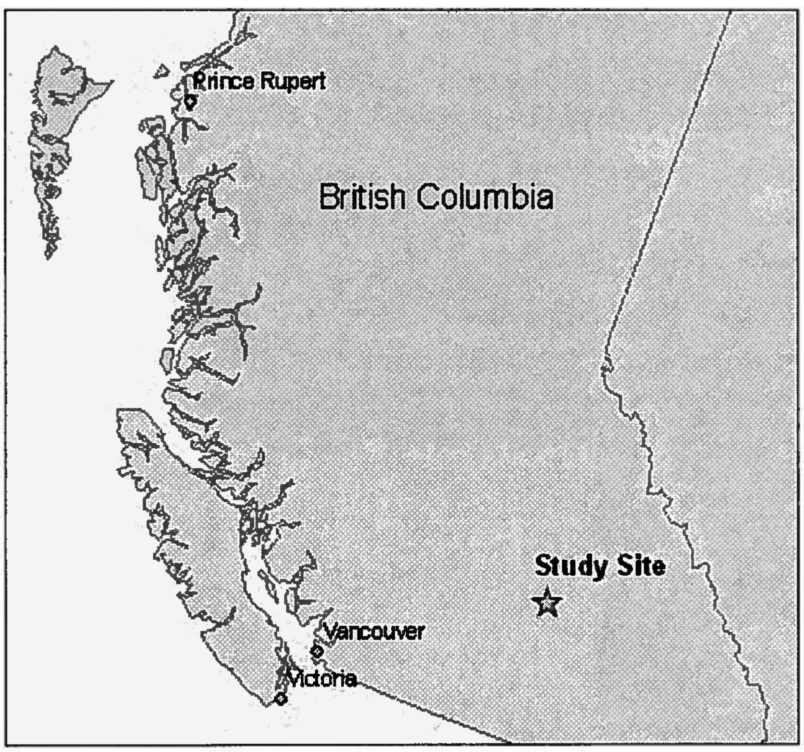


Figure 2.1. Map of Campbell Creek study site (noted by star symbol).

Columbia. The watershed is approximately 530 km^2 in size with dams and headgates at Campbell Lake, Scuitto Lake, and Shumway Lake that control stream discharge. The dams ensure a stable supply of irrigation water during the growing season and buffer the hydraulic regime against extreme runoff events. The study was situated in the Interior

Douglas-fir biogeoclimatic zone. Rain events are scattered and generally do not affect the Campbell Creek hydrologic regime as much as the changes in controls at the dam sites.

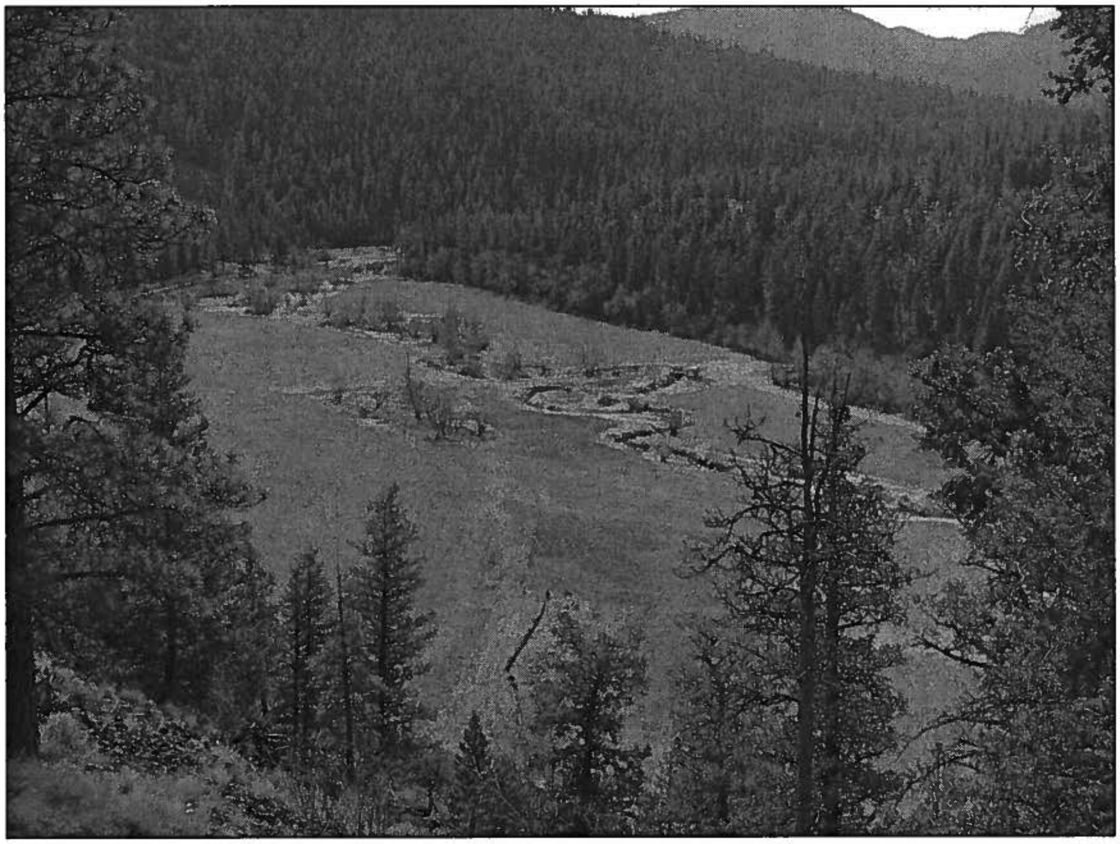


Figure 2.2. Photo of Campbell Creek study site.

The stream meanders through forage crop fields established on a fine textured, Gleyed Rego Black Chernozem soil derived from fluvial parent materials and surrounded by granodioritic rock formations. The field site is privately owned, secure from property theft, and has access to electricity. A stream crossing (Figure 2.3) consisting of two smooth faced pipes (2.5 m by 1 m) was in place, and provided weir control and measurement points for stream flow. The bankfull width at the stream crossing was 5 m, and the substrate sizes ranged from clay to 2 cm gravel. Campbell Creek water chemistry data were sourced from an Agriculture and Agri-Food Canada water quality study (Meays et al., 2000), collected once every two weeks, between February 2000 and November 2001 at a Campbell Creek site located 2.4 km upstream of the study site. Campbell Creek stream water chemistry had the following chemical properties: pH 7.7

(n= 42, SD= 0.21), electrical conductivity 922 μS cm^{-1} (25°C, n= 42, SD= 154.4), 51 mg Ca L^{-1} (n= 42, SD= 9.7), and 67 mg Mg L^{-1} (n= 42, SD= 19.9).

The Campbell Creek water hardness (mg equivalent of $CaCO_3$ per litre), calculated from the Meays et al. (2000) study was 403 mg L^{-1}. This is classified as very hard water according to the Canadian environmental water quality guidelines (CCREM, 1987). Total dissolved solids of 500 mg L^{-1} is the upper limit for drinking water. The presence of large quantities of dissolved solids increases the fluid bulk density, thereby increasing the buoyancy of sediments, and reducing the settling velocity. Dissolved salts also can affect the electrochemical processes of flocculation (Droppo, 2000). It was not determined in this study if the hardness of the Campbell Creek water significantly affected the proportion of mineral particles present as flocs or primary particles.

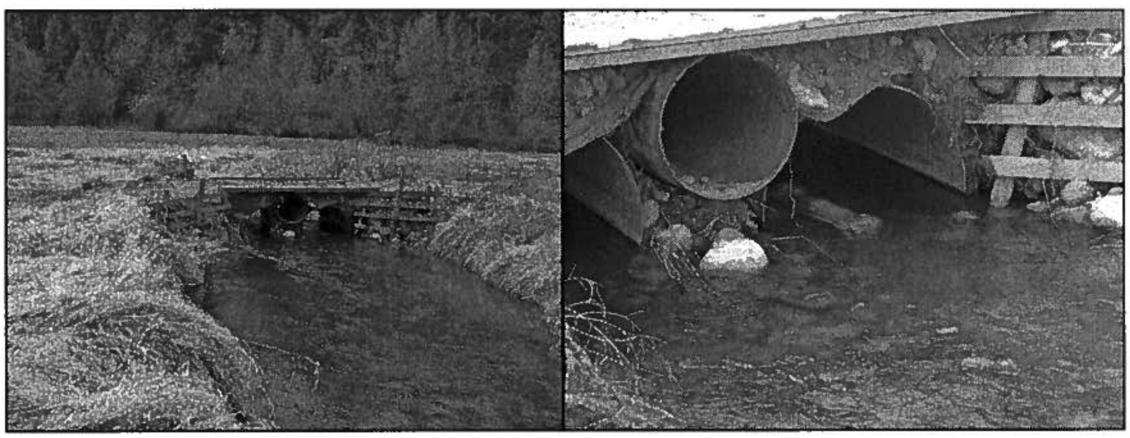


Figure 2.3. Culvert crossing consisting of two 1 m diameter smooth walled pipes. The right hand side of photo is the East side of creek.

2.2.2 Campbell Creek Air and Water Temperature

The air and water temperatures were recorded every hour using Onset™ external sensors and an Onset U12 data logger. Daily averages of water and air temperatures were calculated for the months of May to October, 2006. A gap in the data exists between July 15 and August 15 due to logger failures. Water temperature affects water viscosity and density, which in turn affects the settling velocities of sediment particles, and the sediment transport capacity. During this study, it was not determined if temperature made a significant difference on the flume FSS settling velocities.

2.2.3 Campbell Creek Hydrograph

The Campbell Creek flow rate was determined using a top-setting wading rod and Price™ type AA bucket wheel velocity meter. Measurements were made at the beginning and end of each observation by recording flow velocity at the discharge end of each of the two stream crossing, 3 m length by 1 m diameter culverts. Observations 16 and 17 were not measured. Depths were measured at the deepest point in the culverts. The velocity measurements were taken at the centre of the flow at 60% below the maximum culvert depth. Wetted cross-section area was determined using depth measurements and a web site hydraulic radius calculator for a partially full 1 m diameter pipe (ajdesigner, 2008). The following equation was used to calculate the stream discharge:

$$Q=V*A \qquad 2.1$$

where Q is the Campbell Creek flow rate (L s^{-1}), V is the creek velocity (mm s^{-1}), and A is the wetted cross sectional area (m^2) of the culvert. The flow rate readings from the two culverts were summed to produce a total Campbell Creek flow rate. The two discharge measurements within each observation were averaged to give a 24-hour estimate of stream flow rate.

2.3 Fluvial Suspended Sediment Sampling Equipment

2.3.1 Discrete Pump Sampler

A Sigma 900 max™ automatic programmable portable fixed speed pump sampler was chosen to represent a discrete point-in-time pump sampler for measuring flume FSS expressed as concentration, load, and percent fractions variables. Concentrations were also used to determine the variability of SSC during each of the 24 h observations and for the whole study period. The DPS intake consisted of a 10 cm long diffuser tube plumbed into a 12.7 mm ID pipe. The DPS intake was located at the centre of the flow, 1 m from the discharge end of the flume. The DPS was programmed to collect 750 mL of flume water into a 1 L collection bottle housed in the sampler. The pump flow rate was constant at 2.8 L min^{-1}. During the course of one observation period (24 h) the DPS collected 12 samples, one every 2 hours.

The DPS water samples were each filtered through a 1.5 μm pore size glass filter. The filtrate was collected, measured for volume, and used to determine sample volume for the calculation of SSC. The filters were oven dried (105°C, 12 h) and weighed to determine sediment mass. The filters and dried sediment were then heated to 475°C (12 h) to ignite the volatile organic solids to determine a weight loss difference (APHA, AWWA, WEF, 1998). The weight loss values were used to provide a rough approximation of organic and mineral content within the filtered sediment residue. The ignition temperature was not hot enough to combust or gasify carbonate minerals. This allays the concern that dissolved solids might have influenced the sediment carbon results.

The DPS measured flume FSS variables included: total FSS concentration, mineral concentration, organic concentration, total FSS load, mineral load, organic load, percent organic fraction, and percent mineral fraction. The 2-hour DPS measured flume FSS concentration variables were calculated by dividing the filtered fraction weights by the filtrate volume. The 12 2-hour concentrations were used to estimate a mean and standard deviation for each 24-hour observation period DPS measured flume FSS concentrations. The DPS measured flume FSS load variables were calculated by multiplying the DPS FSS concentrations by the Starflow™ flume flow rate data. Each 2-hour point sediment sample concentration was multiplied by the 2-hour average flume flow rate values to give a 2-hour average FSS discharge. The total 24-hour DPS measured flume FSS loads were calculated from the average of 12 2-hour FSS load averages.

2.3.2 Time Integrated Passive Sampler

A passive fluvial suspended sediment sampler prototype was designed to represent a time integrated passive sampler for measuring flume FSS, expressed as weight and percent fraction variables (Figure 2.4). The TIPS prototype design examined in this study was chosen based on available "off-the-shelf" materials, sizes, and the proportions were based on the ability to service and deploy the sampler in moving water. There are endless possibilities for configurations and sizes of the inlets and outlets in relation to the sizes and shapes of the sampler body. This prototype was not engineered, but instead, was based on a pragmatic guessed design. The TIPS sampler was duplicated and a pair of TIPS samplers was set in the middle of the flume flow, 1 m from the discharge end of the flume for the duration of each 24-hour observation period. The samplers were denoted as TIPS(1) and TIPS(2). The outlet of TIPS(1) was plumbed into a suction pipe attached to a pumping sampler and the TIPS(2) was unencumbered. The sediment that was collected in the TIPS samplers was removed and processed at the end of each 24-hour observation.

The TIPS FSS samples were oven dried at 105°C (12 h) and weighed to determine sediment weight. The dried sediment samples were then heated to 475°C (12 h) to ignite the volatile organic solids to determine a weight loss difference (APHA, AWWA, WEF, 1998). The weight loss values from the ignition were used to determine a rough approximation of organic and mineral content within the collected sediment. The remaining mineral fraction was wet sieved through a 53 μm screen. The retained fraction was oven dried at 105°C (12 h) and weighed to determine the sand fraction (> 53 μm), while the weight difference between the whole mineral sample and sand fraction was used to determine the combined silt/clay fraction (< 53 μm) weight.

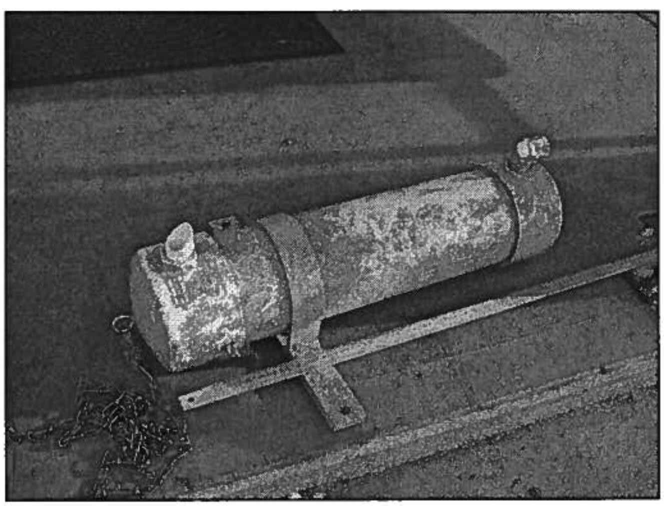


Figure 2.4. Prototype, time integrated passive fluvial suspended sediment sampler.

The following parameters were determined on TIPS flume FSS: total FSS weight, mineral weight, sand weight, silt/clay weight, organic weight, percent organic fraction, percent mineral fraction, percent sand fraction, and percent silt/clay fraction. It was not possible to calculate flume FSS concentration and load because there was no measurement of water volume through the sampler.

The TIPS was constructed of polyvinyl chloride plastic pipe (schedule 40) and fittings. The dimensions were as follows:

- Body: pipe with length = 60 cm, and inside diameter (ID) = 15.5 cm
- End caps: slip cap with inside diameter = 17 cm
- Inlet: male threaded slip coupling cut on a 45-degree angle with minimum inside diameter = 2.5 cm
- Outlet: male threaded 90-degree slip elbow with minimum inside diameter = 2.5 cm.

The inlet and outlet were fitted through holes in the end caps. The inlet cap was slipped on the body and held in place by friction. The outlet cap was glued to the body. When placed in the stream the 45-degree cut on the inlet pointed upstream and the 90-degree elbow outlet was oriented downstream. A chain was fixed to an eyelet on the front cap and anchored the TIPS to the flume.

Trash accumulation on the inlet of instream sediment samplers is a major impediment to continuous sample collection (Phillips et al., 2000, Edwards and Glysson, 1999). The TIPS prototype had a 45-degree inlet design and the use of a retrieval chain which lay on the stream bottom. Both of these innovations minimized the trash interference problem.

Theoretically, the TIPS prototype worked according to the sedimentation principle of Stokes' law in which the fluid shear velocity, density and viscosity of a fluid must overcome the settling velocity of a particle in order to hold a particle in suspension against gravity. According to Bernoulli's principle (Figure 2.5), in order for the flow to be equal through both cross-sections (A1, A2), the velocity (V1,V2) and pressure (P1,P2)

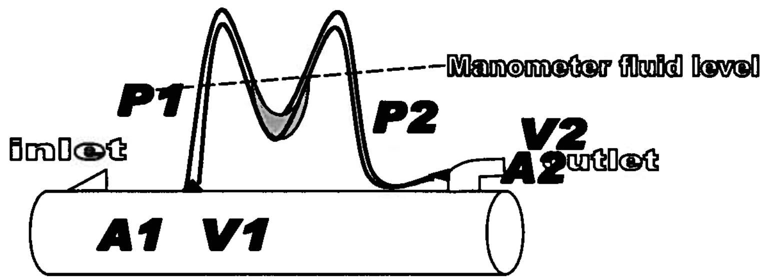


Figure 2.5. Pressure differences measured using a manometer to account for the change in fluid velocity between the cross-section area of time integrated passive sampler body and outlet.

must adjust. The inlet and outlet diameters were six times less than the diameter of the sampler body. Thus, the velocity is less in the body than in the inlet, and, therefore, the transit time through the sampler is long enough that suspended sediment is overcome by gravity and settles in the TIPS body.

2.3.3 Continuous Pump Sampler

A combined FSS sampling pump and filter prototype was designed to represent a continuous variable speed pump sampler for measuring flume FSS expressed as weight, concentration, load, and percent fraction variables (Figure 2.6). The CPS prototype design examined in this study was chosen based on available "off-the-shelf" materials, sizes, and proportions based on a persons' ability to service and deploy the sampler in moving water. This prototype was not engineered, but, instead, was based on a pragmatic guessed design. The CPS sampler was duplicated and the pair was installed in the instream flume. The samplers were denoted as CPS(1) and CPS(2). The CPS(1) intake was plumbed into the outlet of TIPS(1), and the CPS(2) intake was set in the centre of the flow, 1 m from the discharge end of the flume. The intake pipes were attached to paired, removable, inline, sloped, pipe expansions (elutriant tubes) that trapped the heaviest sediment particles. A duplex head, peristaltic pump drew the water through each pipe expansion to each side of the pump at exactly the same pumping rate. The discharge was run through a pair of volume meters and passively over a pair of filter beds that trapped the finest and most floatable suspended sediments. The filtered discharge was returned to the stream. Both samplers were run for the duration of each 24-hour observation. The sediments that were collected in the pipe expansions and on the filter beds were removed, combined, and processed at the end of each observation.

The CPS sediment samples were oven dried at 105°C (12 h) and weighed to determine sediment weight. The dried sediment samples were then heated to 475°C (12 h) to ignite the volatile organic solids to determine a weight loss difference (APHA, AWWA, WEF, 1998). The weight loss values were used as a rough approximation of organic and mineral content within the collected sediment. The remaining mineral fraction was wet sieved through a 53 μm screen. The retained fraction was oven dried at 105°C (12 h) and weighed to determine the sand fraction (> 53 μm), while the weight

(a) **(b)**

Figure 2.6. (a) Continuous pump sampling equipment, including sloped removable pipe expansion, and filter bed. (b) Sediment is evident on the discharge end of the filter bed pipes.

difference between the whole mineral sample and sand fraction was used to determine the combined silt/clay fraction (< 53 μm) weight.

The following parameters were determined on the CPS flume FSS: total FSS weight, organic weight, mineral weight, sand weight, silt/clay weight, total FSS concentration, organic concentration, mineral concentration, sand concentration, silt/clay concentration, total FSS load, organic load, mineral load, sand load, silt/clay load, percent organic, percent mineral, percent sand, and percent silt/clay. The average 24-hour CPS measured flume FSS concentration variables were calculated by dividing the CPS collected FSS weight data by the 24-hour pumped volume meter data. The average

24-hour CPS measured flume FSS load variables were calculated by multiplying the CPS FSS concentration data with the Starflow™ flume 24-hour average flume flow rate.

The CPS apparatus was constructed of polyvinyl chloride plastic pipe (schedule 40). The dimensions were as follows:

- Pipe inlet: male threaded slip coupling cut on a 45° angle with inside diameter = 3.5 cm attached to a 90° elbow. This inlet was the same as the one used on the TIPS(2) sampler.
- Inlet suction pipe: 19 mm ID pipe was attached by pipe unions to a removable 28 mm ID pipe expansion. The expansion was sloped at 45° angle from the creek level up a 1 m elevation over a 3 meter length to the peristaltic pump. At the end of each sampling observation this expansion was removed and emptied of sediments into a 25 L bucket.
- A ¾ hp variable speed peristaltic pump (Watson Marlow™ 521 duplex variable speed) sucked the flume water up through the expansion and discharged it through a water volume meter (Sensus™ SRII 17 mm) that recorded the volume of water filtered during each observation. The pumping rate was fixed during each observation, but was varied (0.00 to 3.01 L min^{-1}) between observations according to stream velocity. The volume was used to determine FSS concentration and load values for each observation.
- The filter apparatus consisted of 2 mm cross weave cheesecloth cut into a 10 m length that was doubled up and stretched though a sloped, 95 mm diameter, 5 m length of pipe. The discharge end of the pipe consisted of a 90-degree elbow angled down into a 5 L settling bucket. The discharge end of the elbow was covered with a removable cheesecloth filter cap. At the end of each observation the cheese cloth filters were removed and rinsed into a 25 L bucket to remove the collected sediments.

Trash accumulation is a major impediment to continuous sample collection and is noted by (Phillips et al., 2000, Edwards and Glysson, 1999). This was minimized by the use of a 45-degree inlet design and the placement of the intake suction pipe on the flume bed.

Theoretically, the CPS sampler worked according to the sedimentation principle of Stokes' law. The inlet pipe diameter was 50% less than the diameter of the removable pipe expansion. The pipe expansion was sloped upward through an elevation change (1 m). The combined effect of expansion and elevation change promoted sediment settling in the removable expansion. The remaining suspended sediments passed through the pump and were trapped by the filter bed. The filter bed promoted the gathering of the finest floatable sediments, by employing a shallow flow of water over a rough surface of cheesecloth fibers, and a downward discharge flow through a cheesecloth filter, which captured the remaining sediments.

2.4 Instream Flume

The development of new FSS samplers requires testing under controlled conditions that include a steady supply of FSS evenly distributed over the stream cross-section and a controlled steady stream flow for each testing period. Pathak (1991) met these conditions by using a mixing chamber and a Parshall flume to test their passive suspended sediment sampler. Phillips et al., 2000 used a laboratory flume and injected dye to test the operational characteristics of their passive suspended sediment sampler. In this study the conditions were controlled by using an adjustable smooth faced metal half pipe flume placed at the downstream end of a smooth faced culvert, in a controlled small second order stream with a bed composed of fine textured materials, and during the warmer part of the year (*i.e.*, May to October)

The FSS supply was generated naturally by the Campbell Creek flow. This was much easier than the method used by Pathak (1991), which required a mixing box and continuous manual additions of sediment into the flow.

2.4.1 Flume Construction

An open half pipe flume was placed in the Campbell Creek study site at the downstream end of the western stream crossing culvert at the beginning of the study (Figure 2.7 and 2.8). The instream flume was constructed from a 1 m diameter, 6 m length of 4 mm steel half pipe. This was used as a smooth walled instream flume to control the cross-section flow of the water flowing past the instruments and FSS collection devices. The flume was intended to linearize the water flow, while retaining enough turbulence to achieve a steady homogeneous suspended sediment supply. The height of the flume was maintained above the stream bed to eliminate suspended bed material from the suspended sediments. Flow control through the flume was achieved by changing the elevation of the flume above the stream bed using winches attached to the flume legs and by diverting water between the two stream crossing culverts. Articulations at the base of the legs prevented binding during the adjustments. Bolts were tightened on the mounts at the side of the flume to lock the legs into position. A

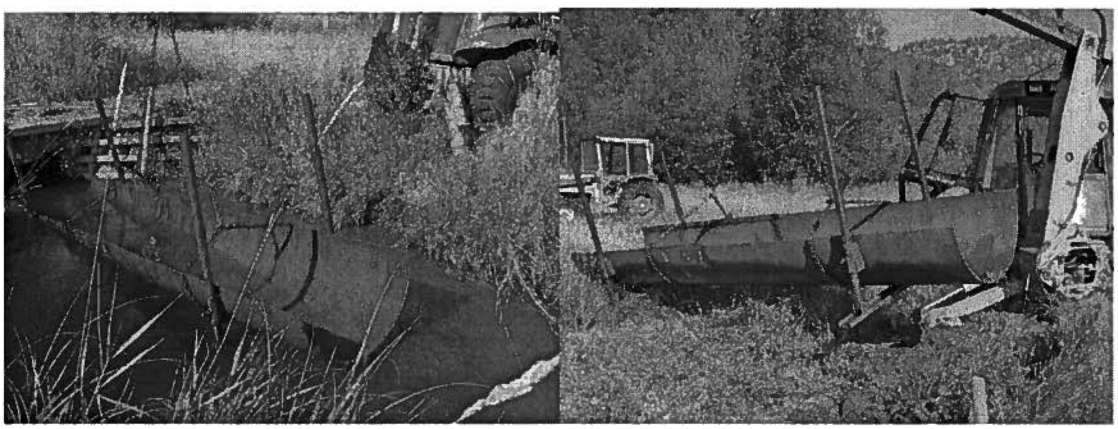


Figure 2.7. Photo of instream flume being positioned downstream of the West culvert crossing.

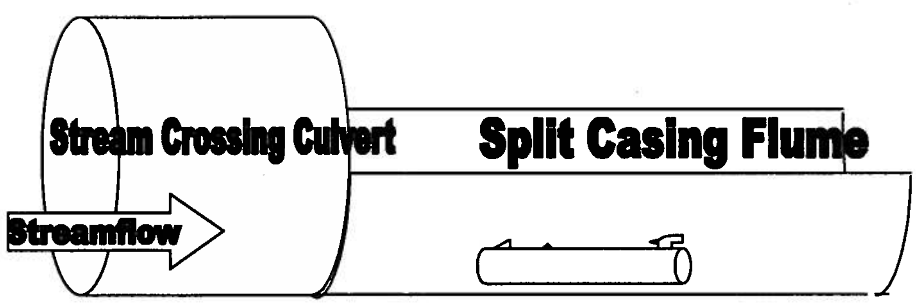


Figure 2.8. Configuration of stream crossing culvert and downstream position of instream flume with an installed time integrated passive sampler.

walk-on platform of removable lumber pieces was placed on top of the flume. The flume created a stream control section in which all the FSS samplers and stream flow measurement instruments were installed, and run concurrently under identical flume flow and FSS conditions.

2.4.2 Flume Hydrograph

A Starflow™ flow recorder was used to measure water velocity and depth in the instream flume to create a 24 h hydrograph. The Starflow™ technology uses the ultrasonic Doppler principle, which relies on suspended particles or small air bubbles in the water to reflect the ultrasonic detector signal. Water depth is gauged by a hydrostatic pressure sensor, and referenced to atmospheric pressure. Water temperature is also measured to adjust for the change in velocity due to speed of sound in water. The instrument was installed at the bottom of the midpoint of the instream flume and pointed upstream. Velocities were scanned every 2 minutes and the averages logged every 30 minutes and used to calculate flow rate. The 48 logged velocities and flow rates were used to calculate a mean and standard deviation for each 24-hour observation during the experimental period of May 15 to October 4, 2006. The Starflow™ recorder calculated the stream flow rate according to Equation 2.1 using the dimensions of the flume and the logged velocity and depth.

Flume flow rate was also determined using a top-setting wading rode and Price™ type AA bucket wheel velocity meter. The results were calculated using the same method as was used to determine the Campbell Creek Hydrograph (Method 2.2.3). These results were regressed against the Starflow™ recorder results as a cross check of flume flow values. Measurements were made at the beginning and end of each observation by recording flow velocity at the mid point of the flume at the centre of the flow at 60% below the maximum flume depth.

2.4.3 Variation in Flume Hydrograph and Suspended Sediment Concentration

During the increase in time through the observation period, the variation in Campbell Creek flow and fluvial suspended sediment load governed the water entering the flume. Consequently, in response to Campbell Creek the following flume parameters varied over time: depth, velocity, flow rate, FSS concentration, particle size distribution and organic matter content. The DPS, CPS, and TIPS response to the flume FSS and water flow conditions were evaluated using correlation and regression analysis conducted using SAS Proc Corr (Pearson's correlation method) and Proc Reg procedures (SAS Institute Inc., 2003).

Variability of flume velocity, flow rate, and FSS concentration were examined within and among observations. Stability within each observation was needed to achieve a representative FSS within the 24-hour period. Variability among observations was needed to expand the range of experimental conditions under which the FSS samplers were tested. The intra-observation flume flow rate and velocity standard deviation was determined from the 48 Starflow™ logged flow rates and velocity readings from each observation. The inter-observation variation was determined from the standard deviation of the 46 observation mean flow rate and velocity values of the experiment. The intra-observation FSS total concentration, mineral concentration and organic concentration was determined from the DPS 12 2-hour samples from each observation. The inter-observation variation was determined from the standard deviation of the 46 DPS observation mean concentrations of the experiment.

2.5 Experiment 1 Design: Cross Comparison of TIPS(2), CPS(2) and DPS

The TIPS(2), CPS(2), and DPS samplers and stream flow measurement instruments were installed in the flume according the configuration shown in Figure 2.9 and 2.10 to allow cross comparison. The TIPS and CPS devices were duplicated for other experiments. Thus, the devices used in this experiment are referred specifically as DPS, TIPS(2) and CPS(2). All three devices were run concurrently under identical flume flow and FSS conditions.

The Pearson's correlation method was used to cross correlate between DPS, TIPS(2), and CPS(2) paired dissimilar and similar variables. Simple linear regression models were used to compare between DPS, TIPS(2), and CPS(2) paired similar variables. The fitted theoretical linear model is expressed as:

$$Y = b_0 + b_1 X + e \qquad 2.2$$

where b_0 is the intercept, b_1 is the slope, e is the residual error.

Although, dependency is implied in this model, the FSS collection device variables were arbitrarily assigned as X or Y.

The TIPS(2) versus DPS calculated variable means and statistical comparisons were calculated on the basis of n=46 observations. The number of observations was less (*i.e.,*34 instead of 46) for comparisons between the CPS device and the DPS and TIPS devices. Twelve observations were discarded because of experimental procedure errors, which were due to procedure development problems and pump failures. The calculated means of variables and statistical comparisons were determined on the basis of n=34 observations.

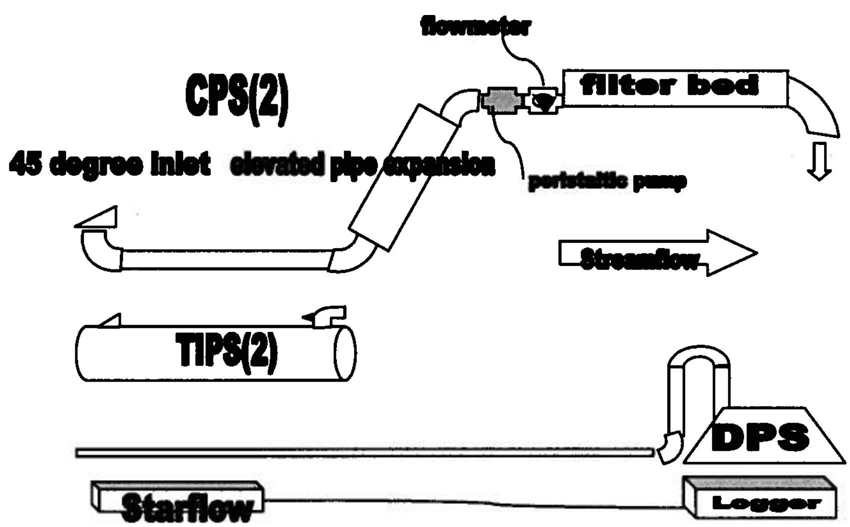


Figure 2.9. Configuration of continuous pump sampler CPS(2), time integrated passive sampler TIPS(2), and discrete pump sampler DPS in association with Starflow™ flume flow logger.

2.6 Experiment 2 Design: TIPS(2), CPS(2) and DPS Related to Flume Flow Rate.

The TIPS(2), CPS(2), and DPS sampler FSS measurements were statistically related to flume flow rate to determine if the results were flow proportional. All three FSS collection devices and stream flow measurement instruments were installed in the flume according the configuration shown in Figure 2.9 and 2.10. The TIPS and CPS devices were duplicated for other experiments. Thus, the devices used in this experiment are referred specifically as DPS, TIPS(2), and CPS(2). All three devices were run concurrently under identical flume flow and FSS conditions.

Pearson's correlation analysis was used to compare DPS, TIPS(2) and CPS(2) variables with flume flow rate. Load variables were not included because of the correlated effect of multiplying concentration by stream flow. Correlation coefficients were determined for each of the three FSS samplers, and respective variables to determine which samplers were most influenced by flume flow rate.

Simple linear regression models were used to compare the natural-log transformed dependent TIPS(2), CPS(2), and DPS variables as a function of the natural-log transformed independent variable flow-rate. The fitted theoretical linear model was derived from the power function form of the rating curve (Equation 2.1) and was expressed as:

$$\ln Y = b_0 + b_1 \ln X + e \qquad 2.3$$

where b_0 is the intercept estimate, b_1 is the slope estimate, e is the residual error, and the DPS, TIPS(2) and CPS(2) FSS variables (Y) are a function of flume flow rate (X). According to Crawford (1991), exponentiated log-transformed estimates of Y are biased. A bias correction factor (Crawford, 1991), was derived from the following expression as:

$$c = \frac{1}{n}\sum_{i=1}^{n} \exp(e_i) \qquad 2.4$$

where c=bias adjustment, n=number of observations and e_i=residual error from each observation and estimate pair. The c was then applied to the inverse transformed version of equation (2.3) to produce an unbiased prediction of SCC and load from the TIPS weight results in the following equation:

$$Y = \exp(b_0) X^{b_1} c \qquad 2.5$$

The bias-corrected exponentiated y-intercept (b_0') is determined from the following equation:

$$b_0' = \exp(b_0) c \qquad 2.6$$

The TIPS(2) versus DPS regression results were calculated on the basis of n=46 observations. The number of observations for the TIPS(2) versus CPS(2) regression results were calculated on the basis of n=34 observations. Twelve observations were discarded because of experimental procedure errors, due to procedure development problems and pump failures.

2.7 Experiment 3 Design: Operating Characteristics of TIPS

The operating characteristics of the TIPS sampler were investigated to better understand how the TIPS design affects FSS measurement. The following characteristics were included: the inlet velocity and the ratio (E:R) of the amount of FSS expelled from the sampler outlet to the amount retained in the sampler. All the FSS collection equipment and stream flow measurement instruments were installed in the flume according the configuration shown in Figure 2.10. The TIPS and CPS samplers were duplicated; therefore, the samplers used in this study are referred specifically as TIPS(1), TIPS(2), CPS(1), and CPS(2).

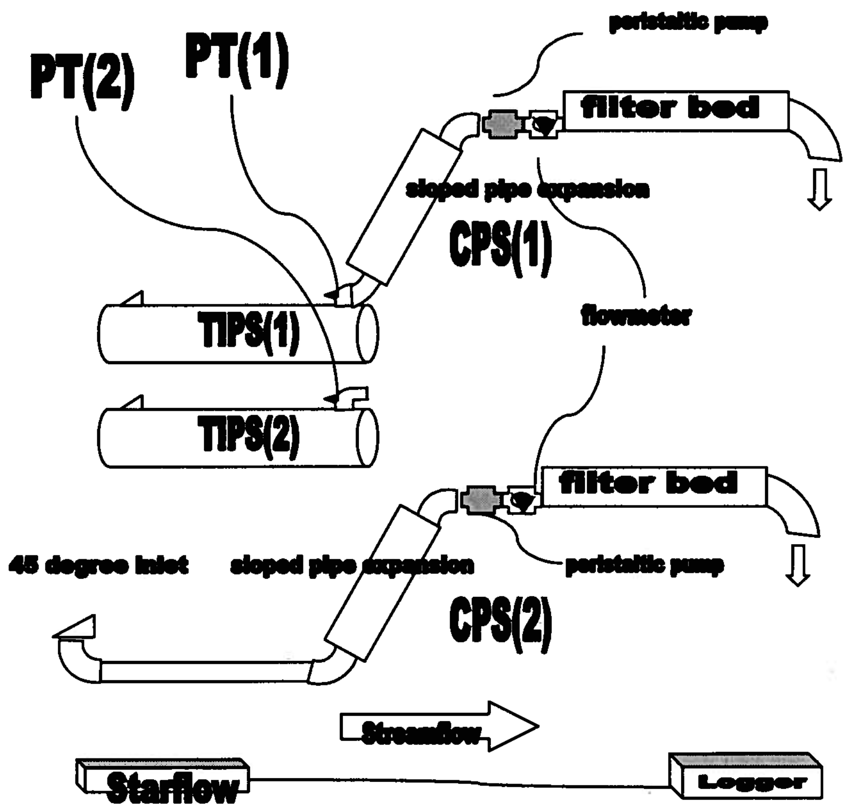


Figure 2.10. Configuration of paired time integrated passive samplers TIPS(1) and TIPS(2), continuous pump samplers CPS(1) and CPS(2), and pressure transducers PT(1) and PT(2).

2.7.1 Balance between TIPS(1) and TIPS(2)

The TIPS(1) and TIPS(2) sampler FSS measurements were compared to select the observations with identical values. It was assumed that on these occasions that the outlet and inlet velocities, and retention capabilities of both samplers were equal. Furthermore, it was then assumed that the CPS(1) FSS measurements and flow velocities could be used to determine the TIPS inlet velocity and retention capabilities in relation to flume flow velocity.

According to Figure 2.10, TIPS(1) and TIPS(2) were paired and installed in the flume side by side and run concurrently under identical flume flow and FSS conditions. Differential pressure transducers PT(1) and PT(2) (Sensotec™ model FDW-WA-2p-5b-6a, wet to wet, and sensitive to 0.025 mm of H_2O) were installed at a tap point on the outlet end of TIPS(1) and TIPS(2). The pressure differential was recorded between the tap and an adjustable level of water in a bucket. The water level was adjusted to achieve a recordable differential within the operating range of the pressure transducers. Theoretically, the outlet tap point acted as a venturi. A recordable pressure drop was measured at the tap point by the differential pressure transducers as the outflow from the outlets increased. Likewise, the outflow rate was directly related to the inflow rate which was, in turn, affected by the ambient flume flow rate.

The CPS(1) was plumbed into the outlet of TIPS(1) to capture and measure the outflow of FSS from the TIPS(1) outlet. One side of the duplex variable speed peristaltic pump was used to lift the expelled sediment from TIPS(1) through CPS(1). The rate of CPS(1) pumping was determined by the differential pressure readings PT(1) and PT(2). At the beginning of each observation TIPS(1) and TIPS(2) were set in the flume and the reference pressure difference between PT(1) and PT(2) was determined before CPS(1) was plumbed into the outlet of TIPS(1). This reference pressure difference, $\Delta P = PT(1) - PT(2)$, was the target pressure difference that was achieved by adjusting the pumping speed after CPS(1) was plumbed into the outlet of TIPS(1). The pump speed was adjusted using a variable frequency drive that could drive the pumping speed between 0.00 L m^{-1} and 3.01 L m^{-1}. The other side of the duplex variable speed peristaltic pump was used to pump CPS(2), which was used to capture and measure the flume FSS variables, at the same pumping speed as CPS(1).

The objective was to regulate the pumping velocity of CPS(1) to match the outlet velocity of TIPS(1) to that of TIPS(2). TIPS(1) was the slave of TIPS(2) based on the TIPS(2) response (ΔP) to the flume flow velocity. Two crosscheck procedures were used to verify that TIPS(1) and TIPS(2) were balanced at the end of each observation. Mathematically, the values of each CPS(1) measured FSS parameter were compared to the sum of each FSS parameter value measured by CPS(2) plus TIPS(2). Also, the values of each TIPS(1) measured FSS parameter were compared to the TIPS(2) measured FSS parameter values. Observations failed the cross-check analysis if there was a greater than 10% difference between the FSS total weight results for TIPS(1) and TIPS(2). The 13 observations (Results 3.4.1) that passed the cross-check analysis were used for the examination of the operating characteristics of the TIPS sampler. The 13 data points were regressed using simple linear models in which X and Y were arbitrarily assigned, and the models were forced through the origin (Equation 2.2).

2.7.2 Inlet Velocity

When TIPS(1) and TIPS(2) were balanced the inlet velocity of both samplers was equal. On these occasions the inlet velocity could be related to the ambient flume flow velocity to determine simple linear relationship between the two variables. The TIPS(1) outlet flow rate and velocity were regulated and measured by the CPS(1) pumping rate. The inlet velocity of TIPS(1) was determined based on the time elapsed to collect a volume of water through the cross-section inlet area. The inlet velocity of TIPS(1) was calculated by using the CPS(1) pump flow rate and velocity through the identical cross-section areas of the TIPS(1) inlet and outlet. The relationship was determined based on only two flume flow values (180 mm s^{-1} and 400 mm s^{-1}) due to the inadequate pumping capacity of CPS(1) at greater ambient flume flow velocities.

2.7.3 Expelled:Retained Ratio

It was postulated that, of the total amount of flume FSS that was sampled by the TIPS(1) or TIPS(2), a certain amount of FSS would be retained (R) and some would be expelled (E). The E:R ratio was investigated using the data collected from the 13 balanced TIPS(1) to TIPS(2) observations. The retention and expulsion characteristics of the TIPS(1) used the results from the TIPS(1) retained sediment variables and CPS(1) expelled sediment variables. The results were plotted using simple linear regression models in which X and Y were arbitrarily assigned (Equation 2.2).

An examination of the E:R ratio over differing flume velocities was conducted to determine if the E:R ratio was changeable due to flume velocity changes. Flume velocity was chosen over flow rate as the independent variable because the ambient velocity was shown by Phillips et al. (2000) to affect passive sampler inlet velocity.

An examination of the E:R ratio over differing flume percent fraction proportions was conducted to determine if the E:R ratio was changeable due to particle size distribution changes. The CPS(2) sampler was used as a measure of the flume FSS percent fraction proportions versus E:R ratio, because the regression analysis of flume percent fraction proportions versus flume flow in Experiment 2 determined that the statistical fit was closer than the DPS sampler measurements. Assuming that this applied to the 13 observations discussed in this experiment, a regression analysis was done to determine if the ratio E:R was influenced by stream percent proportions determined from the CPS(2) flume FSS assessments.

2.8 Experiment 4 Design: TIPS(2) Prediction of CPS(2) and DPS Measured Flume FSS Load

It was postulated, that if the TIPS sampler FSS weight measurements were flow proportional and strongly correlated to the DPS and CPS sampler FSS measurements the TIPS could be calibrated to predict FSS load values. The conclusions of the previous three experiments and the regression of TIPS FSS weight variables against the DPS and CPS(2) load variables were used to support this hypothesis.

All three FSS collection devices and stream flow measurement instruments were installed in the flume according the configuration shown in Figure 2.9 and 2.10. The TIPS and CPS devices were duplicated for other experiments; therefore, the devices used in this experiment are referred to specifically as DPS, TIPS(2) and CPS(2). All three devices were run concurrently under identical flume flow and FSS conditions.

Simple linear regression models (Equation 2.2) were used to compare between TIPS(2) measured FSS weight variables (X), and the CPS(2) and DPS measured FSS load variables (Y). The TIPS(2) versus DPS relationship was based on n=46 observations, and the TIPS(2) versus CPS(2) relationship was based on n=34 observations.

CHAPTER 3
RESULTS

3.1 Experimental Conditions

3.1.1 Campbell Creek Air and Water Temperature

Water temperatures (Figure 3.1) were all above freezing for the duration of the study. The average water temperature was 15°C (n= 46, SD= 3) and ranged from 7°C to 20°C. Air temperatures during the same period ranged from 0°C to 30°C with a mean of 15°C. The water temperatures were above freezing for the duration of the experiment. Air and water temperature affect the availability of water and sediment. Frozen stream beds are armoured against erosion and reduce sediment supply. Air and water temperatures also govern the amount of organic sediments contributed from biological processes. Organic sediments are important constituents of flocs (Droppo, 2000). Cyanobacterium blooms are influenced by higher temperatures and an incidental bloom event was recorded during the study period on August 18, 2006. The Cynaobacterium sediment was trapped and recorded by the TIPS and CPS samplers, but not by the DPS sampler.

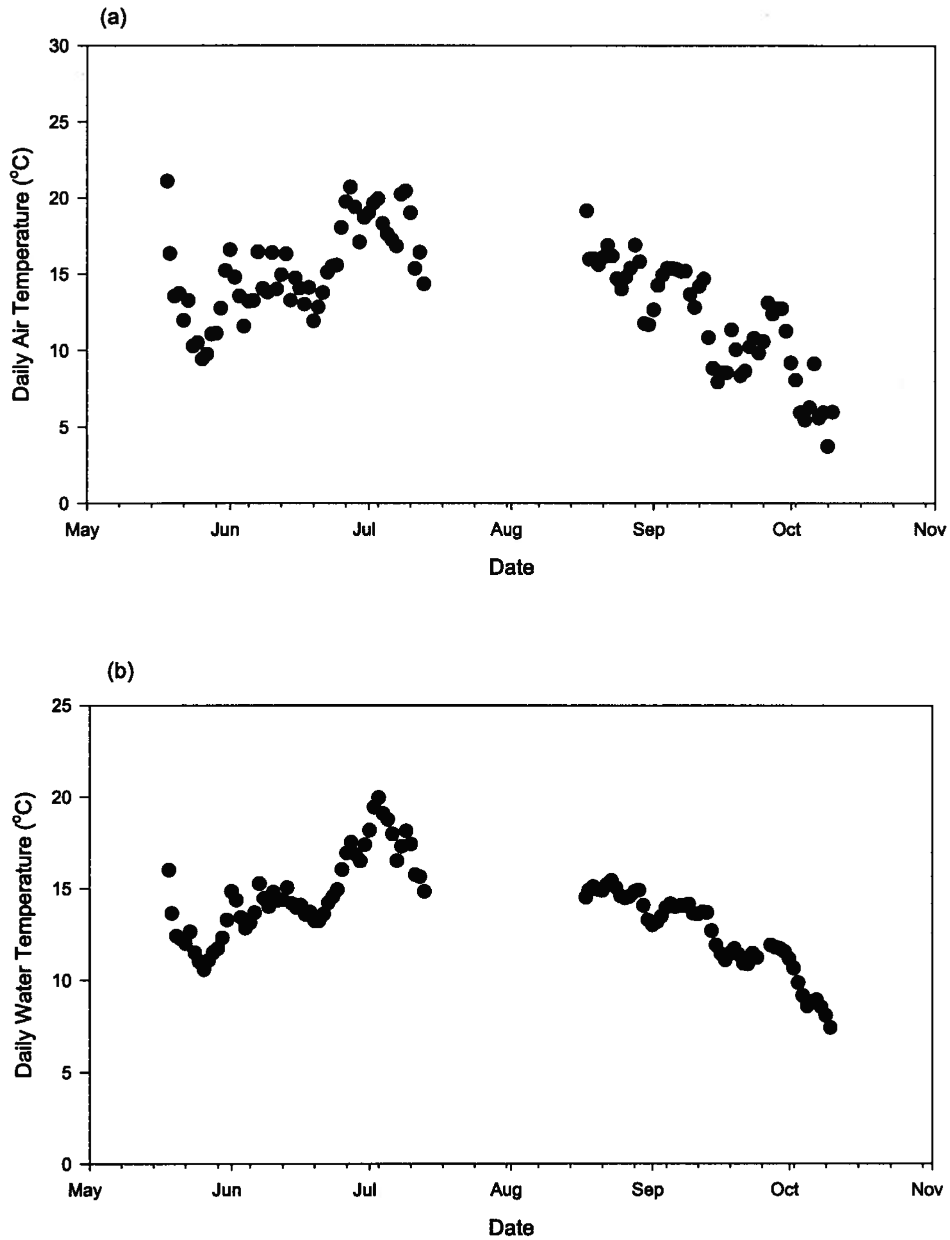


Figure 3.1. Daily average temperature data for the period between May and November 2006. (a) air temperature and (b) water temperature.

3.1.2 Campbell Creek Hydrograph

The mean Campbell Creek flow rate (Figure 3.2) was 459 L s^{-1} (n=46, SD=292 L s^{-1}) and ranged from 13 L s^{-1} to 1065 L s^{-1}. The Campbell Creek hydrograph revealed two substantial drops in flow rate in this creek at observations No. 32 and No. 55. Both of these events were due to a restriction of flow out of Scuitto Lake on July 4 and September 14, respectively. The observation No. 55 event impacted the outcomes of the experiments by creating a gap in the response of the FSS sampling equipment to the rapid transition from a higher stage value to a lower stage value. This is evident in the gap between data points in the TIPS(2) log-log sedi-graphs (Figure 3.19). Other than this instance, the ambient conditions were stable for each of the 24-hour observations.

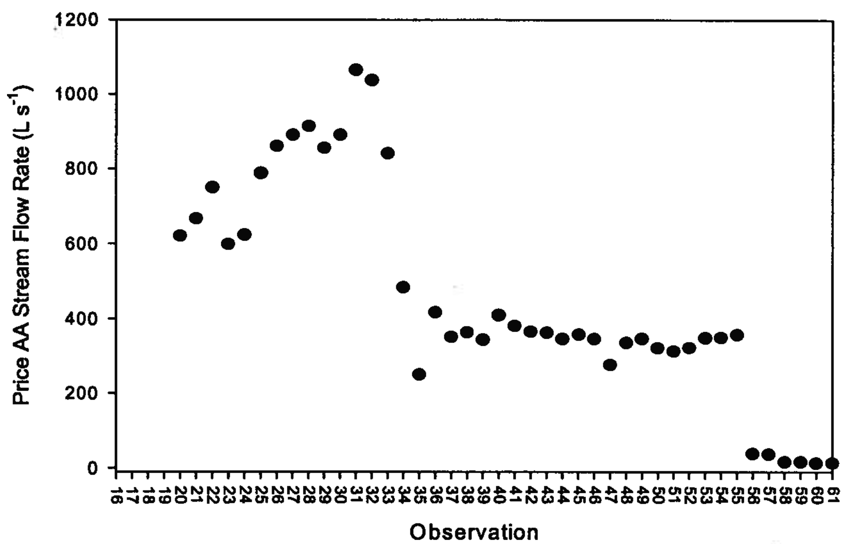


Figure 3.2. Campbell Creek hydrograph produced from Price™ type AA measurements at both culverts in stream crossing at the study site.

3.1.3 Instream Flume

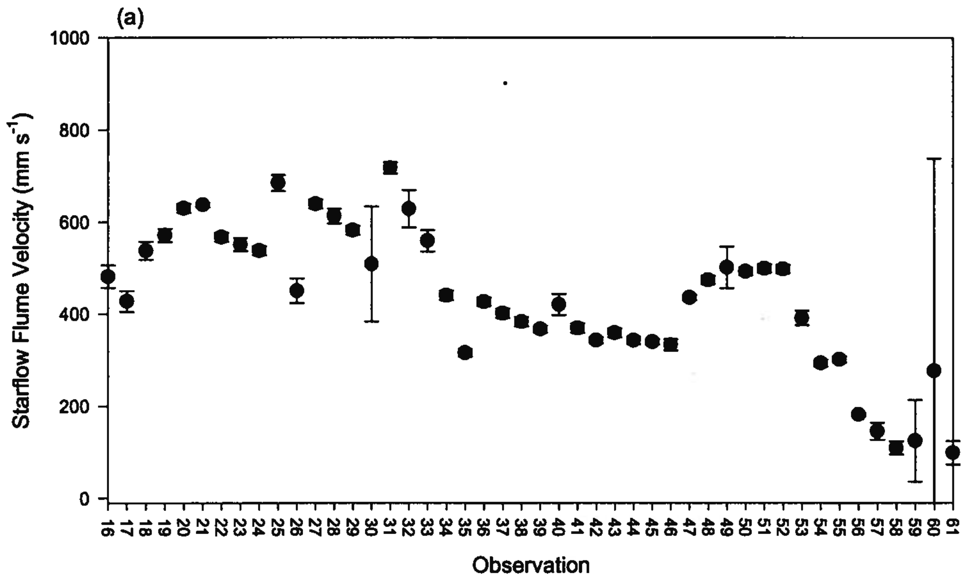
The instream flume created a stream control section in which the FSS supply was mixed naturally and uniformly, and the flow and velocity were adjusted and measured with the least amount of turbulence as was practicable. Very little bed material sediment accumulated in the bottom of the flume. The instream flume successfully isolated the suspended bed material from the wash load, by allowing the bed material to pass below the suspended flume. The flume provided a convenient working platform over the control section for installing and monitoring flume and stream FSS and flows. The instrumentation was easy to access and maintain by walking on top of the flume removable wood platform. The round 1 m diameter shape and defined length of 6 m made calculations of flow cross-sectional area accurate and easy. The winching assembly and adjustable legs worked well, enabling the flume to be adjusted to the changing conditions of the stream flow.

3.1.4 Flume Hydrograph Variation

The Starflow™ measured flume flow rate varied minimally within the 24-hour period, but widely over the 46 observations. The range of flow velocities for testing a passive sampler in a small stream was wider than the range (0 to 600 mm s^{-1}) recommended by Phillips et al. (2000). The mean flume flow rate (Figure 3.3) was 128 L s^{-1} (n= 46 SD= 57.6) and ranged from 14 L s^{-1} to 245 L s^{-1} with an average 24 h standard deviation of 8.0 L s^{-1} (n= 46). The mean velocity was 434 mm s^{-1} (n= 46, SD= 154 mm s^{-1}) and ranged from 99 mm s^{-1} to 717 mm s^{-1} with an average standard deviation of 28.0 mm s^{-1} (n= 46). The sources of variability included experimental error and the variation of the combined natural and controlled flow of Campbell Creek.

The instream flume hydrograph did not show the same dramatic drops in flow that existed in the Campbell Creek hydrograph because the flume was lowered to maximize the amount of flume flow. At observation 55 (9/14/06), the flume flow rate and Campbell Creek flow rate converged because at this late stage all the available stream flow was diverted through the flume. Thus, the hydrographs show the same drop in flow due to a sudden closing of the control dams on Campbell Creek at the end of the irrigation season.

The Starflow™ Doppler measurement was easy to set up because the 1 m pipe configuration was listed in the instrument setup options. A check of the Starflow™ data was performed by correlating the Starflow™ data with the Price-AA method data (Figure 3.4). The methods were linearly related but the Price-metered discharge was consistently higher over the range of measurements. The systematic differences were not applied to the Starflow™ data, because the Price-AA is not continuous and there was too great a risk of introducing error into the continuous velocity measurements.



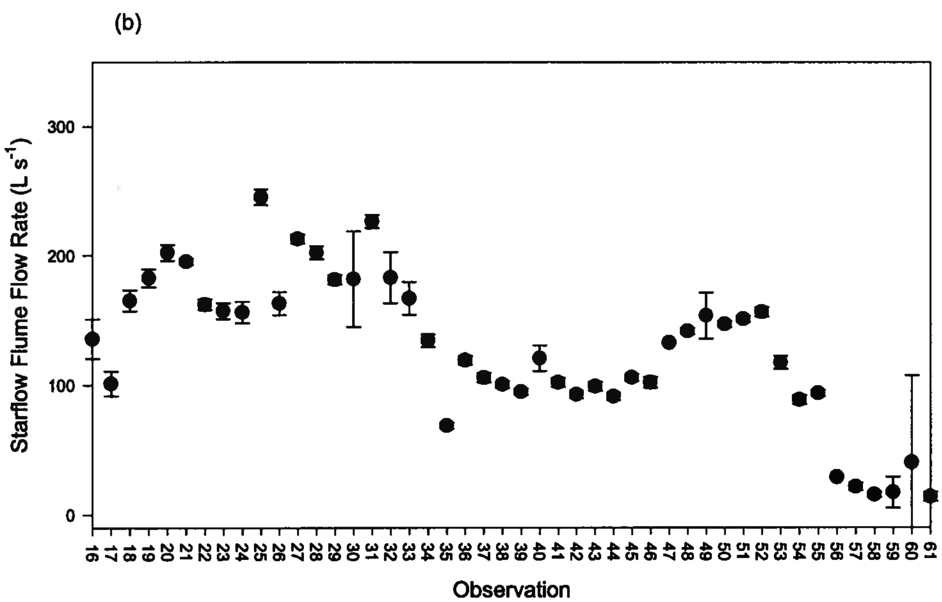


Figure 3.3. Instream flume hydrograph showing (a) velocity and (b) flow rate recorded during May 15 to October 4, 2006. Each data point is an average of 46 data samples taken during a 24-hour period. The error bars show the standard deviation based on the 30-minute logged values.

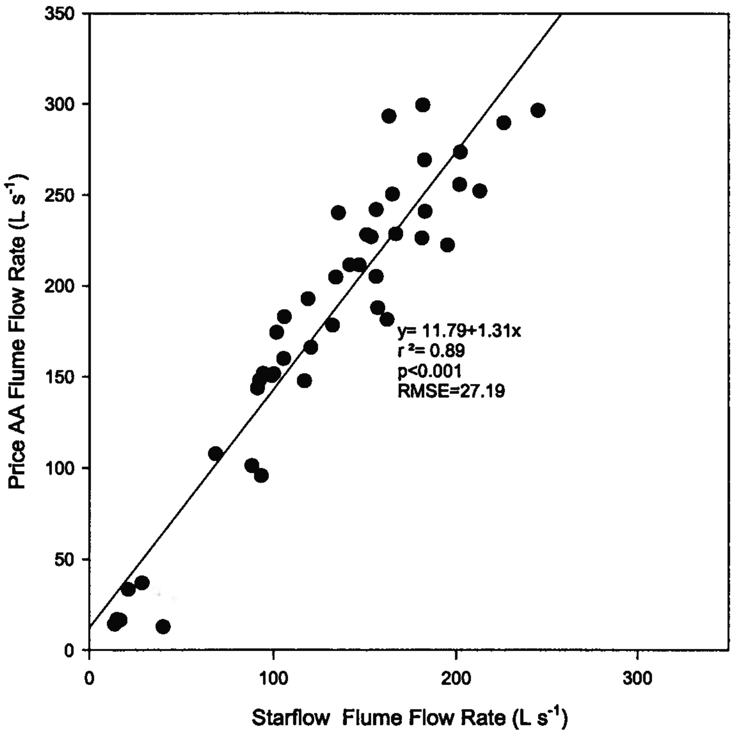


Figure 3.4. Relationship between Price AA™ flume flow rate and Starflow™ flume flow rate.

3.1.5 Flume Suspended Sediment Concentration Variation

The average SSC (Figure 3.5a) was 13.3 mg L^{-1} (n= 545, SD= 6.82 mg L^{-1}), and ranged from 0.7 mg L^{-1} to 32.4 mg L^{-1}, with a standard deviation of 2.7 mg L^{-1} for the 24-hour means. The average mineral concentration (Figure 3.5b) was 9.1 mg L^{-1} (n= 545, SD= 5.03 mg L^{-1}), and ranged from 0.1 mg L^{-1} to 26.4 mg L^{-1} with an average 24-hour standard deviation of 2.0 mg L^{-1} (n= 46). The average organic concentration (Figure 3.5c) was 4.2 mg L^{-1} (n= 545, SD= 2.30) and ranged from 0.3 mg L^{-1} to 17.47 mg L^{-1} with an average 24-hour standard deviation of 0.91 mg L^{-1} (n= 46).

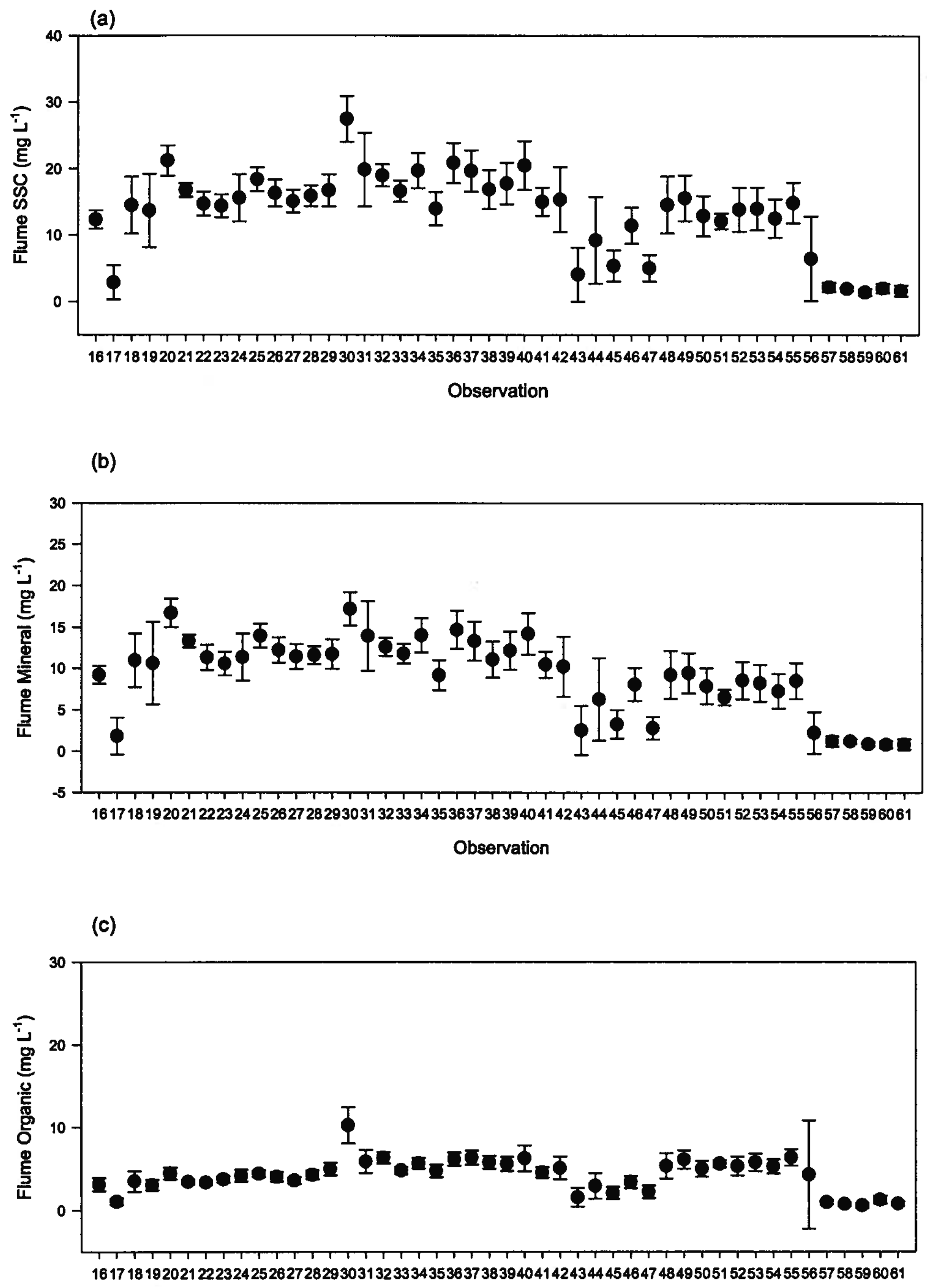


Figure 3.5. Automatic pump sampler measured flume suspended sediment: (a) total concentration, (b) mineral concentration, and (c) organic concentration. Each observation value is the mean of 12 samples with standard deviation shown as error bars.

The Sigma automatic pump sampler was programmed to sample 750 mL of flume water every two hours in a 24-hour period. This amounts to 8.0 x 10^{-5} percent of the average flume discharge in a 2-hour period, which is a very small sample size. Thus, for the collected samples to be representative of the average discharged FSS through the flume in a 24-hour period, it is important that the 24-hour variability is kept at a minimum. Within the 24-hour observation period, there was minimal variance in the flume FSS observations. This variability included sources of experimental error, including the effects of ducks which were observed feeding and disturbing the stream bed upstream of the flume. The flume FSS observations varied moderately over the 46 observations. This variability included sources of experimental error, but was mainly due to the variability of FSS in Campbell Creek over all observations. There was no hysteresis effect evident within the data because Campbell Creek supplied FSS at all stages of the hydrograph. The SSC ranged from very low to less than the Canadian environmental water quality guidelines criterion for good fishery in the South Thompson River (25 mg L^{-1} non-filterable residue). The instream flume created a stream control section in which the inter-observation FSS concentrations and flume discharges varied enough to expand the range of experimental conditions under which the FSS samplers were compared. The range of measured flume flow rate values, over all observations, was adequate. The measured flume SSC range achieved very low readings, and no high readings. The variation in the flume flow and suspended sediment concentration was appropriate for the study of FSS collection and measurements at Campbell Creek in 2006.

3.2 Experiment 1: Cross Comparison of TIPS(2), CPS(2) and DPS

3.2.1 Time Integrated Passive Sampler(2) and Discrete Pump Sampler Comparison

A barchart view of the TIPS(2) and DPS flume FSS data (Figure 3.7) reveals some of the characteristics of both samplers when they were operated according to Figure 3.6 over the range of flume experimental conditions (Figures 3.3, and 3.5).

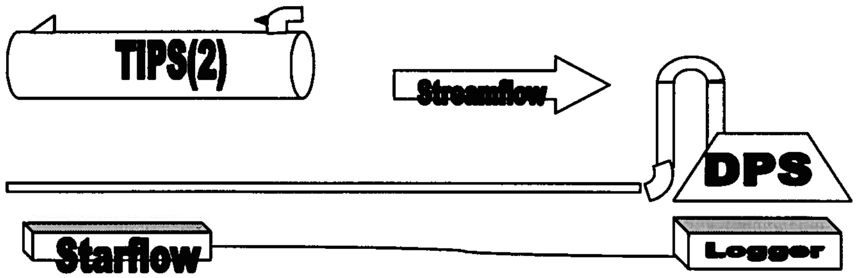


Figure 3.6. Configuration of time integrated passive sampler (TIPS(2)) versus discrete passive sampler (DPS) and flow rate instrument in the instream flume.

The percent organic and percent mineral fractions obtained by both samplers appear to be visually correlated between both samplers (Figures 3.7a and b). An increase in the percent organic fraction and decrease in the percent mineral fraction with observation number is apparent in both devices. However, the DPS change in percent fractions appears to be steeper and greater than the TIPS(2) method.

Total values obtained by both samplers (Figures 3.7c and d) have a similar trend: a rise toward observation No. 40 and then a fall towards observation No. 55 where the data falls off dramatically. Both samplers appear to reflect the dramatic change in stream flow beginning at observation No. 56. This was due to the sudden shut off of flow from an upstream storage dam. The Campbell Creek flow rate (Figure 3.2) reflects the sudden drop in available water from the stream to the flume; however, there is a trough in the DPS concentration data at observation No. 43 to No. 47 that is not as pronounced in the TIPS(2) weight data.

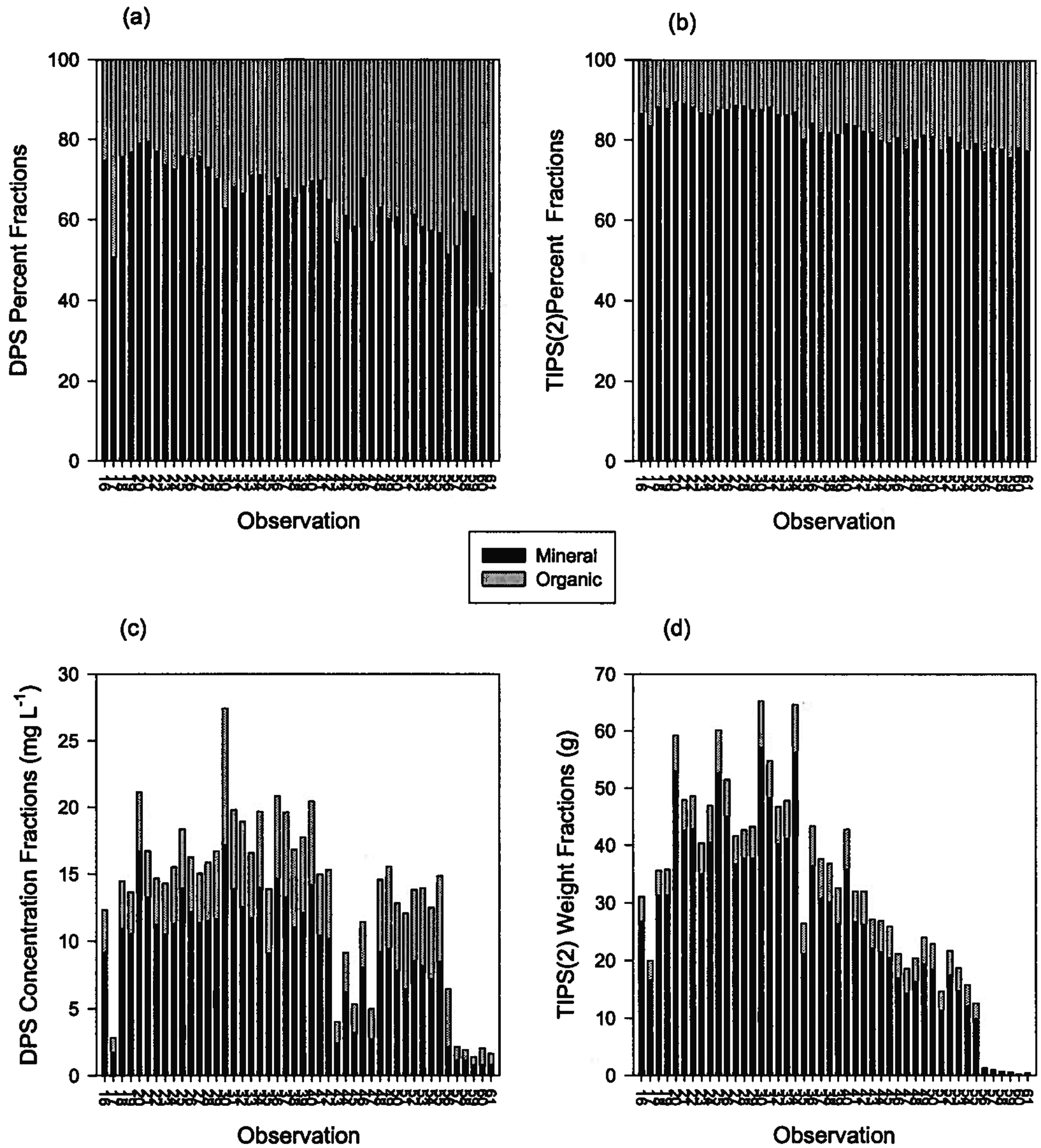


Figure 3.7. Time integrated passive sampler(2) (TIPS(2)) and discrete pump sampler (DPS) measured flume variables versus observation. (a) DPS measured flume percent of sediment fractions (b) TIPS(2) measured flume percent of sediment fractions (c) DPS measured flume concentration of sediment fractions (d) TIPS(2) measured flume weight of sediment fractions. Stacked bars are summed to totals.

The profile of the TIPS(2) barcharts appears to be smoother than that of the DPS sampler. The greater observation to observation fluctuations in the DPS measurements might have been due to the sensitivity in FSS concentrations or experimental error. The TIPS(2) sampler has a smoother appearance that may have been due to the continuous sampling properties of the sampler that modified extreme events during the collection period. Overall, the TIPS(2) and DPS barchart trends are visually similar and appear to be correlated.

The Pearson's correlation results for the contrasts of similar and dissimilar variables are presented in Table 3.1. The coefficient of correlation values between the samplers range from r =0.54 to r =0.93 over the 46 observations. The correlations are all significant ($p < 0.001$). The results demonstrate that the TIPS(2) sampler and the DPS sampler were closely and positively correlated with the exception of TIPS(2) organic weight versus DPS organic concentration.

TIPS(2) total weight was closely correlated (r =0.74) with the DPS total concentration and total load values. Averaged over 46 observations the TIPS(2) sampler collected 38 g (24 h) of total FSS from an average DPS sampler measured concentration of 13 mg L^{-1}. In particular, there was strong correlation between both samplers for the percent mineral fractions and the percent organic fractions (r =0.78), indicating that the samplers were comparable. The DPS organic concentration versus TIPS(2) organic weight had the weakest correlation (r =0.54) value. The DPS organic load versus TIPS(2)

Table 3.1. Correlations between discrete pump sampler (DPS) and time integrated passive sampler(2) (TIPS(2)) variables. Pearson's Correlation Method

TIPS(2)				DPS						
Variable	Units	Mean	SD	Variable	Units	Mean	SD	n	r	p-value
total wt.	g	38	26.4	total conc.	mg L^{-1}	13	6.2	46	0.74	<0.001
mineral wt.	g	33	24.1	mineral conc.	mg L^{-1}	9	4.6	46	0.81	<0.001
Organic wt.	g	5	2.6	organic conc.	mg L^{-1}	4	2.0	46	0.54	<0.001
total wt.	g	38	26.4	total load	mg s^{-1}	1939	1278.0	46	0.89	<0.001
mineral wt.	g	33	24.1	mineral load	mg s^{-1}	1352	946.4	46	0.93	<0.001
Organic wt.	g	5	2.6	organic load	mg s^{-1}	587	370.4	46	0.71	<0.001
Organic %	%	16	5.0	organic %	%	35	9.3	46	0.78	<0.001
mineral%	%	84	5.0	mineral%	%	64	9.3	46	0.78	<0.001

Note: Standard deviation (SD). Number of observations (n). Coefficient of correlation (r).

organic weight had a stronger correlation result (r =0.71). The positive correlation results demonstrate that the TIPS(2) sampler responded to the fluctuating flume total FSS concentration and load in a similar manner compared to the DPS method.

Simple linear regression models in Figure 3.8 compare the DPS and TIPS(2) sampler measurement of flume FSS on a percentage basis. The model for each of the relationships fits the data moderately well and explains 60% of the total variation. The regression models are significant (p<0.001), which suggests that the TIPS(2) sampler measurements were linearly different than the DPS method.

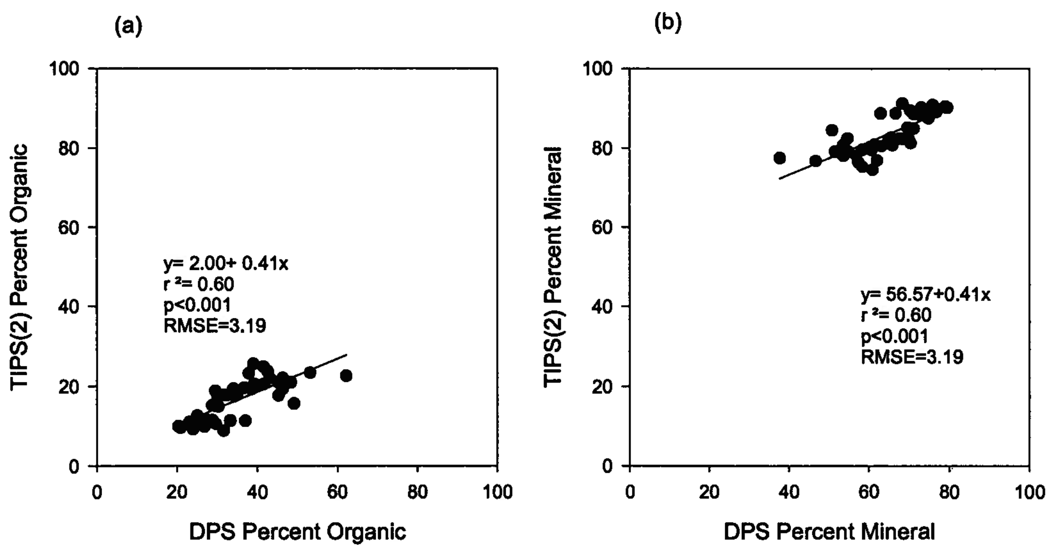


Figure 3.8. Regression of the time integrated passive sampler(2) (TIPS(2)) versus discrete pump sampler (DPS) for measuring the following flume sediment percent fractions: (a) organic, and (b) mineral.

There was no agreement between samplers for the measurement of flume FSS percent variables (b_1= 0.41, r^2= 0.61 p<0.001). Averaged over 46 observations, the mean DPS sediment percent organic fraction content was 35% and the TIPS(2) sediment percent organic fraction content was 16%. Averaged over 46 observations, the mean DPS sediment percent mineral fraction content was 65%, and the TIPS(2) sediment percent mineral fraction content was 84%.

The comparison between the DPS sampler and the TIPS(2) sampler reveals that the samplers were strongly correlated and the differences between samplers were consistent and linear over the full range of observations. There was no agreement on the assessment of flume FSS. The DPS sampler favoured the collection of the FSS organic fraction, while the TIPS(2) sampler favoured the collection of the FSS mineral fraction. The DPS sample size was not large enough to conduct a particle size analysis.

3.2.2 Continuous Pump Sampler(2) and Discrete Pump Sampler Comparison

A barchart view of CPS(2) and DPS flume FSS data (Figure 3.10) reveals some of the characteristics of both samplers when they were operated according to Figure 3.9 over the range of flume stream conditions as described previously (Figures 3.3 and 3.5).

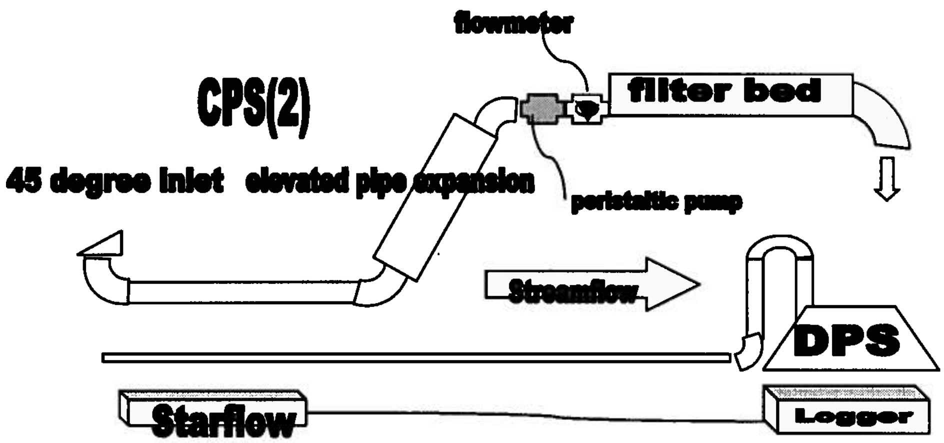


Figure 3.9. Configuration of continuous pump sampler(2) (CPS(2)) versus discrete pump sampler (DPS) and the flow rate instrument in the instream flume.

The percent organic and mineral fractions appear to be visually correlated between both samplers (Figures 3.10a and b). An increase in the percent organic fraction and decrease in the percent mineral fraction with increasing observation number is apparent in both samplers. The DPS change in percent sediment fractions appears to be steeper and greater than the CPS(2) method.

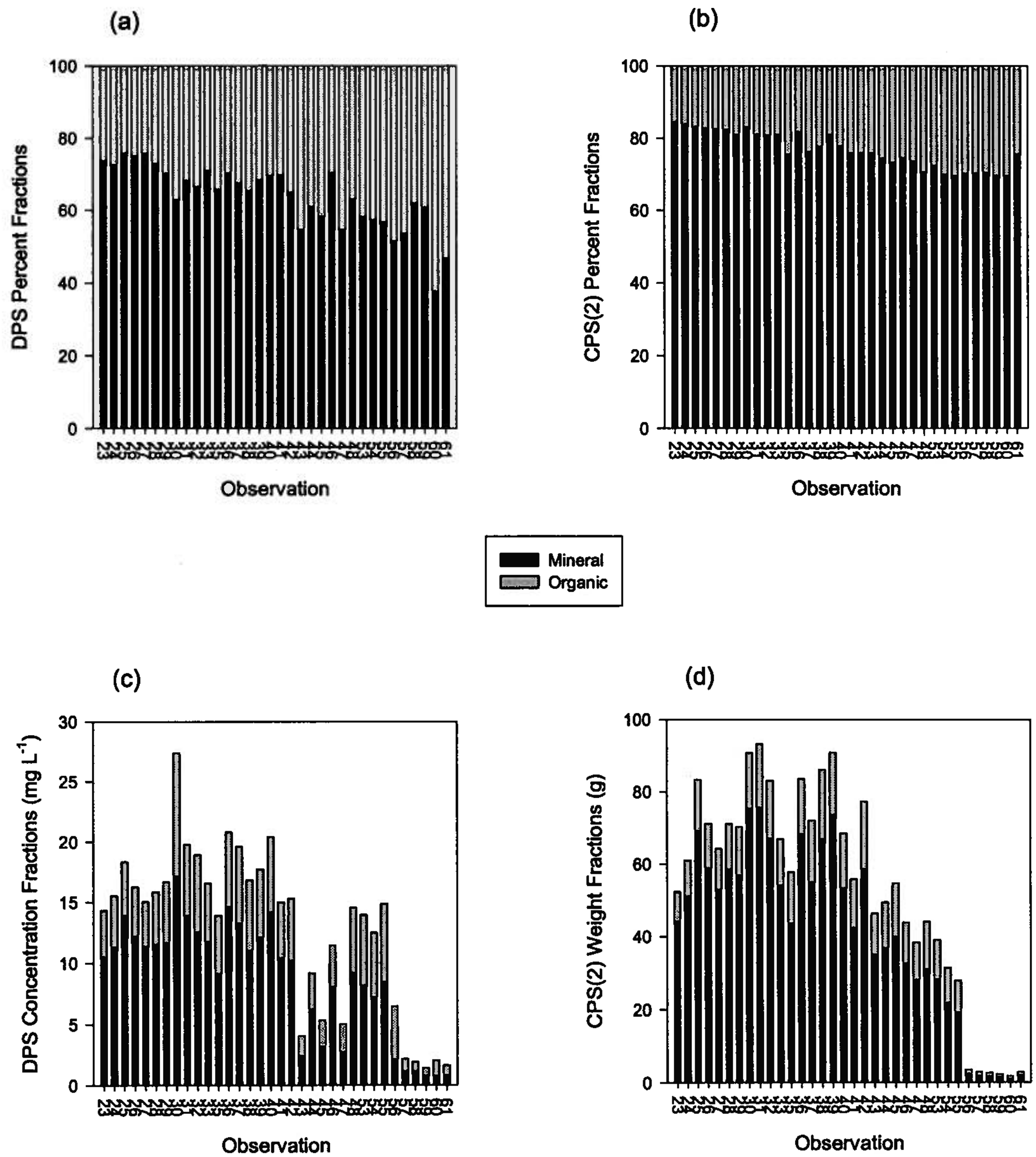


Figure 3.10. Continuous pump sampler(2) (CPS(2)) and discrete pump sampler (DPS) measured flume variables versus observation. (a) DPS measured flume percent of sediment fractions (b) CPS(2) measured flume percent of sediment fractions (c) DPS measured flume concentration of sediment fractions (d) CPS(2) measured flume weight of sediment fractions. Stacked bars are summed to totals.

Total values obtained by both samplers (Figures 3.10c and d) have a similar trend: a rise toward observation No. 40 and then a fall towards observation No. 55 where the data falls off dramatically. Both samplers reflect the dramatic change in stream flow beginning at observation No. 56. There is a trough in the DPS concentration data at observation No. 43 to No. 47 that is not as pronounced in the CPS(2) weight data. The profile of the CPS(2) barcharts appears to be smoother than that of the DPS barcharts. The greater observation-to-observation fluctuations in the DPS measurements might have been due to the sensitivity in FSS concentration assessment and/or experimental error. Overall, the CPS(2) and DPS barchart trends are visually similar and appear to be correlated.

The correlation results for the contrasts of similar and dissimilar variables (Table 3.2) reveal that the CPS(2) sampler and the DPS sampler were closely and positively correlated. The correlation coefficient ranges from r= 0.70 to r= 0.91 over the 34 observations.

Table 3.2. Correlations between discrete pump sampler (DPS) and continuous pump sampler (CPS(2)) variables. Pearson's Correlation Method

Variable	CPS(2) Units	Mean	SD	Variable	DPS Units	Mean	SD	n	R	p-value
total wt.	g	53	29.1	total conc.	mg L^{-1}	13	6.7	34	0.87	<0.001
mineral wt.	g	42	24.1	mineral conc.	mg L^{-1}	9	4.8	34	0.91	<0.001
organic wt.	g	11	5.5	organic conc.	mg L^{-1}	4	2.1	34	0.70	<0.001
total conc.	Mg L^{-1}	12	1.1	total conc.	mg L^{-1}	13	6.7	34	0.83	<0.001
mineral conc.	Mg L^{-1}	10	0.9	mineral conc.	mg L^{-1}	9	4.8	34	0.88	<0.001
organic conc.	Mg L^{-1}	3	0.2	organic conc.	mg L^{-1}	4	2.1	34	0.64	<0.001
total load	mg s^{-1}	1729	1296	total load	mg s^{-1}	1808	1363	34	0.94	<0.001
mineral load	mg s^{-1}	1382	1084	mineral load	mg s^{-1}	1244	977	34	0.95	<0.001
organic load	mg s^{-1}	347	219	organic load	mg s^{-1}	563	409	34	0.84	<0.001
organic %	%	23	5.0	organic %	%	36	8.8	34	0.75	<0.001
mineral %	%	77	5.0	mineral %	%	64	8.8	34	0.75	<0.001

Note: Standard deviation (SD). Number of observations (n). Coefficient of correlation (r).

The correlations are all significant ($p< 0.001$). CPS(2) total weight was closely correlated with the DPS total concentration (r= 0.87). Averaged over 34 observations, the CPS(2) sampler collected 53 g of total sediment from an average DPS sampler measured concentration of 13 mg L^{-1}. In particular, there was good correlation (r= 0.91) between the mineral components of both samplers and there was less of a correlation (r= 0.70) between the organic components. The positive correlation results demonstrate that the CPS(2) sampler responded to the fluctuating flume total FSS concentration and load in a similar manner to the DPS method.

Simple linear regression models (Figures 3.11 , 3.12 , and 3.13) suggest that the CPS(2) sampler was consistently linearly related to the DPS sampler assessment of flume FSS. When FSS variables were expressed on a percent basis (Figure 3.11), there was no agreement between the two samplers. The regression models are all significant ($p<0.001$). Averaged over 46 observations, the experimental mean of the DPS sediment percent organic fraction content was 36% for the DPS and 23% for the CPS(2).

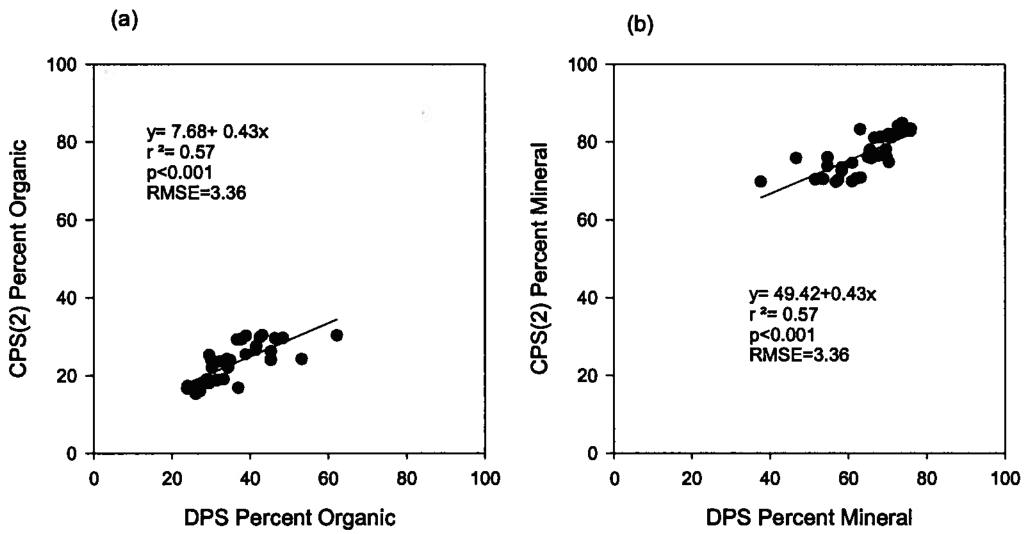


Figure 3.11. Regression of the continuous pump sampler(2) CPS(2) versus discrete pump sampler (DPS) for measuring the following flume sediment percent fractions: (a) organic, and (b) mineral.

Averaged over 46 observations, the experimental mean of the DPS sediment percent mineral fraction content was 64% and the CPS(2) sediment percent mineral fraction content was 77%.

When data were expressed as concentrations there was good agreement ($b_1= 0.95$, $r^2= 0.77$, $p<0.001$)) between the samplers for the estimation of flume mineral concentrations (Figure 3.12b), less agreement between samplers for total concentration (Figure 3.12a), and no agreement for organic concentration (Figure 3.12c).

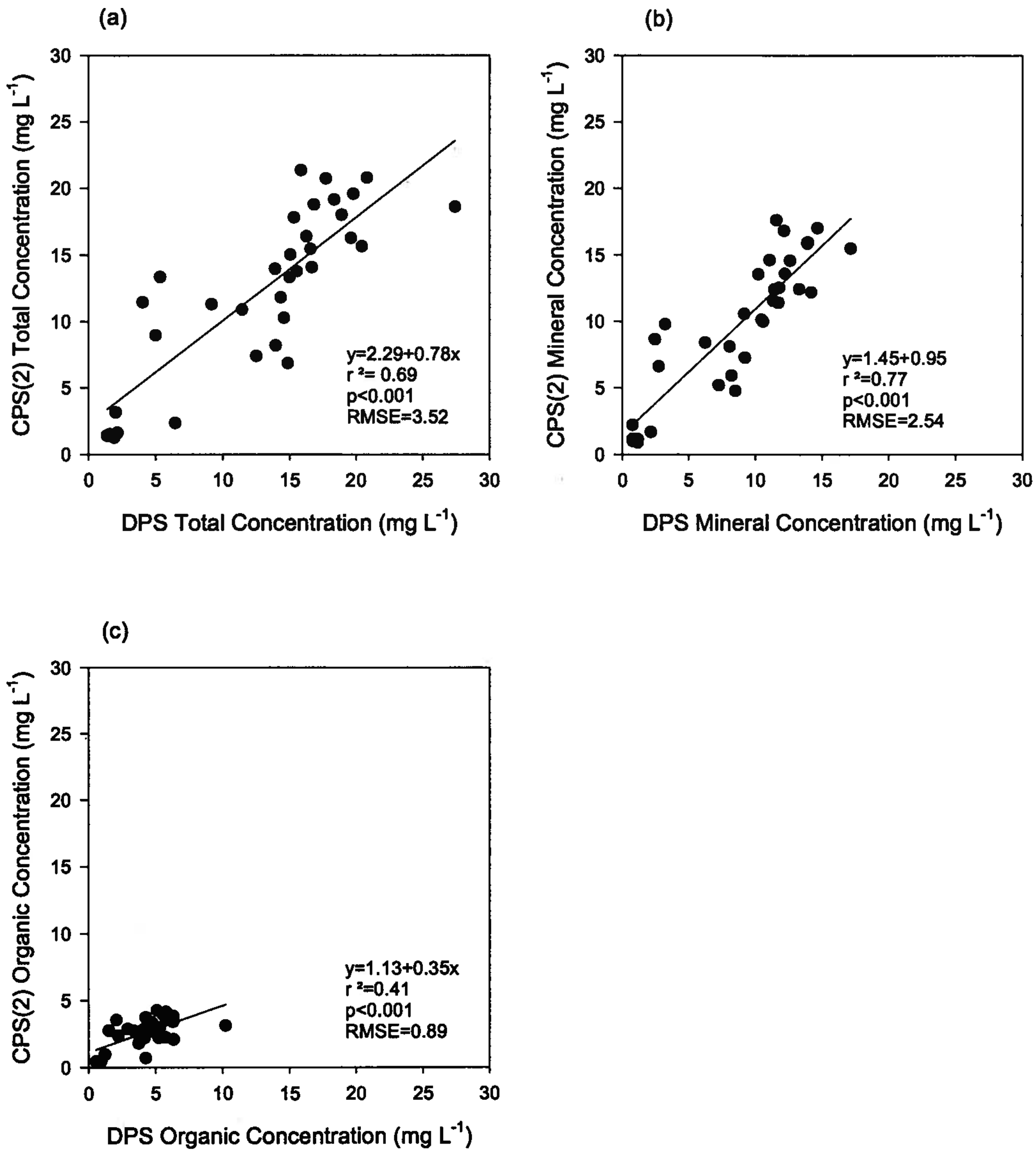


Figure 3.12. Regression of the continuous pump sampler(2) (CPS(2)) versus discrete pump sampler (DPS) for measuring the following flume sediment fraction concentrations: (a) total, (b) mineral, and (c) organic.

On a load basis (Figure 3.13), there was good agreement (b_1= 1.06, r^2= 0.91, $p<0.001$) between the samplers for the assessment of flume mineral load (Figure 3.13b). There was good agreement (b_1= 0.89, r^2= 0.87, $p<0.001$) between samplers for the assessment of total load (Figure 3.13a). There was no agreement between samplers for the assessment of organic load (Figure 3.13c).

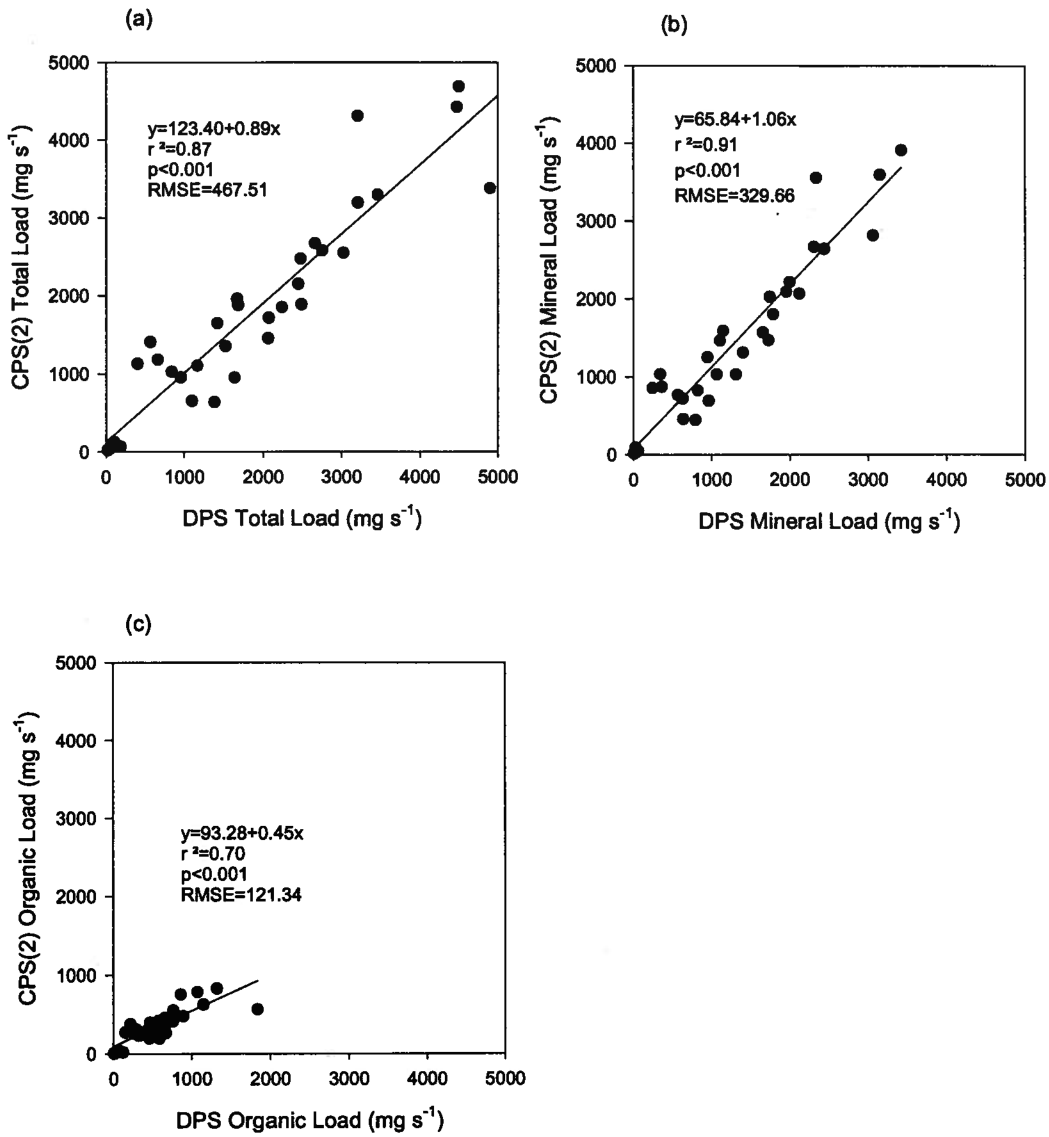


Figure 3.13. Regression of the continuous pump sampler(2) (CPS(2)) versus discrete pump sampler (DPS) for measuring the following flume sediment fraction loads: (a) total, (b) mineral, and (c) organic.

The samplers were strongly correlated and the differences between samplers were consistent and linear over the full range of observations. The comparison between the CPS(2) sampler and the DPS sampler reveals that there was no agreement between samplers based on percent fractions. A good agreement between two samplers was observed when data were expressed as mineral concentration and load. Finally, a reasonable agreement between the two samplers was found based on total concentration and load.

3.2.3 Time Integrated Passive Sampler(2) and Continuous Pump Sampler(2) Comparison

A barchart view of TIPS(2) and CPS(2) flume FSS data (Figure 3.15) reveals some of the characteristics of both samplers when they were operated according to Figure 3.14 over a range of flume stream conditions as described previously (Figures 3.3 and 3.5).

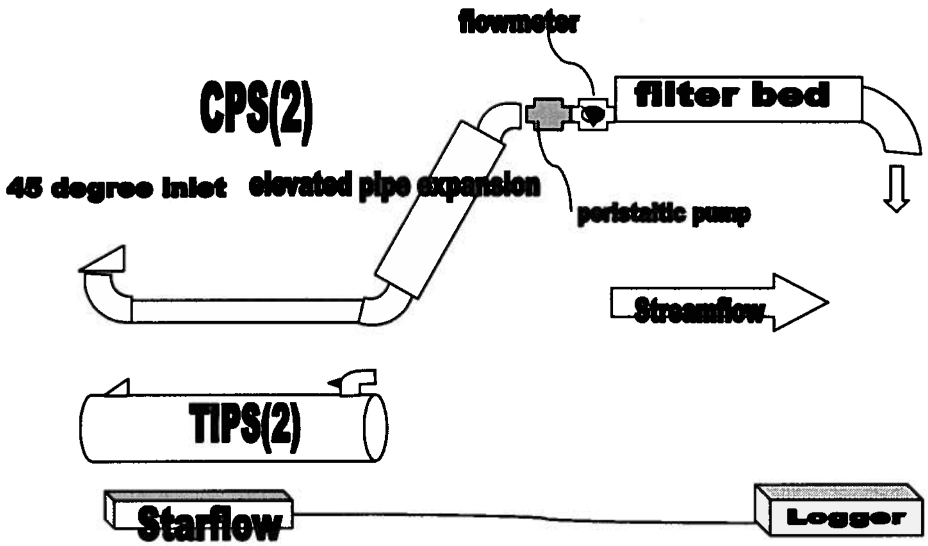


Figure 3.14. Configuration of time integrated passive sampler TIPS(2) versus continuous pump sampler CPS(2) and the flow rate instrument in the instream flume.

On a percentage basis (Figures 3.15a and b) the sediment fraction appears to be correlated between both samplers. For both samplers, the percent organic fraction and the percent silt/clay fractions increased through time and was offset by a decrease in the percent sand fraction with increasing observation number. The TIPS(2) percent sand fraction was greater and had a steeper and more extended decline over the full range of observations when compared to the CPS(2) method. It appears that at very low flows the TIPS(2) sampler is effective at collecting sand size fractions.

Total weights collected by both samplers were very close, indicating that the sediment recovery from the flume was comparable (Figure 3.15c and d). Both samplers had the appearance of a similar trend: a rise toward observation No. 40 and then a fall towards observation No. 55, where the data fall off dramatically. Both samplers reflect the substantial change in stream flow beginning at observation No. 56.

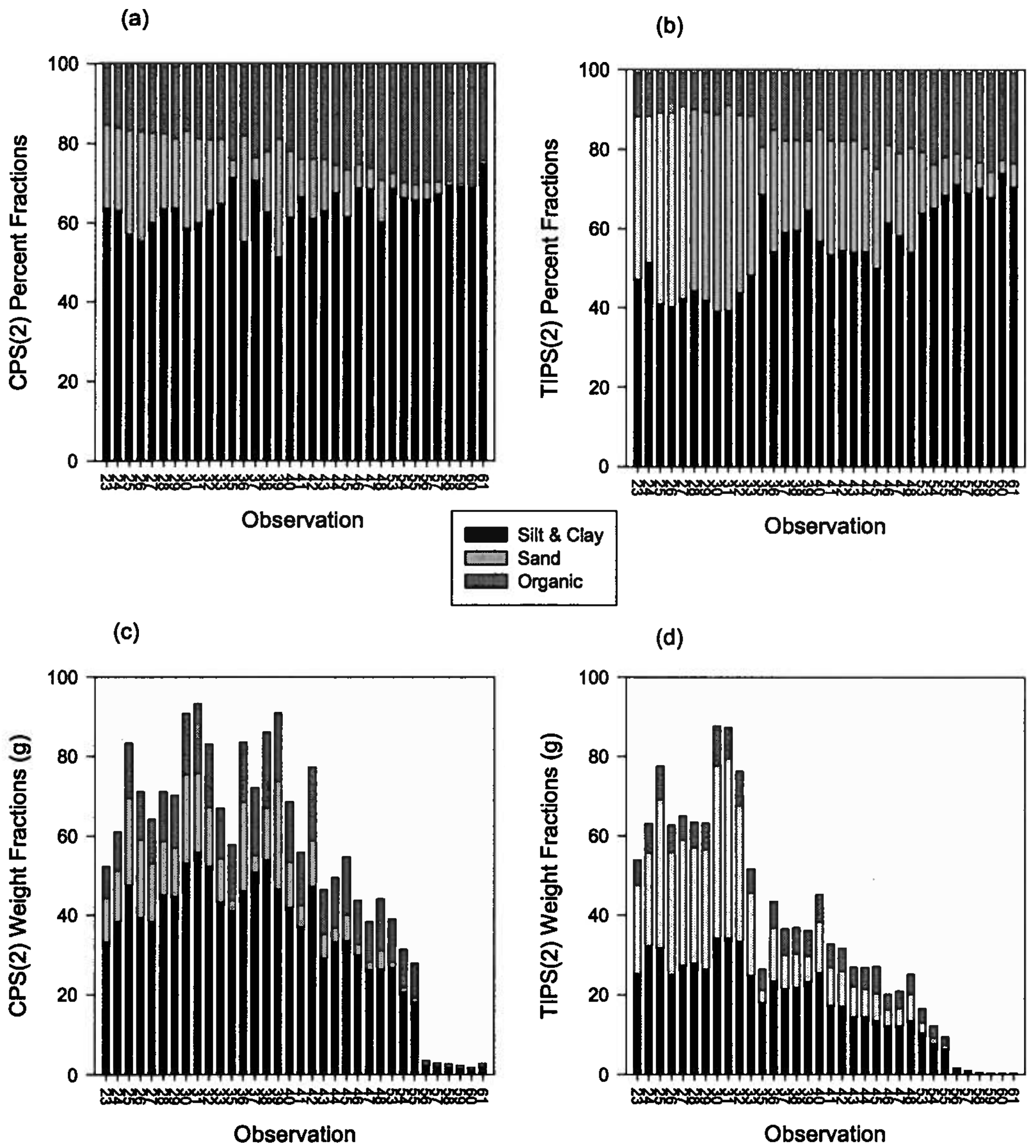


Figure 3.15. Time integrated passive sampler(2) (TIPS(2)) and continuous pump sampler(2) (CPS(2)) measured flume variables versus observation. (a) CPS(2) measured flume percent of sediment fractions (b) TIPS(2) measured flume percent of sediment fractions (c) CPS(2) measured flume concentration of sediment fractions (d) TIPS(2) measured flume weight of sediment fractions. Stacked bars are summed to totals.

The TIPS(2) sampler total weight appears to drop more dramatically at observation No. 32 than the CPS(2) method. Overall, the TIPS(2) and CPS(2) barchart trends are visually similar and appear to be correlated.

The Pearson's correlation results for the contrasts of similar and dissimilar variables are presented in Table 3.3. With the exception of percent silt/clay (r= 0.59) all the correlation coefficient values are very strong between the samplers, over the 34 observations. The correlations are all significant ($p < 0.001$). These results imply that the TIPS(2) and CPS(2) were closely and positively correlated.

Table 3.3. Correlations between the discrete pump sampler (CPS(2)) and time integrated passive sampler (TIPS(2)) variables. Pearson's Correlation Method

TIPS(2) Variable	Units	Mean	SD	CPS(2) Variable	Units	Mean	SD	n	r	p-value
total wt.	g	36	26.5	total load	mg s^{-1}	1729	1296.0	34	0.95	<0.001
Mineral wt.	g	31	24.1	mineral load	mg s^{-1}	1382	1084.0	34	0.95	<0.001
Organic wt.	g	5	2.7	organic load	mg s^{-1}	347	219.3	34	0.87	<0.001
sand wt.	g	14	13.9	sand load	mg s^{-1}	314	332.9	34	0.90	<0.001
silt/clay wt.	g	18	11.0	silt/clay load	mg s^{-1}	1068	771.9	34	0.92	<0.001
total wt.	g	36	26.5	total conc.	mg L^{-1}	12	6.2	34	0.82	<0.001
Mineral wt.	g	31	24.1	mineral conc.	mg L^{-1}	10	5.2	34	0.83	<0.001
Organic wt.	g	5	2.7	organic conc.	mg L^{-1}	3	1.2	34	0.83	<0.001
sand wt.	g	14	13.9	sand conc.	mg L^{-1}	2	1.8	34	0.74	<0.001
silt/clay wt.	g	18	11.0	silt/clay conc.	mg L^{-1}	8	3.7	34	0.89	<0.001
total wt.	g	36	26.5	total wt.	g	53	29.1	34	0.85	<0.001
Mineral wt.	g	31	24.1	mineral wt.	g	42	24.0	34	0.86	<0.001
Organic wt.	g	5	2.7	organic wt.	g	11	5.5	34	0.87	<0.001
sand wt.	g	14	13.9	sand wt.	g	9	8.0	34	0.75	<0.001
silt/clay wt.	g	18	11.0	silt/clay wt.	g	33	17.3	34	0.91	<0.001
Organic %	%	17	5.1	organic %	%	23	5.0	34	0.91	<0.001
Mineral %	%	83	5.1	mineral %	%	77	5.0	34	0.91	<0.001
sand %	%	27	15.4	sand %	%	13	9.1	34	0.82	<0.001
silt/clay %	%	56	10.8	silt/clay %	%	64	5.1	34	0.59	<0.001

Note: Standard deviation (SD). Number of observations (n). Coefficient of correlation (r).

TIPS(2) total weight was closely correlated with the CPS(2) total concentration ($r = 0.82$). Averaged over 34 observations, the TIPS(2) sampler collected 36 g of total sediment from an average CPS(2) sampler measured concentration of 12 mg L^{-1}. In particular, there were strong correlations between both samplers in the assessment of flume FSS variables on a percent and weight basis. The TIPS(2) sampler responded to the fluctuating FSS in a similar manner to the CPS(2) method.

Simple linear regression models (Figures 3.16 and 3.17) suggest that the TIPS(2) sampler was consistently linearly related to the CPS(2) sampler. The regression models are all significant ($p<0.001$) but vary in the degree of fit to the data. On a percent fraction basis (Figure 3.16), there was good agreement ($b_1 = 0.92$, $r^2 = 0.82$, $p < 0.001$) between the samplers for the estimation of flume percent organic fraction (Figure 3.16a) and percent mineral fraction (Figure 3.16d). Within the mineral fraction, there was no agreement between the TIPS(2) and CPS(2) sampler assessment of percent silt/clay size component (Figure 3.16b) percent sand component (Figure 3.16c). Averaged over the 34 observations the TIPS(2) and CPS(2) percent silt/clay was 56% and 64% , respectively. The TIPS(2) and CPS(2) percent sand (n=34) were 27% and 13%, respectively. It appears that the TIPS(2) and CPS(2) total percent mineral values were in agreement because the magnitude of the retained sand component was offset by the opposite magnitude of the silt/clay component, depending on the sampler.

On a weight basis (Figure 3.17) the TIPS(2) collected 78% less total weight than the CPS(2) method. Of this weight, the TIPS(2) collected 43% less organic than the CPS(2) method. Within the mineral fraction, the TIPS(2) collected 58% less silt/clay size component and 133% more sand size component than the CPS(2) method. The CPS(2) method, averaged over the 34 observations, collected 53 g and the TIPS(2) sampler collected 36 g. The TIPS(2) sampler collected more sand size fractions and less of the finer sized silt/clay fractions. The TIPS(2) sampler also trapped less of the organic fractions. On an organic weight and silt/clay weight basis, CPS(2) appears to have a greater range of data values and be more sensitive than the TIPS(2) method.

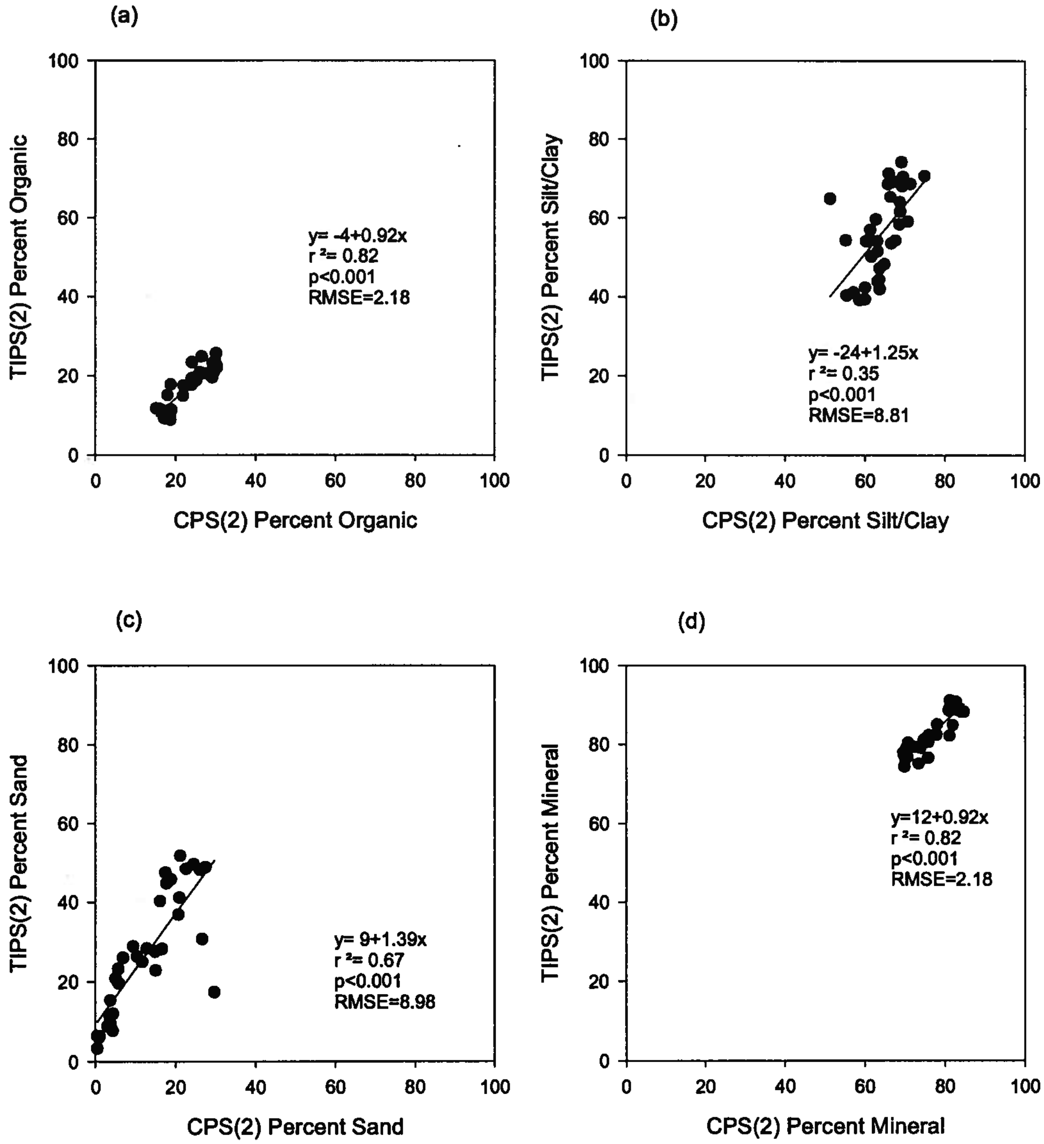


Figure 3.16. Regression of the time integrated passive sampler(2) (TIPS(2)) versus continuous pump sampler(2) (CPS(2)) for measuring the following flume sediment percent fractions: (a) organic, (b) silt/clay, (c) sand, and (d) mineral.

On the basis of sand weight the TIPS(2) sampler appears to have a greater range of data values and therefore to be the more sensitive method. The range of total weight data appears to be balanced between both samplers, indicating that they were equally sensitive to changes in total FSS weight in the flume.

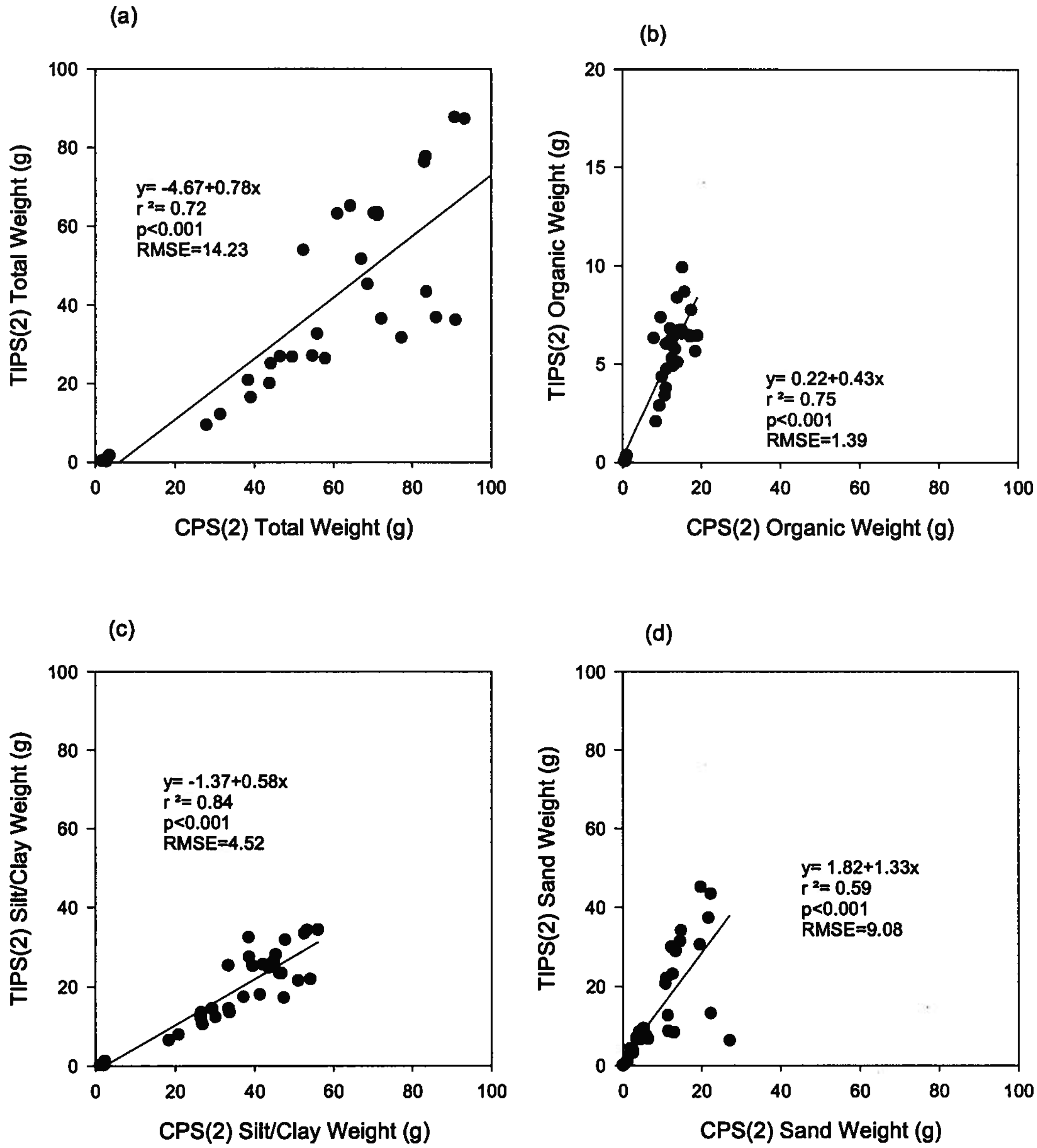


Figure 3.17. Regression of the time integrate passive sampler(2) (TIPS(2)) versus continuous pump sampler(2) (CPS(2)) for measuring the following flume sediment fraction weights: (a) total, (b) organic, (c) silt/clay, and (d) sand.

Within the 24-hour collection period, both samplers collected enough FSS to complete a particle size analysis. Both sampler blends of flume organic, sand and silt/clay overlapped, provided the percent sand component was less than 35% by weight (Figure 3.18). The arrangement of the data points is in a vertical line, which might be indicative of the stream textural class as it shifts through time. The textural class might be used to classify the stream based on this visual signature.

The comparison between the CPS(2) and TIPS(2) reveals that there was good agreement between samplers based on percent organic fractions and percent mineral fractions. The samplers were strongly correlated, and the differences between samples were consistent and linear over the full range of observations. Both samplers agreed on the blend of organic, sand and silt/clay within the flume, provided the percent sand component is less than 35% by weight.

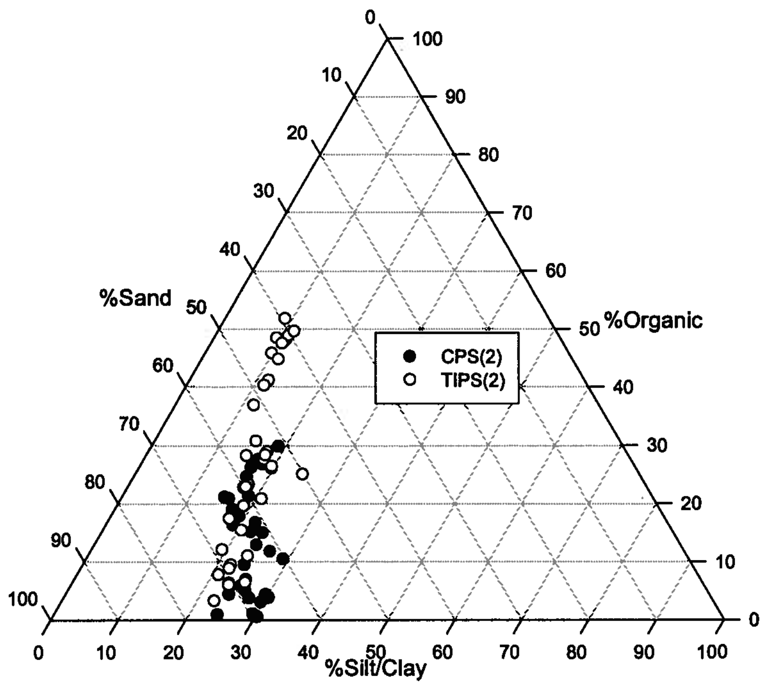


Figure 3.18. Percent organic, sand, and silt/clay fractions for continuous pump sampler(2) (CPS(2)) and time integrated pump sampler(2) (TIPS(2)).

3.3 Experiment 2: TIPS(2), CPS(2) and DPS Related to Flume Flow Rate

All correlations among TIPS(2), CPS(2), and DPS assessment of flume FSS and flume flow rate (Table 3.4) are highly significant ($p<0.001$); however, the degree of correlation to flume flow rate varied depending on the sampler and measured variable. The DPS sampler was less correlated with flume flow than that of the other two samplers. The DPS sampler r-values range from 0.46 to 0.75, and the CPS(2) sampler r-values range from 0.57 to 0.78. The TIPS(2) sampler correlations were stronger (r-values range from 0.78 to 0.89), and correlated reasonably well with the flume flow rate values over the 46 observations.

Table 3.4. Correlation coefficients of weight, concentration and load variables of continuous pump sampler (2) (CPS(2)), time integrated passive sampler(2) (TIPS(2)), discrete pump sampler (DPS) versus flume flow rate based on the Pearson's Correlation Method.

Sampler	Dependent Variable	Units	Flow Rate mean ($L s^{-1}$)	Flow Rate SD	Sampler mean	Sampler SD	n	R	p-value
DPS	total conc.	$mg L^{-1}$	128	57.6	13	6.2	46	0.70	<0.001
DPS	mineral conc.	$mg L^{-1}$	128	57.6	9	4.6	46	0.75	<0.001
DPS	organic conc.	$mg L^{-1}$	128	57.6	4	1.9	46	0.46	<0.001
DPS	organic %	%	128	57.6	35	9.3	46	-0.67	<0.001
DPS	mineral %	%	128	57.6	65	9.3	46	0.67	<0.001
TIPS(2)	total wt.	g	128	57.6	38	26.4	46	0.85	<0.001
TIPS(2)	mineral wt.	g	128	57.6	33	24.1	46	0.85	<0.001
TIPS(2)	sand wt.	g	128	57.6	14	14.2	46	0.82	<0.001
TIPS(2)	silt/clay wt.	g	128	57.6	19	10.8	46	0.82	<0.001
TIPS(2)	organic wt.	g	128	57.6	5	2.6	46	0.78	<0.001
TIPS(2)	organic %	%	128	57.6	16	5.0	46	-0.83	<0.001
TIPS(2)	mineral %	%	128	57.6	84	5.0	46	0.83	<0.001
TIPS(2)	sand %	%	128	57.6	28	15.0	46	0.89	<0.001
TIPS(2)	silt/clay %	%	128	57.6	55	10.3	46	-0.87	<0.001
CPS(2)	total wt.	g	117	62.0	53	29.1	34	0.77	<0.001
CPS(2)	mineral wt.	g	117	62.0	42	24.0	34	0.78	<0.001
CPS(2)	sand wt.	g	117	62.0	9	8.0	34	0.70	<0.001
CPS(2)	silt/clay wt.	g	117	62.0	33	17.3	34	0.76	<0.001
CPS(2)	organic wt.	g	117	62.0	11	5.5	34	0.62	<0.001
CPS(2)	total conc.	$mg L^{-1}$	117	62.0	12	6.2	34	0.75	<0.001
CPS(2)	mineral conc.	$mg L^{-1}$	117	62.0	10	5.2	34	0.77	<0.001
CPS(2)	sand conc.	$mg L^{-1}$	117	62.0	2	1.8	34	0.70	<0.001
CPS(2)	silt/clay conc.	$mg L^{-1}$	117	62.0	8	3.7	34	0.75	<0.001
CPS(2)	organic conc.	$mg L^{-1}$	117	62.0	3	1.2	34	0.59	<0.001
CPS(2)	organic %	%	117	62.0	23	5.0	34	-0.77	<0.001
CPS(2)	mineral %	%	117	62.0	77	5.0	34	0.77	<0.001
CPS(2)	sand %	%	117	62.0	13	9.1	34	0.75	<0.001
CPS(2)	silt/clay %	%	117	62.0	64	5.1	34	-0.57	<0.001

Note: Standard deviation (SD). Number of observations (n). Coefficient of correlation (r).

The percent organic fraction was negatively correlated to flume flow rate according to all three samplers (Table 3.4); therefore, the greater the flume flow rate, the less organic sediment was collected as a proportion of the total sediment sample. The percent silt/clay fraction was also negatively correlated with flow rate according the TIPS(2) and CPS(2) samplers.

3.3.1 Time Integrated Passive Sampler(2) Related to Flume Flow Rate

The flume FSS weights collected by the TIPS(2) sampler did respond to the flume flow rate (Figure 3.19). All simple linear regression models and parameter estimates are highly significant ($p<0.001$). The coefficients of determination range from $r^2=0.82$ to 0.86, implying that the log-log transformed power function models were successfully linearized. Sand weight (Figure 3.19a) had the strongest positive relationship to flume flow rate ($b_1= 2.85$). Bias-corrected intercept estimates (b_0 *'*) for the TIPS(2) sampler imply that the sampler would collect 2 mg sediment (24 h) when the flume flow rate was 1 L s^{-1}, mostly silt/clay (3 mg) and organic fractions (1 mg), but virtually no sand fractions. This prediction implies that the flow rate at the intercept was not capable of suspending sand sediment in the flow. Of the total weight, the collected mineral fraction (Figure 3.19b) was more responsive to flume flow rate ($b_1= 2.07$) than was the collected organic fraction weight (Figure 3.19e) ($b_1=1.69$), probably by virtue of the mineral fractions overwhelming contribution to the total weight. Of the mineral fraction, the collected sand fraction weight (Figure 3.19c) was more responsive ($b_1= 2.85$) to flume flow rate than the collected silt/clay fraction weight (Figure 3.19d) ($b_1= 1.81$), probably by virtue of the sand fractions overwhelming contribution to the total weight.

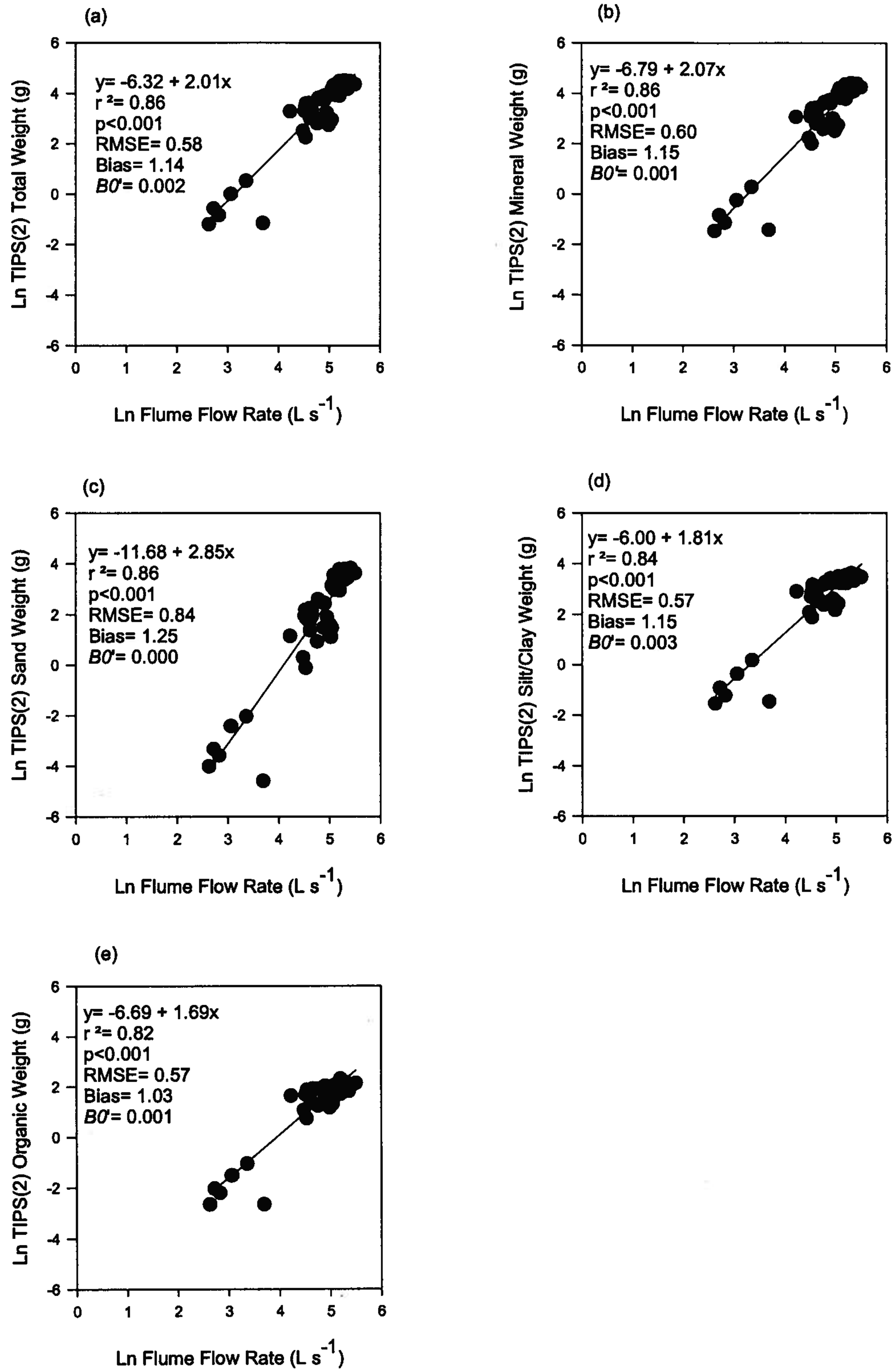


Figure 3.19. Regressions of log-natural time integrated passive sampler(2) (TIPS(2)) sampler weight variables versus log-natural flume flow rate for the following weight fractions: (a) total weight, (b) mineral weight, (c) sand weight, (d) silt/clay weight, and (e) organic weight. Bias-corrected exponentiated intercept (b_0').

The flume FSS percent fraction proportions collected by the TIPS(2) method did respond to flume flow rate (Figure 3.20). All simple linear regression models and parameter estimates are highly significant ($p<0.001$). The coefficients of determination range from $r^2=0.61$ to 0.76, and the slopes range from $b_1= -0.16$ to $+0.23$. The collected percent organic matter fraction (Figure 3.20a) decreased as flume flow rate increased ($b_1= -0.07$), while the collected percent mineral fraction (Figure 3.20b) increased ($b_1= 0.07$) as the flume flow rate increased.

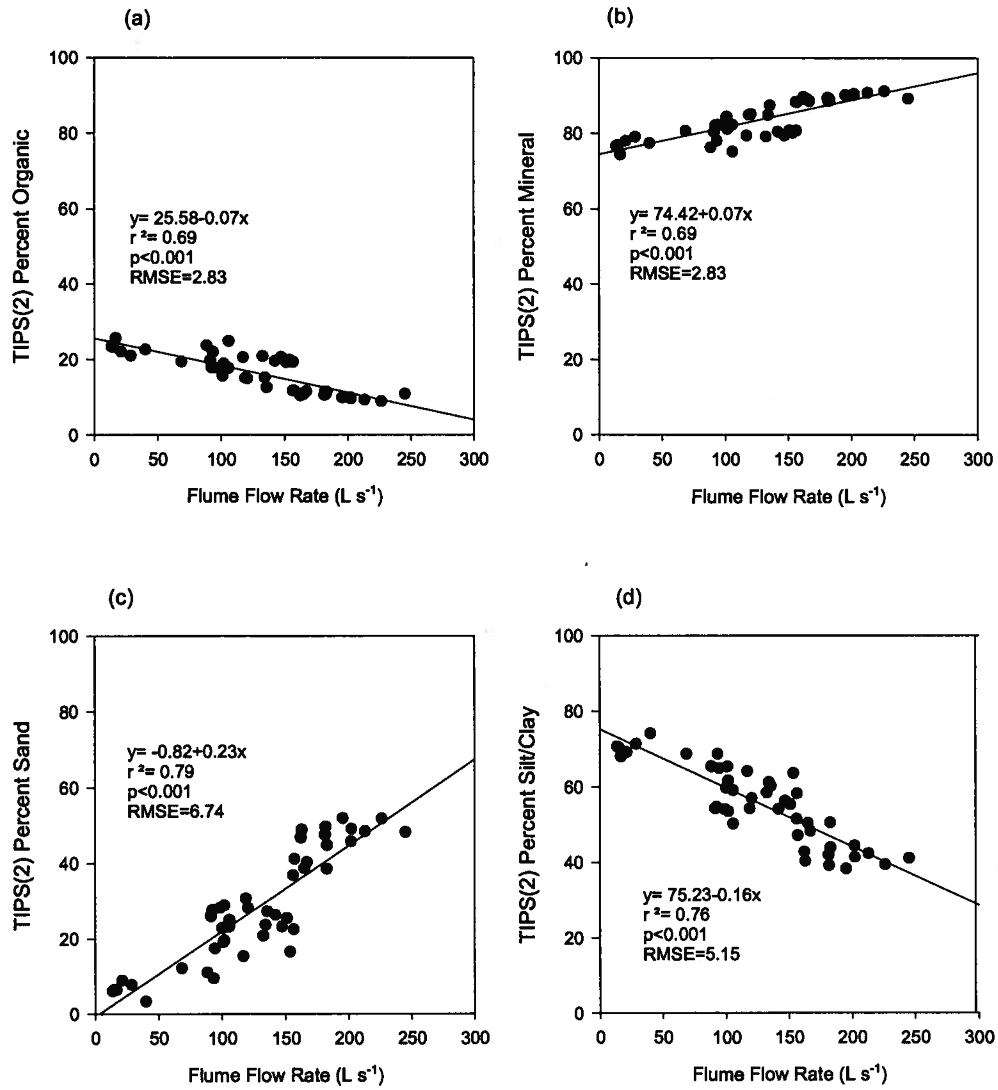


Figure 3.20. Regressions of time integrated passive sampler(2) (TIPS(2)) sampler percent variables versus flume flow rate for the following percent fractions: (a) organic percent, (b) mineral percent, (c) sand percent, and (d) silt/clay percent.

As a proportion of the mineral fraction, the percent sand fraction (Figure 3.20c) increased (b_1= 0.23) with increasing flume flow rate, while the percent silt/clay fraction (Figure 3.20d) decreased (b_1= -0.16) with increasing flume flow rate. The net effect was a lesser positive response (b_1= 0.07) of the collected percent mineral fraction to flume flow rate. The collected organic fraction and silt/clay fraction decreased with increasing flume flow rate, while the sand fraction increased with increasing flume flow rate. This implies that as the flume flow rate increased, the percent proportion of heavier particles collected by the TIPS(2) sampler increased at the expense of the lighter and smaller sized fractions.

3.3.2 Discrete Pump Sampler Related to Flume Flow Rate

The flume FSS concentration variables collected by the DPS did respond to the flume flow rate (Figure 3.21). All simple linear regression models and parameter estimates are highly significant ($p<0.001$). The coefficients of determination are moderate for total concentration ($r^2=0.68$) and mineral concentration ($r^2=0.71$), but weak for organic concentration ($r^2=0.51$), suggesting that the log-log transformed power function models were only partially successfully linearized. Bias-corrected intercept estimates for the DPS sampler imply that the sampler would record a 0.180 mg L^{-1} total sediment concentration when the flume flow rate was 1 L s^{-1}, mostly organic fractions (0.182 mg L^{-1}), and lesser amounts of mineral fractions (0.060 mg L^{-1}) . This result implies that the flow rate at the intercept was not capable of suspending heavier mineral sediments in the flow. The slopes are positive, ranging from b_1= 0.66 to 1.04. The total FSS concentration increased as the flume flow rate according to the slope b_1= 0.89 (Figure 3.21a). The collected organic concentration had a weaker response (b_1= 0.66) (Figure 3.21c) to flume flow rate than the collected mineral concentration (b_1= 1.04) (Figure 3.21b).

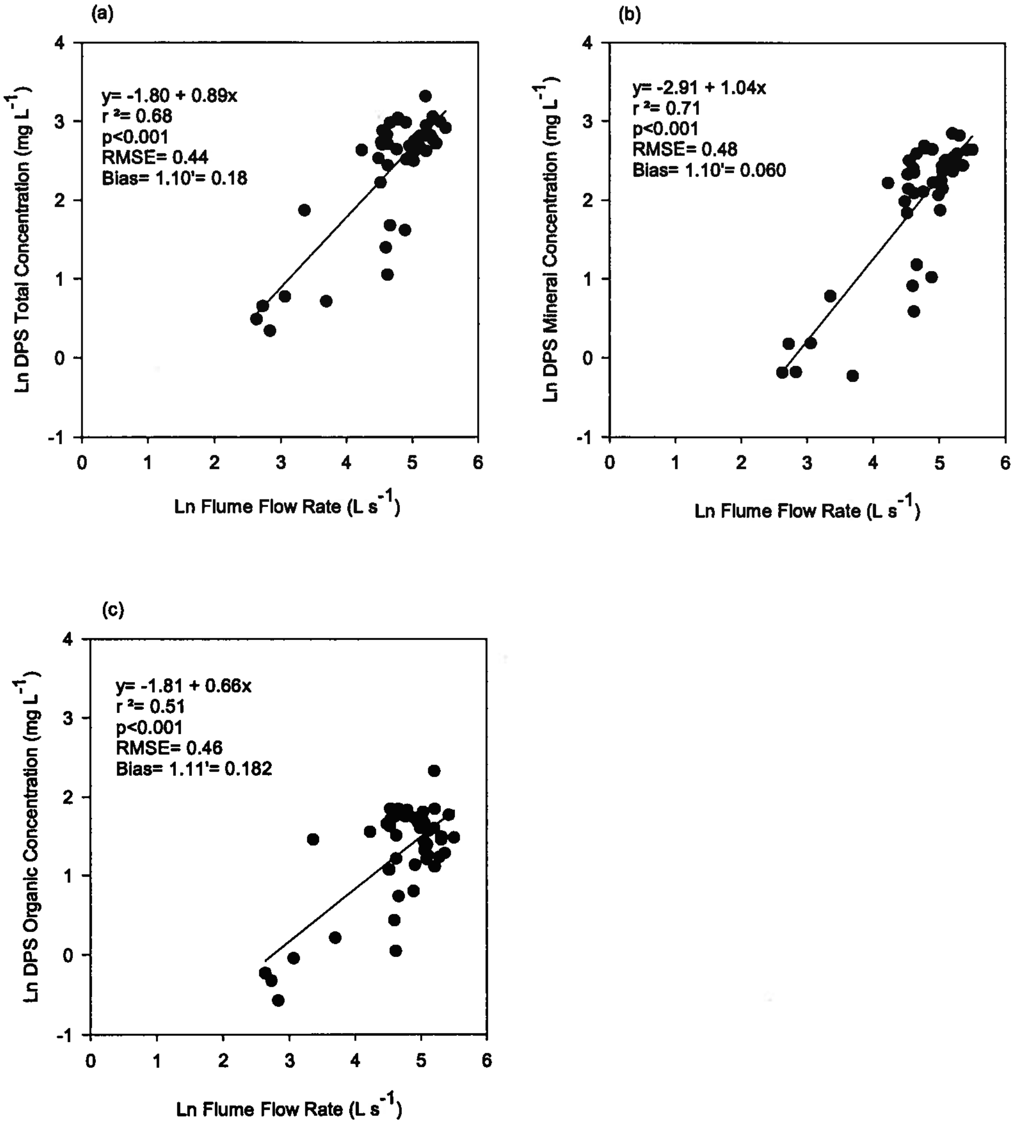


Figure 3.21. Regressions of log-natural discrete pump sampler (DPS) concentration variables versus log-natural flume flow rate for the following concentration fractions: (a) total concentration, (b) mineral concentration, and (c) organic concentration. Bias-corrected exponentiated intercept (b_0').

The flume FSS percent fraction proportions collected by the DPS method did respond to the flume flow rate (Figure 3.22). All simple linear regression models and parameter estimates are highly significant (p<0.001); however, the coefficients of determination are weak (r^2=0.45). The slopes range from b_1= -0.11 to +0.11. The slope estimates are negative b_1= -0.11 (Figure 3.22b) for the smaller organic fractions and positive b_1= 0.11 (Figure 3.22a) for the larger mineral fraction. This implies that as the flume flow rate increased, the proportion of heavier mineral particles collected by the

DPS sampler increased at the expense of the lighter organic fractions, on a percent proportional basis.

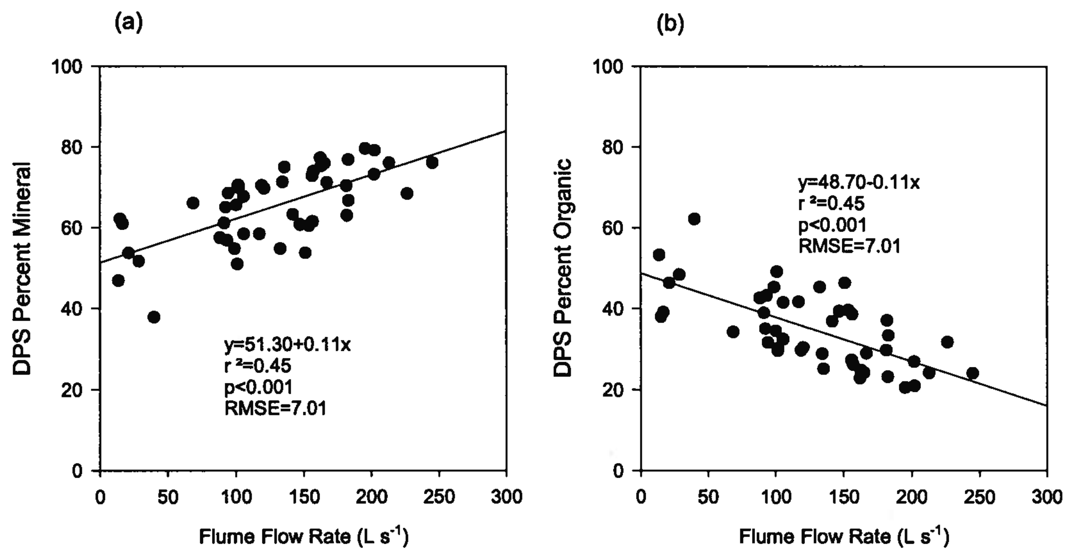


Figure 3.22. Regressions of discrete pump sampler (DPS) percent variables versus flume flow rate for the following percent fractions: (a) organic percent and (b) mineral percent.

3.3.3 Continuous Pump Sampler(2) Related to Flume Flow Rate

The flume FSS weight variables collected by the CPS(2) did respond to the flume flow rate (Figure 3.23). All simple linear regression models and parameter estimates are highly significant ($p<0.001$). The coefficients of determination range from $r^2=0.77$ to 0.83, implying that the log-log transformed power function models were successfully linearized. Bias-corrected intercept estimates (b_0 ') for the CPS(2) sampler suggest that the sampler would collect 54 mg sediment (24 h) when the flume flow rate was 1 L s^{-1}, mostly silt/clay (45 mg), organic matter (29 mg), and sand (39 mg).

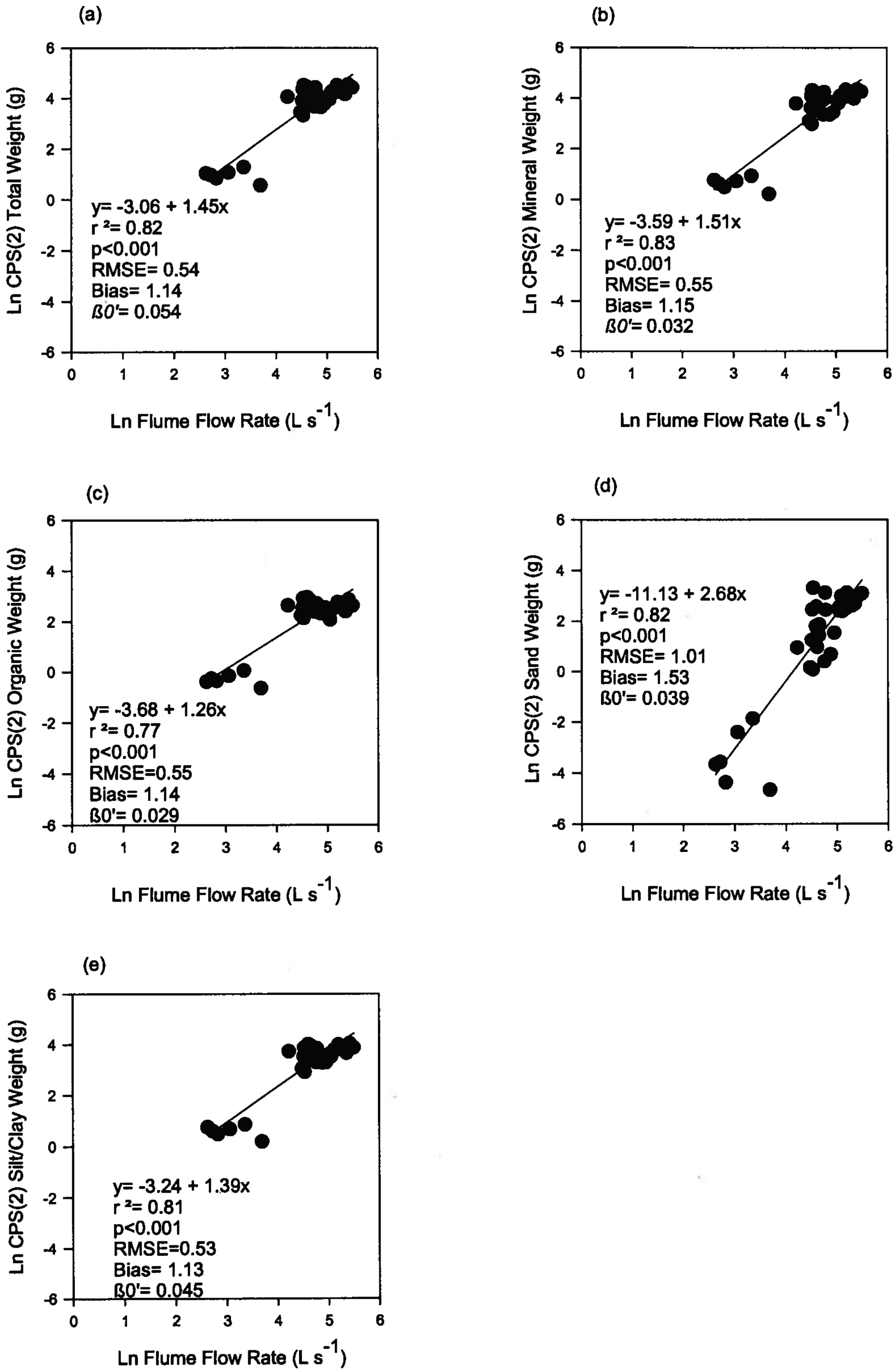


Figure 3.23. Regressions of log-natural continuous pump sampler(2) (CPS(2)) weight variables versus log-natural flume flow rate for the following weight fractions: (a) total weight, (b) mineral weight, (c) sand weight, (d) silt/clay weight, and (e) organic weight. Bias-corrected exponentiated intercept (b_0').

The slopes range from b_1= 1.26 to 2.68. Of the total weight, the collected mineral fraction (Figure 3.23b) was more responsive to flume flow rate (b_1= 1.51) than was the collected organic fraction weight (Figure 3.23e) (b_1= 1.26), probably by virtue of the mineral fractions overwhelming contribution to the total weight. Of the mineral fraction, the collected sand fraction weight (Figure 3.23c) was more responsive (b_1= 2.68), to flume flow rate than the collected silt/clay fraction weight (Figure 3.23d) (b_1= 1.39), probably because the sand fractions contributed the most to total weight.

The flume FSS concentration variables collected by the CPS(2) did respond to the flume flow rate (Figure 3.24). All simple linear regression models and parameter estimates are highly significant ($p<0.001$). The coefficients of determination range from r^2= 0.77 to 0.85, implying that the log-log transformed power function models were successfully linearized with relatively small scatter. Bias-corrected intercept estimates for the CPS(2) sampler imply that the sampler would record a 0.104 mg L^{-1} total sediment concentration when the flume flow rate was 1 L s^{-1}: mostly silt/clay fractions (0.071 mg L^{-1}), lesser amounts of organic fractions (0.057 mg L^{-1}), and no sand fractions. The slopes are positive ranging from b_1= 0.82 to 2.24. The total FSS concentration increased as the flume flow rate according to the slope b_1= 1.01 (Figure 3.24a). The collected organic concentration had a weaker response (b_1= 0.82) (Figure 3.24c) to flume flow rate than the collected mineral concentration (b_1= 1.07) (Figure 3.24b). Of the mineral fraction, the collected sand fraction concentration was more responsive slope (b_1= 2.24) (Figure 3.24c) to flume flow rate than the collected silt/clay fraction concentration (b_1= 0.95) (Figure 3.24d).

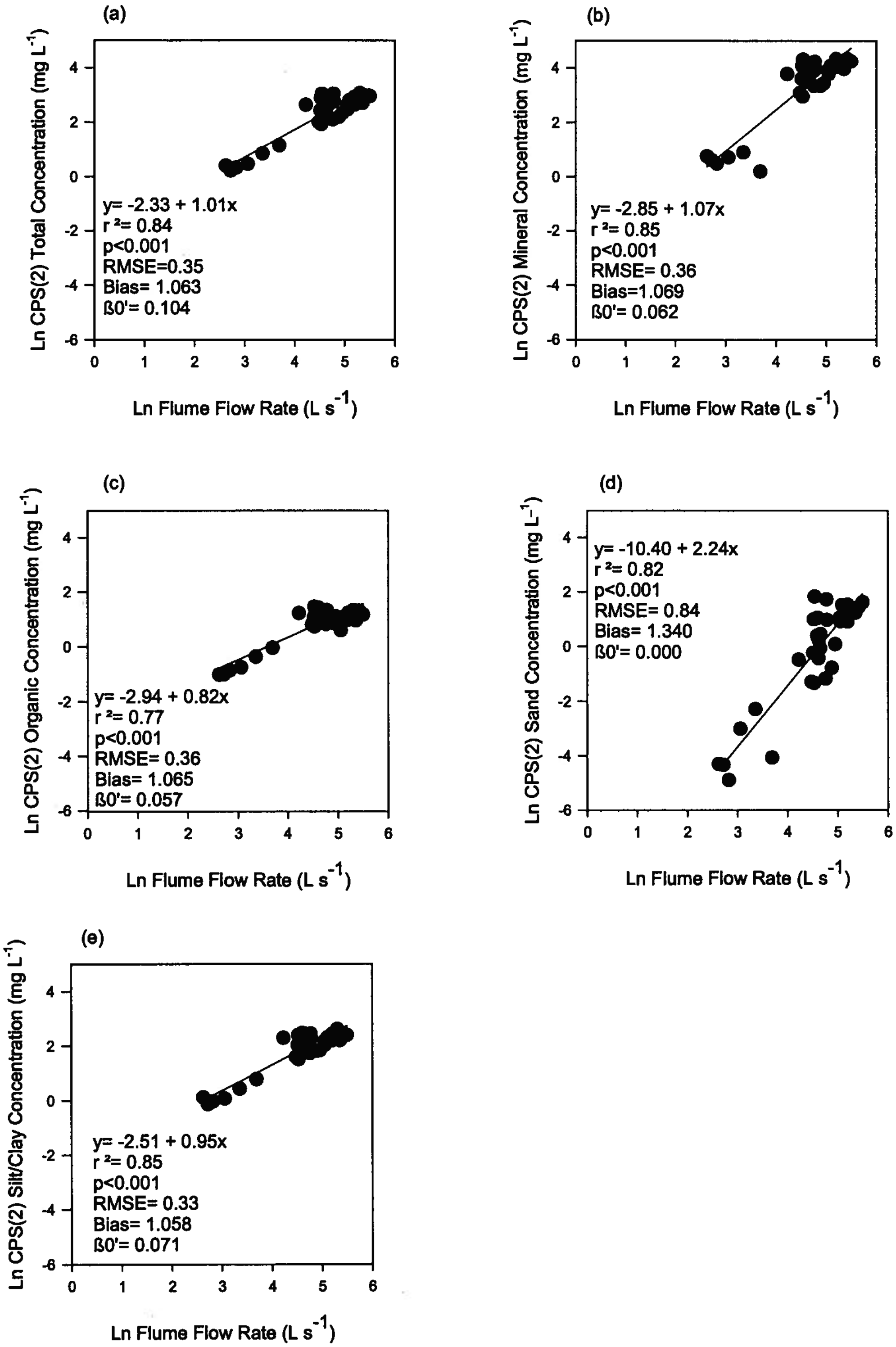


Figure 3.24. Regressions of log-natural continuous pump sampler(2) (CPS(2)) concentration variables versus log-natural flume flow rate for the following concentration fractions: (a) total concentration, (b) mineral concentration, (c) sand concentration, (d) silt/clay concentration, and (e) organic concentration. Bias-corrected exponentiated intercept (b_0').

The flume FSS percent fraction proportion variables collected by the CPS(2) method (Figure 3.25) did respond to flume flow rate. All simple linear regression models and parameter estimates are highly significant ($p<0.001$); however, the coefficients of determination are weak ($r^2=0.33$ to 0.59). The slopes range from $b_1= -0.05$ to 0.11. The slope estimates are negative for the organic and silt/clay fractions and positive for the

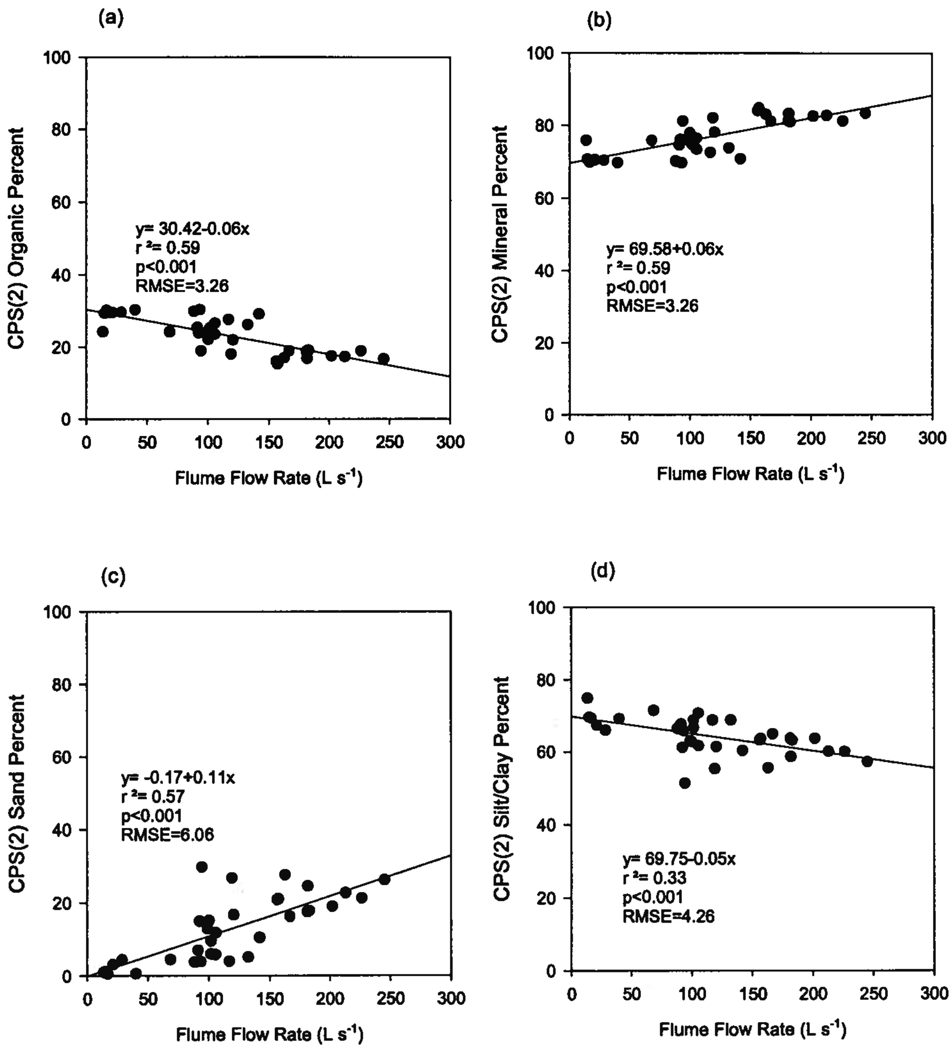


Figure 3.25. Regressions of continuous pump sampler(2) (CPS(2)) percent variables versus flume flow rate for the following percent fractions: (a) organic percent, (b) mineral percent, (c) sand percent, and (d) silt/clay percent.

sand fraction. The slope estimates imply that as the flume flow rate increased that the proportion of heavier and larger particles collected by the CPS(2) sampler increased at the expense of the lighter and smaller sized fractions.

3.3.4 Comparison among TIPS(2), CPS(2) and DPS Flume FSS Percent Organic Matter Related to Flume Flow Rate

Of the three samplers' assessment of FSS percent organic matter (Figure 3.26), the TIPS(2) sampler related most strongly to flume flow rate, and had the best fit (r^2=0.69). Although, the CPS(2) sampler had a lower coefficient of determination, it had closer intercept and slope estimates to the TIPS(2) sampler than to the DPS sampler.

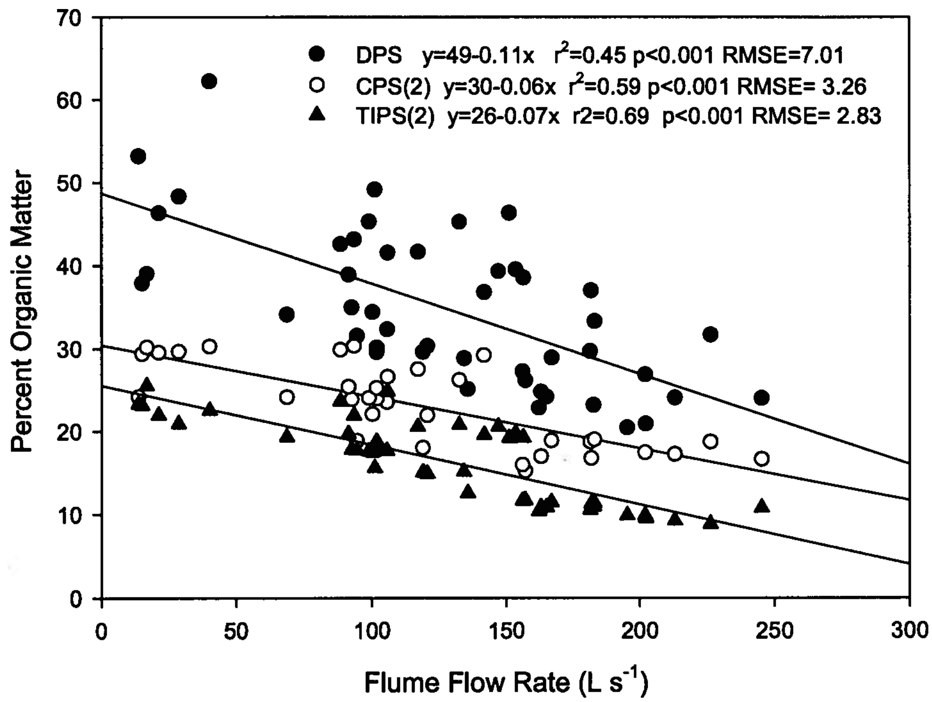


Figure 3.26. Regressions of time integrated passive sampler(2) (TIPS(2)), continuous pump sampler(2) (CPS(2)), and discrete pump sampler (DPS) measured flume percent organic matter versus flume flow rate.

The DPS sampler results are more dispersed, and were not as fit at assessing flume percent organic matter. The TIPS(2) and CPS(2) percent organic matter results were more flow proportional than the DPS results. Thus, for assessing flume percent organic matter, the TIPS(2) and CPS(2) samplers produced tighter regressions fits than the DPS sampler.

3.4 Experiment 3: Operating Characteristics of TIPS

3.4.1 Balance Between TIPS(1) and TIPS(2)

The objectives of this experiment were not all successfully achieved. The study gave some insight into the relation between the TIPS(1) inlet velocity and the flume velocity, and the E:R ratio in relation to flume velocity and flume FSS concentration. The experiment was less successful at regulating a variable speed peristaltic pump in relation to pressure differentials measured at the outlet of the TIPS(1). The use of pressure differential feedback through a variable frequency drive control of the pumping speed did prove to be operable, but lacked pumping capacity to be effectively assessed at all flume flow rates.

Of the 46 observations, 13 were selected to explore the FSS collection characteristics of the TIPS sampler. Figure 3.27 is a barchart view of the percent differences for total weight, organic weight, silt/clay weight, and sand weight respectively for all 46 observations. For the first 41 observations the pump was unable to match the control pressure difference between the TIPS(1) PT(1) and TIPS(2) PT(2), even though the pump was operating at 100% capacity. As the flume velocity eased during the course of the experiment the pump capacity was reduced (observation 56 to 61), on the basis of the control pressure difference ΔP between the TIPS(1) PT(1) and TIPS(2) PT(2), in an attempt to balance the two samplers. At times the percent difference in TIPS(1) and TIPS(2) FSS variables favoured opposite samplers, as can be observed by the negative differences.

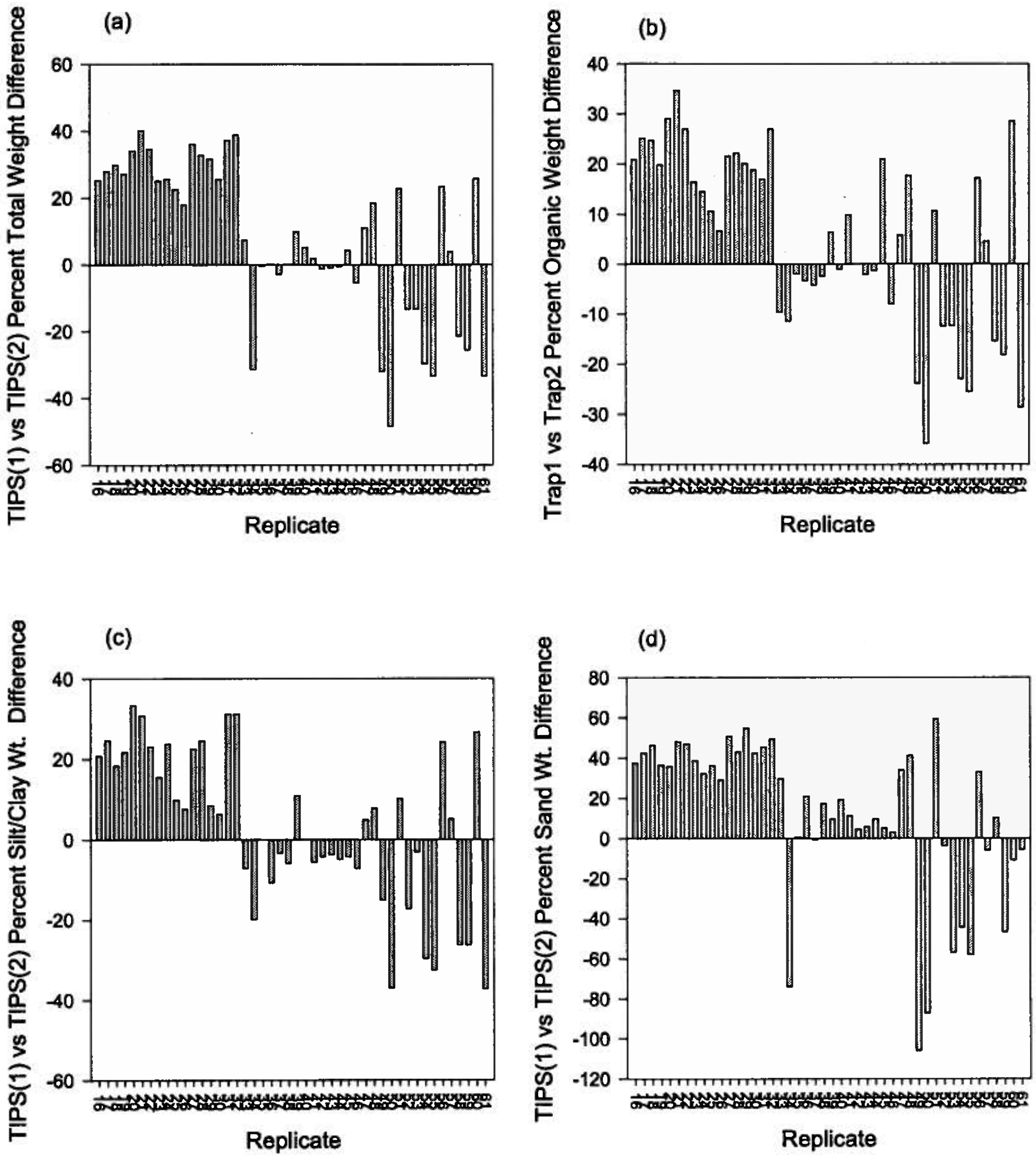


Figure 3.27. Time integrated passive sampler(1) (TIPS(1)) versus TIPS(2) percent weight differences for all observations for the following variables: a) total weight, b) organic weight, c) silt/clay weight, and d) sand weight.

Figure 3.28 is a barchart view of the percent differences for total weight, organic weight, silt/clay weight, and sand weight respectively for 13 selected observations. The 13 observations were chosen on the basis of an arbitrary maximum 10% total weight difference in collected sediment between TIPS(1) and TIPS(2), but the organic, silt/clay and sand fractions at times exceeded this guideline. The percent difference sand fraction exceeded the limit by the most, in some instances by as much as 20% in favour of

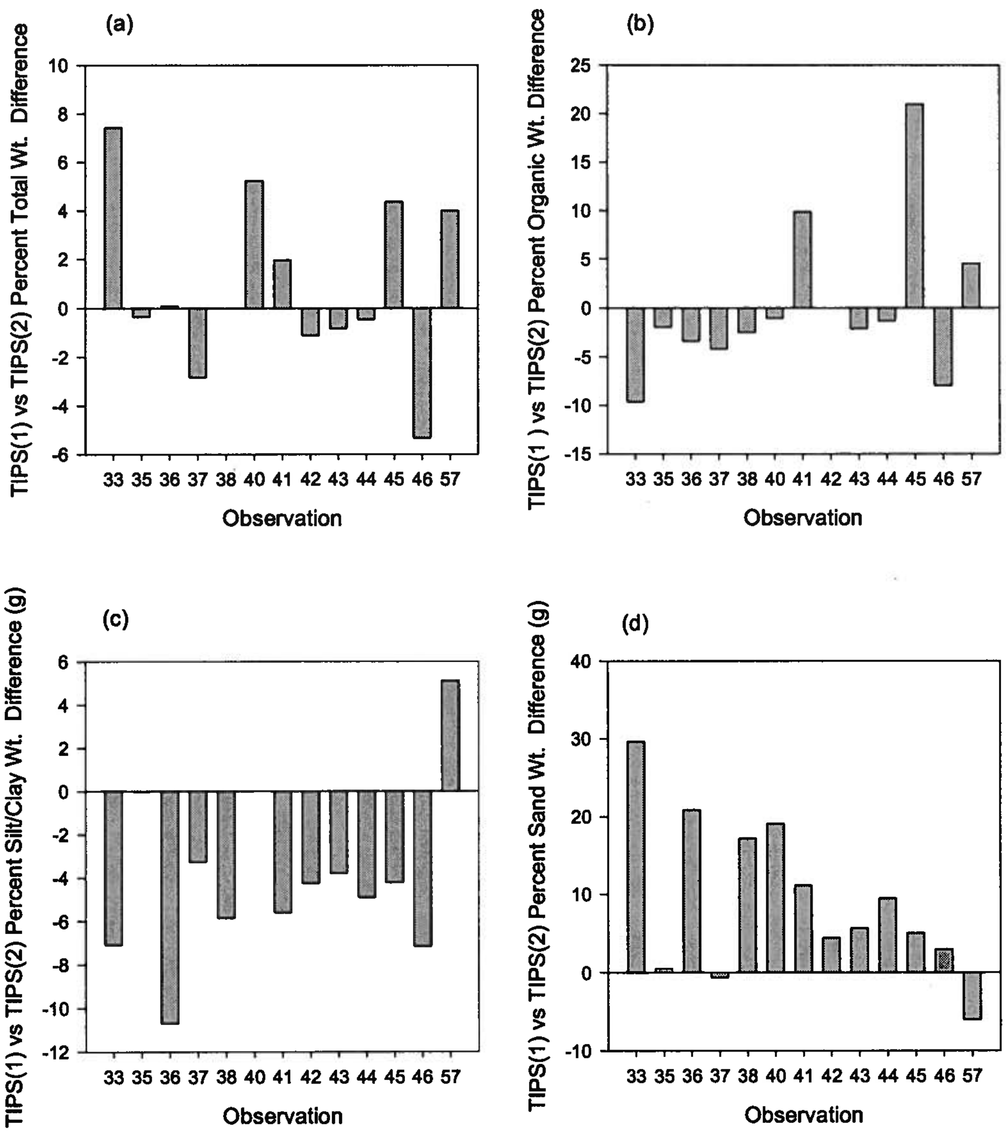


Figure 3.28. Time integrated passive sampler(1) TIPS(1) versus TIPS(2) for selected observations with a total percent weight difference <10% for the following variables: a) total weight, b)organic weight, c) silt/clay weight, and d) sand weight.

TIPS(2). These 13 observations were used to verify the agreement between the TIPS(1) and TIPS(2). The agreement confirmed that the TIPS(1) was pumped at the correct exit velocity to simulate the conditions of the TIPS(2) sampler.

A crosscheck of the data collection integrity was conducted by comparing the sediment weights collected by TIPS(1) to TIPS(2). The simple linear regression results (Figure 3.29) of the comparisons between collected weights of sediment for TIPS(1) and

TIPS(2) gave very favourable (almost unity) results for total sediment, silt/clay, and organic. Sand weight was less satisfactory, as TIPS(1) collected 82% less sand weight

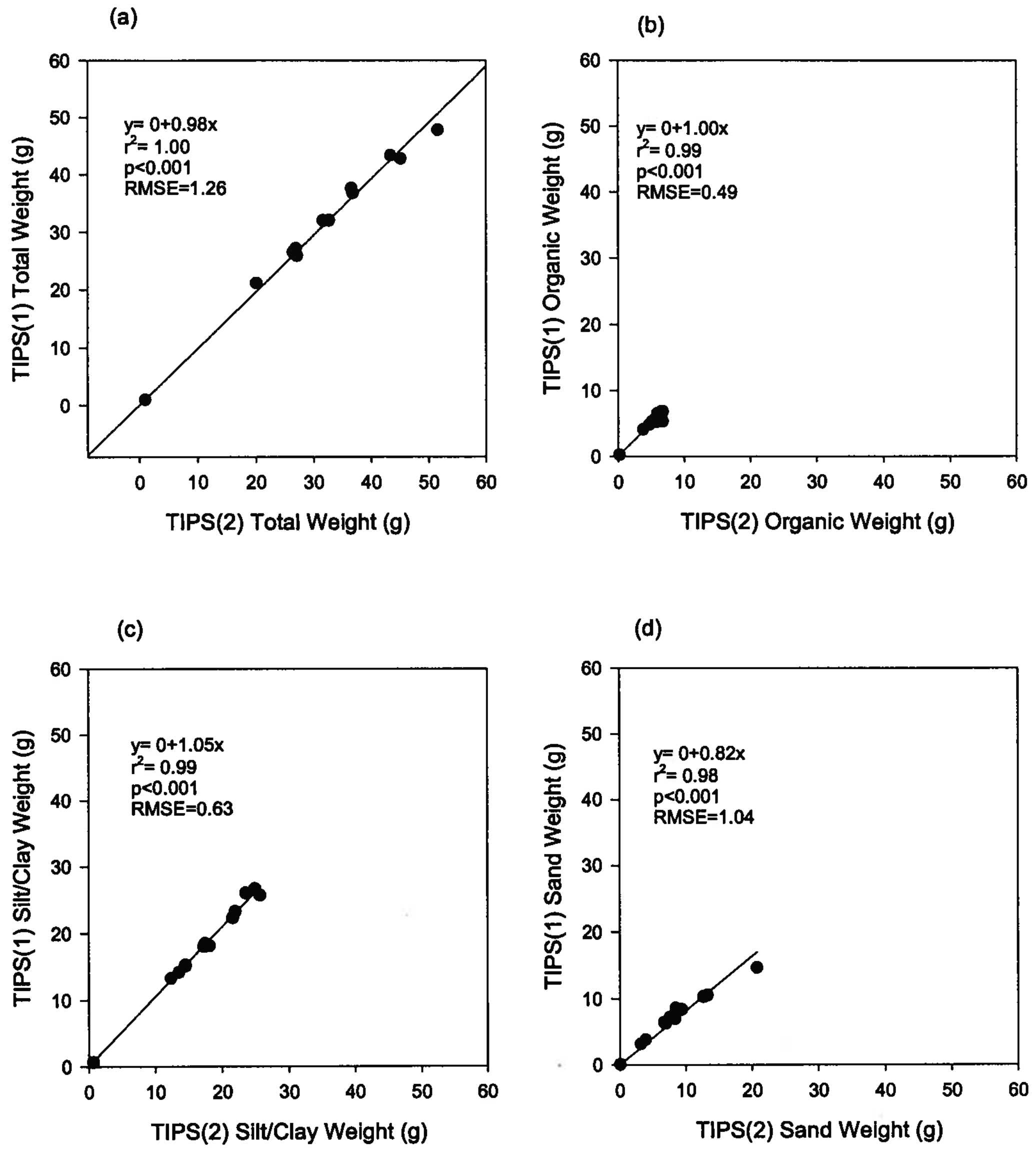


Figure 3.29. Time integrated passive sampler(1) (TIPS(1)) versus TIPS(2) simple linear regressions using least squares analysis for selected observations with a total percent weight difference <10% for the following variables: a) total weight, b) organic weight, c) silt/clay weight, and d) sand weight. Regression is forced though origin.

than TIPS(2). The regression results support the assumption that the TIPS(1) and TIPS(2) behaved equally during all 13 observations, and therefore, the parameter values were confident enough to characterize the expelled and retained properties of the TIPS method.

A further crosscheck was conducted by comparing the total sediment collected by CPS(2) against the sum of that collected in TIPS(1) and that collected in CPS(1) (Figure 3.30). Theoretically the amounts should be equal if both TIPS(1) and TIPS(2) behave the

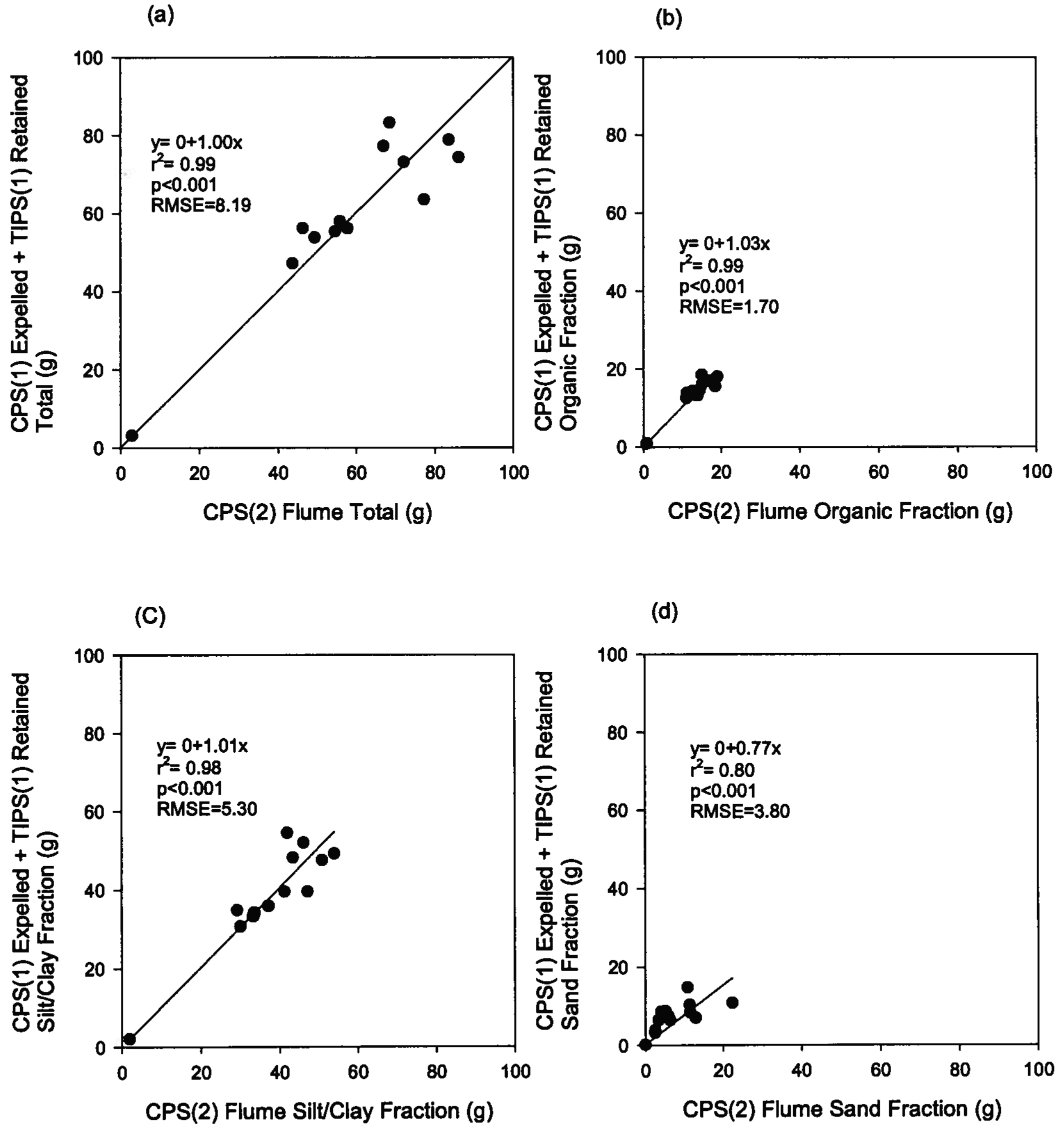


Figure 3.30. Continuous pump sampler(1) (CPS(1)) weight plus time integrated passive sampler(1) (TIPS(1)) versus CPS(2) weight. Simple linear regressions using least squares analysis for the following variables: a) total weight, b) organic weight, c) silt/clay weight, and d) sand weight. Regression is forced though origin.

same for each of the observations. The regressed results show that there was good agreement (b_1= 1.00 to 1.03) for the sediment total, silt/clay, and organic weight, but less (b_1= 0.77) for the sand fraction weight. The TIPS(2) collected 23% more sand than the sum of the TIPS(1) and CPS(1) samplers. Since the regression results between the

TIPS(1) and TIPS(2) samplers indicated that the TIPS(2) collected 18% more sand than the TIPS(1), then it is reasonable to conclude that the pumping apparatus reduced the sand collection capabilities of TIPS(1). The peristaltic pump pulsed according to the revolution of the rollers and the resulting surges might have cumulatively reduced the intake of the heavier sediment particles. The isokinetic properties of TIPS samplers are discussed in Phillips et al. (2000). Their concern was that a decrease in velocity in front of the opening would cause the sand fractions to settle before they could be captured. However, with the exception of the sand fraction, the CPS(1) apparatus configuration appeared to be satisfactory for the 13 observations to be used to explore the collection characteristics of the TIPS method.

3.4.2 Inlet Velocity

At ambient flume velocities of 180 mm s^{-1} and 400 mm s^{-1}, the CPS(1) measured TIPS(1) outlet flow rates of 1.32 L min^{-1} and 3.01 L min^{-1}, respectively (Table 3.5). The inlet and outlet have equal flow rates; therefore, using the inlet inside diameter (ID) of 25 mm and cross-section area of 491 mm^2, the outlet flow rate values translated into inlet velocities of 44.9 mm s^{-1} and 102.2 mm s^{-1}, respectively. The TIPS(1) inlet

Table 3.5. Comparison of Inlet velocity against ambient velocity for Phillip's sediment sampler and TIPS Prototype.

	Phillip's Sampler Inlet				TIPS Prototype Inlet			
Ambient Velocity (mm s^{-1})	ID (mm)	Area (mm^2)	Flow (L min^{-1})	Velocity (mm s^{-1})	ID (mm)	Area (mm^2)	Flow (L min^{-1})	Velocity (mm s^{-1})
180	4	12.6	0.02	26.4	25	491	1.32	44.9
400	4	12.6	0.11	138.3	25	491	3.01	102.2

velocities were less than the ambient flume velocities; therefore, the TIPS(1) inlet design was non-isokinetic. Phillips et al. (2000) investigated the isokinesity of their prototype TIPS and determined the sampler was non-isokinetic with an inlet inside diameter of 4 mm, body inside diameter of 98 mm and length of 1 m. The inlet velocity was less than the ambient stream velocity according to a log-log relationship. At ambient velocities of

180 mm s^{-1} and 400 mm s^{-1} the inlet velocities were 26.4 mm s^{-1} and 138.3 mm s^{-1} respectively. Furthermore, using the inlet cross-section area of 12.6 mm^2, the two previous inlet velocities translated into an inlet flow values of, 0.02 L min^{-1} and 1.65 L min^{-1}, respectively. Phillips et al. (2000) assumed that an inlet velocity, less than the ambient stream velocity, would result in greater proportions of sand sized particles becoming trapped by the sampler compared to the ambient FFS. This was confirmed in their research results.

3.4.3 Expelled:Retained Ratio

Upon regressing the expelled sediment versus the retained sediment, the results (Figure 3.31) demonstrate that the TIPS(1) split the total sample weight almost in half (0.91:1): 9% less sediment weight was expelled than retained. This is advantageous from a storage perspective. Although the experiment duration was 24 hours, an actual field application might be weeks long between retrieval and collection of trapped sediment. In heavy FSS loads the sampler could become overfilled. The silt/clay fraction weight E:R ratio behaved close to unity as well (0.91:1), whereby 9% less is expelled than retained. The organic fraction weight, however; was out of balance by a ratio of 1.61 g of organic material expelled for every gram retained.

Although the crosscheck analysis indicated that there is a problem with the use of the sand fraction data for the E:R ratio analysis, there is some insight to be gleaned from Figure 3.31(d). Ninety nine percent of the sand fraction was retained by the TIPS(1) and 1% was expelled and collected by CPS(1). The TIPS(1) was very efficient at retaining the sampled sand fraction.

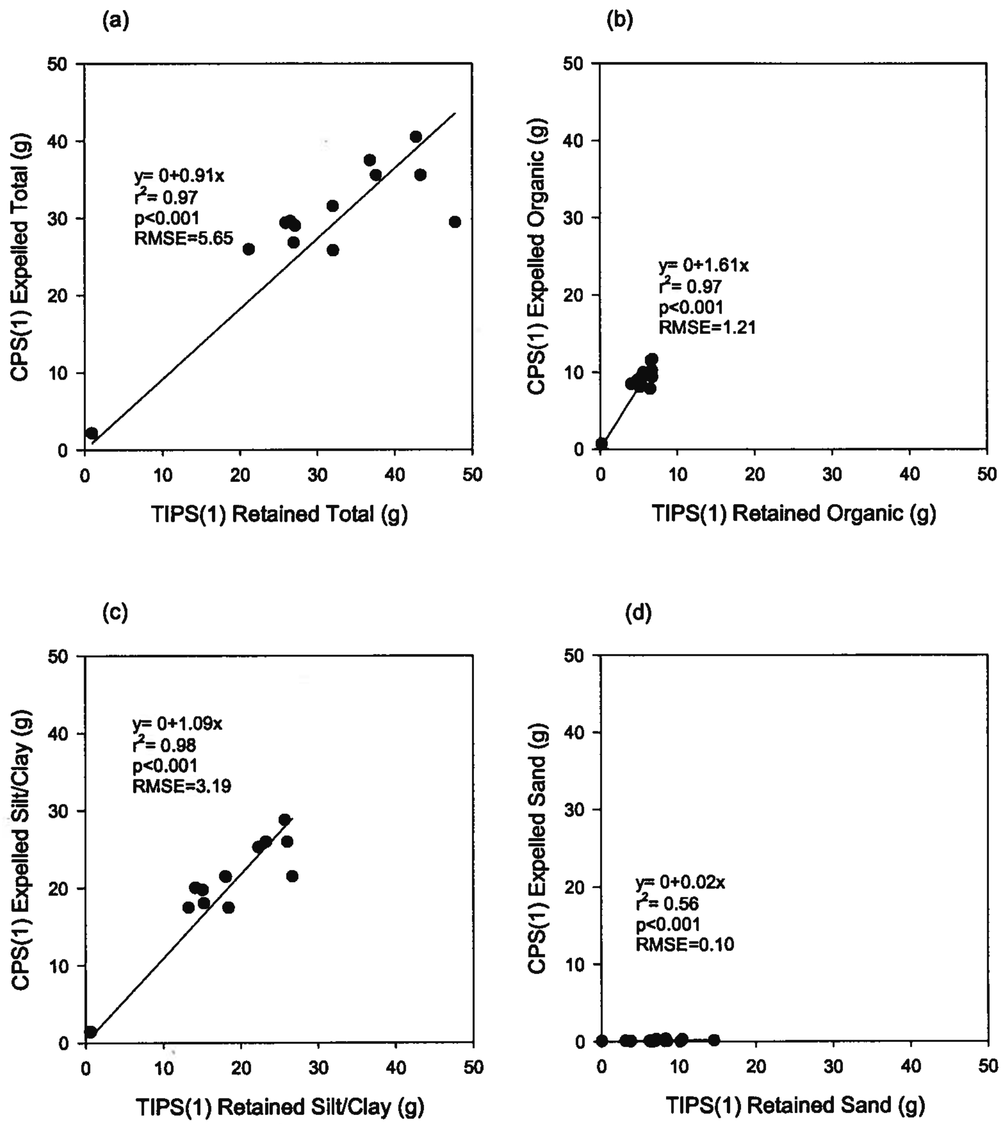


Figure 3.31. Continuous pump sampler(1) CPS(1) weight (expelled) versus time integrated passive sampler(1) (TIPS(1)) weight (retained). Simple linear regressions using least squares analysis for the following variables: a) total weight, b) organic weight, c) silt/clay weight, and d) sand weight. Regression is forced though origin.

A tenary view (Figure 3.32) of the TIPS(1) and CPS(1) collected sediment fractions illustrates the distinction between the retained and expelled portions. The retained portion varied with changes in percent sand fraction (10% to 30%) of the flume flow, whereas, the expelled portion was predominantly silt/clay fractions in a narrow range (25% to 35%). The percent organic was consistently within a narrow range for both portions (retained, 15% to 20%; expelled 25% to 35%).

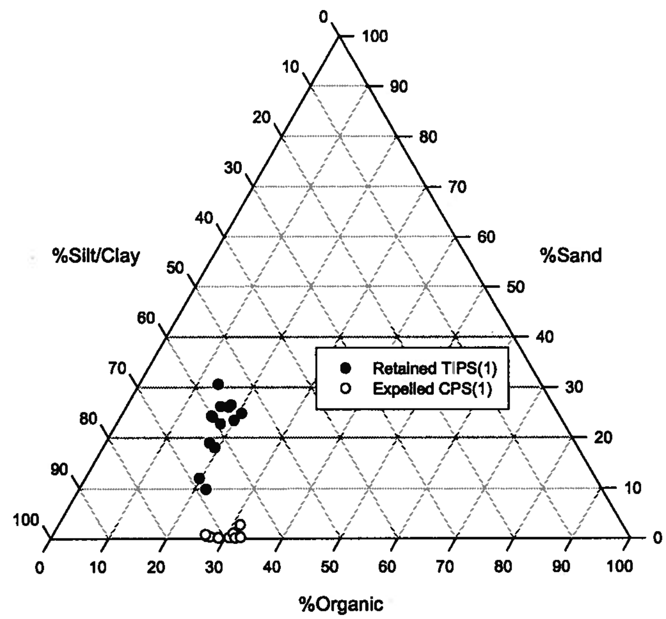


Figure 3.32. Continuous pump sampler (1) (CPS(1)) (expelled) related to time integrated passive sampler(1) (TIPS(1)) (retained) sediment fractions; percent organic versus percent sand, versus percent silt/clay.

A barchart view (Figure 3.33) of the expelled and retained proportions shows that the sand fractions were out of balance between the expelled and retained samples. On a percent weighted basis this biased the results and skewed the proportions in favour of the sand fraction and against the organic fraction, but not the silt/clay fraction, which remained representative of the total intake. Thus, there was a selective process within the TIPS which skewed the sediment proportions, and was not representative of the ambient flume FSS proportions.

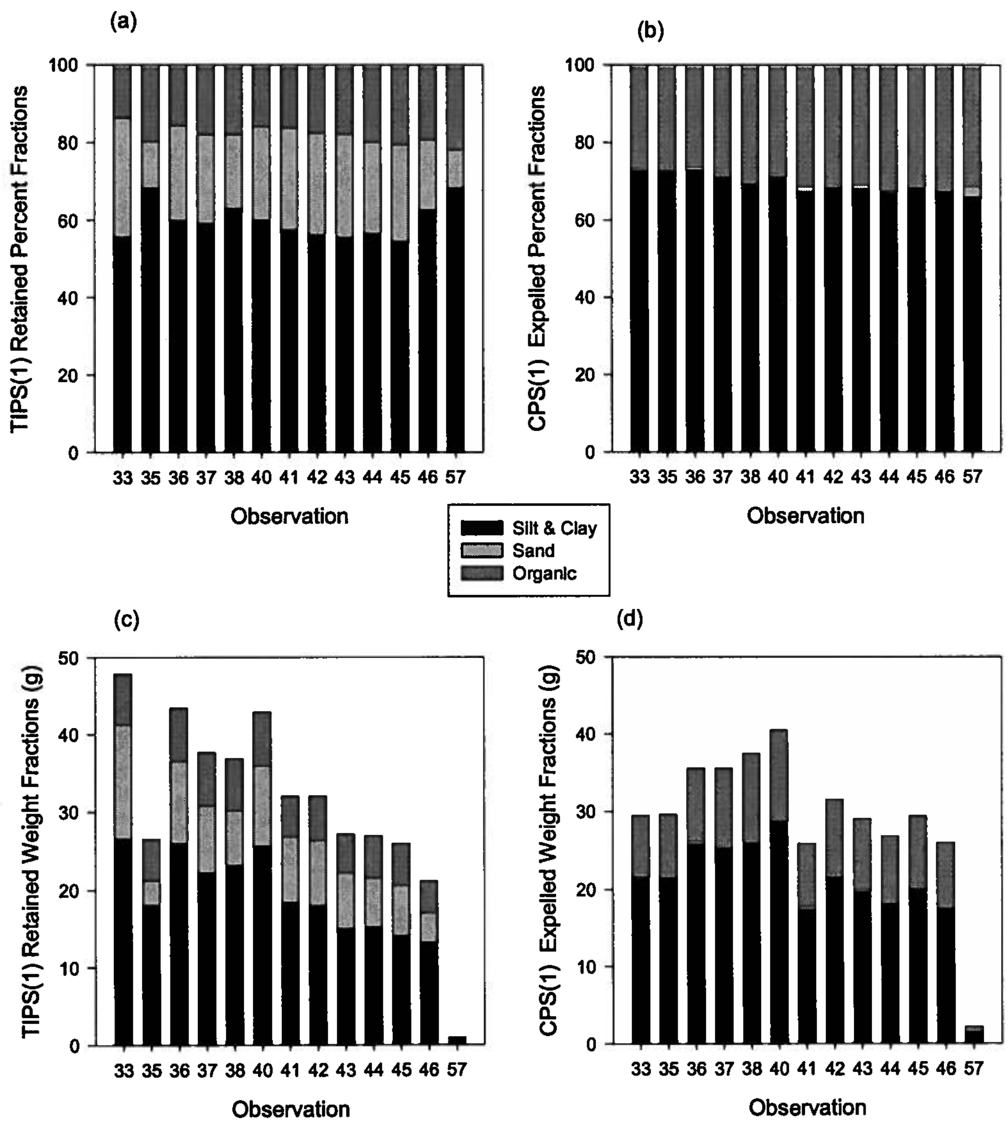


Figure 3.33. Expelled (continuous pump sampler(1), CPS(1)) and retained (time integrated passive sampler(1), TIPS(1)) proportions of silt/clay fraction, sand fraction, and organic fraction for selected observations with a total percent weight difference <10%. (a) percent retained sediment fractions collected in TIPS(1). (b) percent expelled sediment fractions collected in CPS(1). (c) weight of retained sediment fractions collected in TIPS(1). (d) weight of expelled sediment fractions collected in CPS(1). Stacked bars are summed to totals.

The E:R ratio for total weight and fractional weights varied with flume velocity (Figure 3.34). The linear models were all significant ($p<0.001$). The E:R ratio was

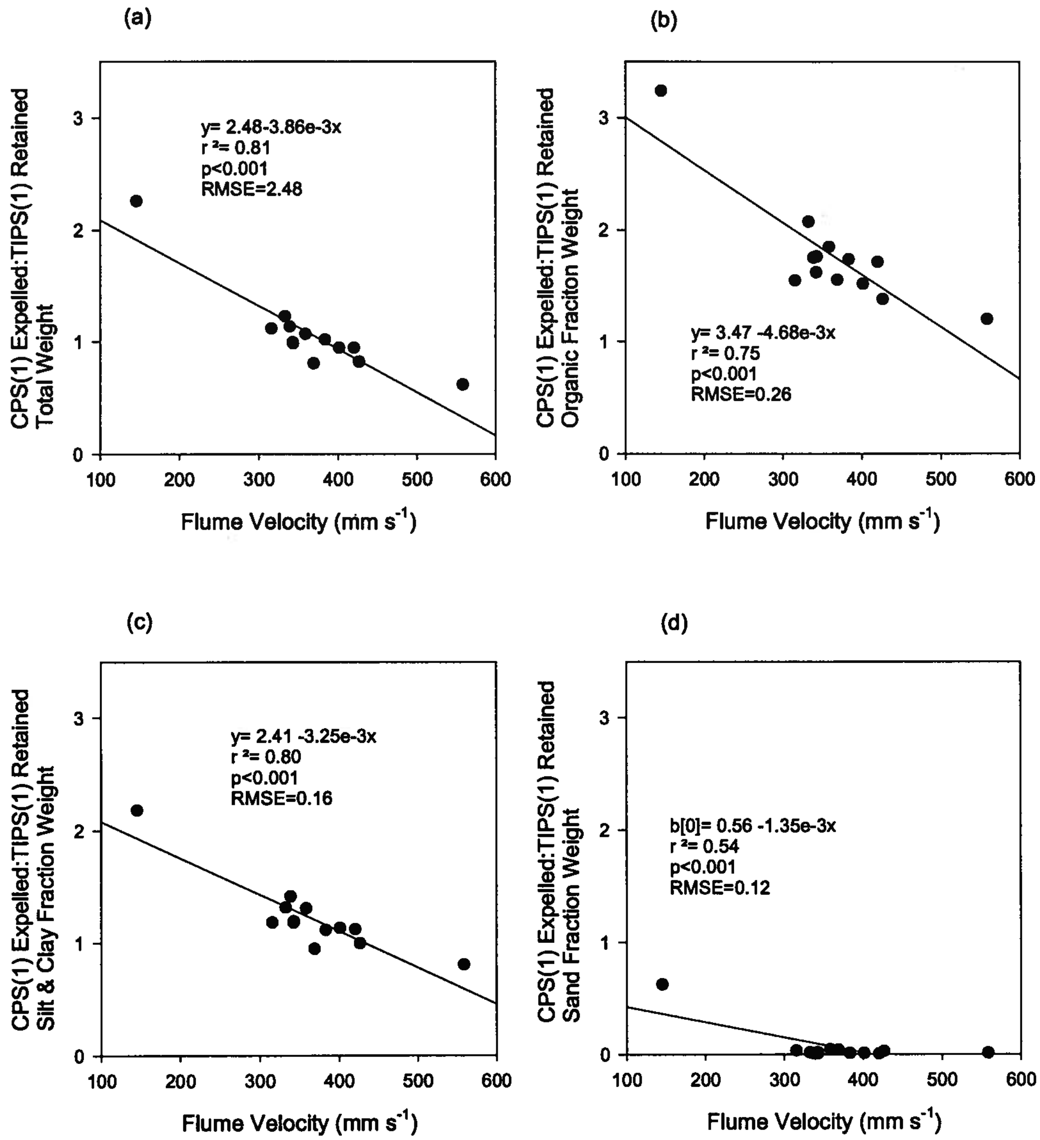


Figure 3.34. Ratio of expelled weight variables (continuous pump sampler(1), CPS(1)) to retained weight variables (time integrated passive sampler(1), TIPS(1)) versus flume velocity, for the following variables: a) total weight, b) organic weight, c) silt/clay weight, and d) sand weight. Regression is forced though origin.

related negatively to flume velocity for total and fraction weights, indicating that the retention capabilities of the TIPS(1) increased as the ambient flume velocity increased. This could have negative ramifications for the sampler design because it did not perform consistently over a range of stream velocity conditions. There was, however, a favourable flume velocity range (300 to 450 mm s^{-1}) in which the E:R ratio was approximately unity for total weight (Figure 3.34a) and silt/clay weight (Figure 3.34c).

In both cases, most of the observation E:R ratio data were within the unity range. This is a useful finding for stream conditions of similar velocities because the accumulation of total suspended sediment and silt/clay fraction was not biased by the TIPS design. The organic and sand E:R ratio data were never in the range of unity, and were greatly biased in favour of sand retention and organic expulsion.

The retention of organic fractions (Figure 3.34b) increased with flume velocity. This counter-intuitive result implies that, at lower velocities, a greater proportion of these fractions were expelled rather than retained. The organic fraction was expelled at a ratio of 3:1 at the lowest velocity observed (146 mm s^{-1}) and within the range of 1.5:1 to 2:1 for most of the observations over the stream velocity range 300 to 450 mm s^{-1}. These organic fractions may not have been flocculated with mineral components because they likely had low settling velocities, contrary to the findings of Droppo (2000). Organic fractions are comprised of low specific gravity carbon chain molecules that have a large surface area. At lower flume velocities, it appears that only the most floatable organic particles remain entrained. Thus, the proportion that was likely retained or trapped was lower because they floated through the body of the sampler and were expelled. At velocities less than 330 mm s^{-1} it might be advantageous to use a longer sampler body that has a greater transient time from inlet to outlet of the sampler.

The sand fraction E:R results (Figure 3.34d) clearly shows that the TIPS(1) was very efficient at retaining this size of sediments. The E:R ratio was consistent throughout the observed range of stream velocities and strongly favoured retention over expulsion of the sand sized fraction.

An examination of the E:R ratio measured over differing CPS(2) assessed flume percent fraction proportions (Figure 3.35) was performed to determine if the E:R ratio might be changeable due to particle size distribution changes. The simple linear models produced weak regression results of low significance. It appears that on a percent weight proportional basis (Figure 3.35a) the amount of organic matter expelled increased in relation to the amount retained by TIPS(1), while the proportions of the flume organic material increased. Thus, flume percent organic values over the narrow range of 18% to 20% influenced the retention of organic material in the TIPS(1) by increasing the E:R

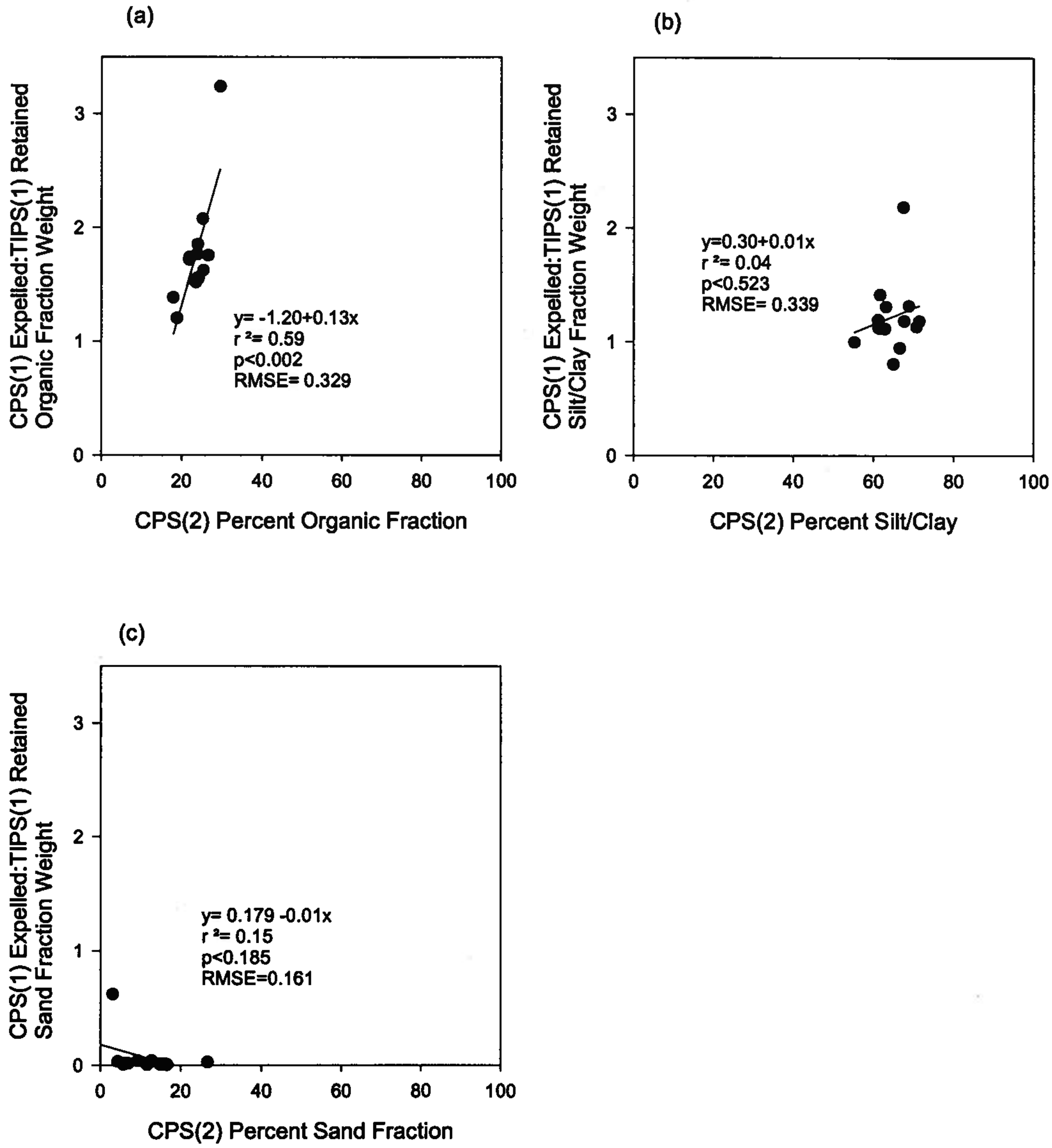


Figure 3.35. Ratio of expelled weight variables (continuous pump sampler(1), CPS(1)) to retained weight variables (time integrated passive sampler(1), TIPS(1)) versus CPS(2) measured flume sediment percent fractions, including: (a) organic weight ratio vs. organic percent, (b) silt/clay weight ratio vs. silt/clay percent, and (c) sand weight ratio vs. sand percent.

ratio from 1:1 to 3:1. This is in agreement with the influence of flume velocity because as flume velocity decreases the CPS(2) percent proportion of organic increases (established in Experiment 2). Thus, the impact of flume velocity and CPS(2) percent proportions of flume organic are positively correlated on the E:R organic fraction weight ratio.

The regression results for percent silt/clay and sand proportions reveals that these variables had little or no influence on the respective E:R ratio variables. Regardless of what these suspended sediment fraction proportions were in the flume, the E:R ratio remained stable at approximately unity for silt/clay and near zero for sand. When the CPS(2) measured flume concentrations of silt/clay were approximately 60% then the TIPS(1) expelled and retained silt/clay on a 1:1 basis.

3.5 Experiment 4: TIPS(2) Prediction of CPS(2) and DPS Measured Flume FSS Load

The DPS flume FSS total load values predicted from the TIPS(2) total weight values (Figure 3.36a) appear to be quite certain. The linear relationship is very significant and fits the data well ($p<0.001$, $r^2=0.80$). The same observation applies to the of DPS FSS mineral load values predicted from the TIPS(2) mineral weight values ($p<0.001$, $r^2=0.86$) (Figure 3.36b). The prediction of DPS flume organic load from TIPS(2) organic weights is less confident ($p<0.001$, $r^2=0.50$) (Figure 3.36c). On a scale of 0 to 5000 mg s^{-1}, all the y-intercept load estimates are close to zero. In similar circumstances the TIPS(2) weight values could be used to predict load values when it is calibrated to the DPS measured flume FSS loads.

The CPS(2) flume FSS total load values predicted from the TIPS(2) total weight values (Figure 3.37a) appear to be quite certain. The linear relationship is very significant and fits the data well ($p<0.001$, $r^2=0.90$). The same observation applies to the following predictions: CPS(2) flume FSS mineral load values predicted from the TIPS(2) mineral weight values ($p<0.001$, $r^2=0.90$) (Figure 3.37b), the CPS(2) flume FSS organic load values predicted from the TIPS(2) organic weight values ($p<0.001$, $r^2=0.76$) (Figure 3.37c), the CPS(2) flume FSS sand load values predicted from the TIPS(2) sand weight values ($p<0.001$, $r^2=0.82$) (Figure 3.37d), and the CPS(2) flume FSS silt/clay load values predicted from the TIPS(2) silt/clay weight values ($p<0.001$, $r^2=0.84$) (Figure 3.37e). On a scale of 0 to 5000 mg s^{-1} the y-intercept load estimates are close to zero. In similar circumstances the TIPS(2) weight values could be used to predict FSS load values when it is calibrated to the CPS(2) measured flume FSS loads.

A comparison between the TIPS(2) weight variable predictions of DPS and CPS(2) load variables shows that the intercepts are different but the mineral and total load slopes are similar while the organic load slope predictions are quite different.

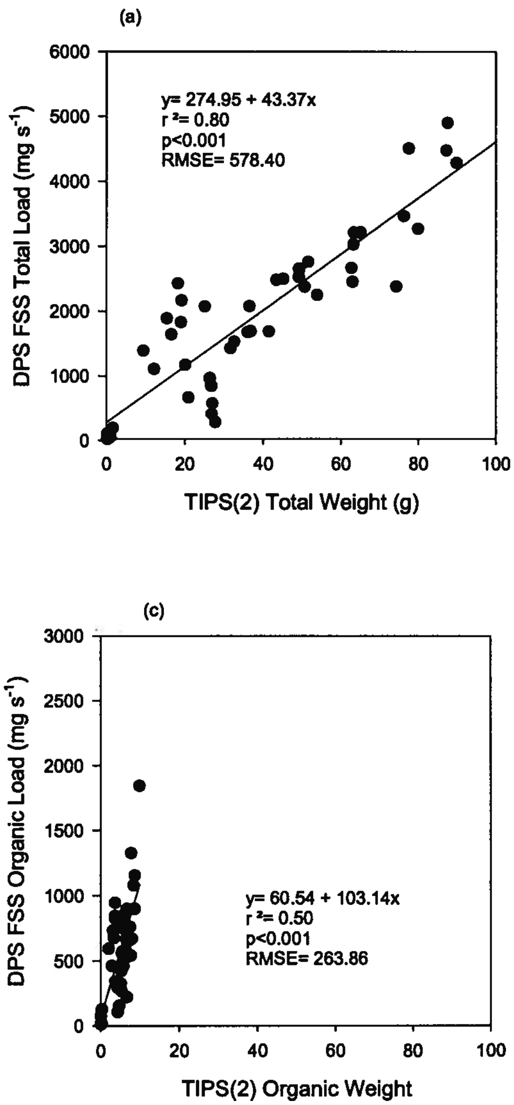


Figure 3.36. Regression predictions of discrete pump sampler (DPS) FSS load variables from TIPS(2) weight variables flume flow rate for the following fractions: (a) total, (b) mineral, and (c) organic.

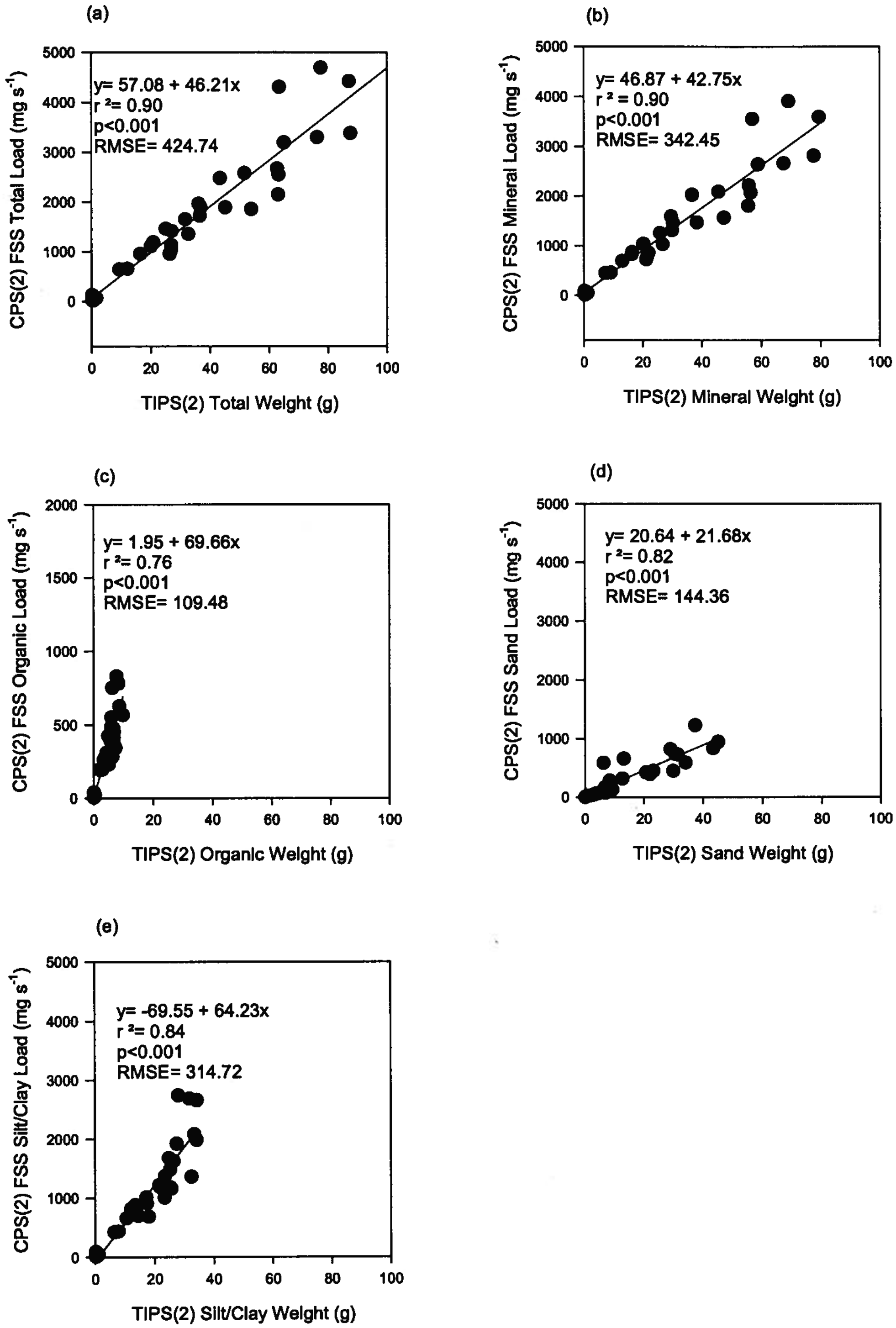


Figure 3.37. Regression predictions of continuous pump sampler(2) (CPS(2)) FSS load variables from TIPS(2) weight variables flume flow rate for the following fractions: (a) total, (b) mineral, (c) organic, (d) sand, and (e) silt/clay.

CHAPTER 4
DISCUSSION

4.1 Experiment 1: Cross Comparison of TIPS(2), CPS(2) and DPS

Fluvial suspended sediment concentration and particle size distribution in watercourses are estimated from water samples collected from points in time and space. Current fluvial suspended sediment research relies on automation to control the sampling frequency and to capture data that reflect the fluxes in FSS and water discharge. Automated pumping samplers are a preferred method of collecting water samples because the onboard computers can be programmed to sample according to random events, such as precipitation, temperature, and water discharge (Thomas and Lewis, 1995; Wren et al., 2000). Automated samplers are categorized as discrete point-in-time samplers because they are programmed to collect a specified sample of water from a point-in-time (instantaneous) and point in the cross-section of a stream. Confidence in the results of automatic pump sampling is increased by constraining the use to small watershed catchments with suspended sediment sizes less than <63 μm (Walling and Teed, 1971; Edwards and Glysson, 1999; U.S.A.C.E., 1989). If the automatic sampler is calibrated to samples collected from a depth integrated isokinetic sampler, then the research results are considered confidently accurate (Eads and Thomas, 1983; Richards and Moore, 2003; Walling and Teed, 1971). In spite of this confidence, some researchers (Edwards and Glysson, 1999; Graczyk et al., 2000; McDowell and Wilcock, 2004; Moody and Meade, 1994; Phillips et al., 2000; U.S.A.C.E., 1989; Walling and Woodward, 1993) have developed alternative samplers such as the flow proportional continuous flow centrifuge, single stage siphon sampler, water elutriation apparatus, and time integrated passive samplers. These new samplers were validated by cross correlation with other established FSS samplers, such as the depth integrated isokinetic sampler and the automatic pump sampler. The validation was more complete if particle size distribution and organic matter content were included with SSC results (Moody, and Meade, 1994; Phillips, et al., 2000; Walling and Woodward, 1993). Thus, the two prototype samplers in this experiment were evaluated by cross comparison with a discrete pump sampler. The results of this experiment were also used to validate the use of the CPS sampler in conjunction with the TIPS sampler to explore the operating characteristics of the TIPS sampler.

Correlation results from the cross comparison experiment between TIPS(2), CPS(2) and DPS showed that all three samplers were significantly positively correlated for similar FSS variables, particularly for the sediment mineral fractions. All samplers responded to changes in FSS associated with changing streamflow. The correlation results can be used to argue that the three samplers react similarly to the same combination of flume flow and FSS factors.

The CPS(2) and TIPS(2) measured similar blends of percent organic, percent sand, and percent silt/clay fractions, particularly if the TIPS(2) measured percent sand fraction was less than 35%. These blends could be used to characterize a stream suspended sediment textural class. The ternary diagram is used to categorize soils textural class and might also work for stream characterization. It appears that the blend drifts in a distinct linear pattern over time on a ternary diagram and could be considered a property of the stream textural signature.

The regression results were used to determine to what degree the three samplers agree on the reaction to flume flow and FSS factors. There was no agreement between the DPS measured percent organic and percent mineral fractions with the CPS(2) or the TIPS(2) results. The CPS(2) and DPS samplers measured mineral concentrations were in agreement. The TIPS(2) sampler appeared to be more sensitive in the assessment of the sand size fraction compared to the CPS(2) sampler. Compared to the CPS(2) sampler, the TIPS(2) sampler was very effective at collecting sand fractions.

The comparison among the three FSS samplers indicated that the CPS(2) and TIPS(2) samplers had advantages over the DPS sampler. The DPS sampler was limited to one fixed pumping speed. Conversely, the CPS(2) pump speed was fixed for the 24-hour period but was dynamically adjustable between observations, whereas the TIPS(2) sampler was fully dynamic and responded continuously to changing flume conditions. The TIPS(2) sampler had a greater sampling capacity and can be deployed for longer periods than the 24 hours used in this study. The CPS(2) and TIPS(2) samplers yielded enough sediment to conduct a more complete fractional sieve analysis of the mineral component (sand and silt/clay) than the DPS sampler. The TIPS(2) sampler and CPS(2) samplers were time integrated, flow proportional and reflected the composite changes in SSC over the sampling period. The TIPS(2) could not be used to calculate FSS concentration or load values, because there was no corresponding inlet volume data.

4.2 Experiment 2: TIPS(2), CPS(2) and DPS Related to Flume Flow Rate

There is an intrinsic relationship between flow velocity and fluvial suspended sediment concentration. The velocity and turbulence in a watercourse flow will suspend sediments according the balance between fluid shear forces and the settling velocities of the entrained particles. Furthermore, because flow rate (discharge) is the product of stream velocity and stream cross-section area, there is a relationship between SSC and stream discharge. At sediment gage sites, sediment discharge rating curves (sedi-graphs) are established by regressing SSC point data against continuous stream flow rate data.

Considering that SSC and stream flow rate are related, then it follows that the FSS collectors must be responsive to stream flow rate and velocity. Experiment 1 introduced two prototype sampling devices, a) continuous variable speed pump sampler and b) time integrated passive sampler, and cross compared them with a Sigma™ automatic discrete pump sampler in an instream flume. Experiment 1 concluded that the three sampling devices were correlated and related in the ability to collect and measure flume FSS concentration, particle size distribution, and organic matter. From this finding it is proposed that the all three samplers were related by a common response to flume flow rate. The objective of Experiment 2 was to individually relate each sampler (TIPS, CPS and DPS) to flume flow rate. The hypothesis was that it was possible to determine which sampler was most appropriate for assessing flume FSS properties based on this relationship.

According to correlation and regression results, of the three samplers it was demonstrated that the TIPS sampler was most responsive to flume flow rates. The CPS sampler had a strong relationship to flume flow rate, and the DPS sampler had the weakest relationship to flume flow rate. Walling and Teed (1971) were not able to define a confident relationship between DPS measured load and discharge. The TIPS(2) sampler responded dynamically to the changing flume aquatic environment because the flow rate at the inlet and outlet were dependent on the ambient flume flow rate (Experiment 3), and the measurements were flow proportional. The TIPS(2) sampler reacted dynamically to flume flow rate because it collected flume FSS as a function of the stream flow continuously. The DPS and CPS(2) samplers were not as flow dynamic and did not respond to continuous changes in the flume hydrodynamics and FSS discharge character. The CPS sampler was less reactive to flume flow rate because the pumping capacity was inadequate to adjust to the full range of flume flow rates. The CPS sampler had the same inlet design as the TIPS and sampled continuously. The DPS sampler was least reactive to flume flow rate because of sources of experimental error and variation from small sample weights collected intermittently, and an inlet design which is more appropriate for dissolved solids, not suspended solids. The DPS inlet is designed like a diffuser with several holes in the side of the inlet. This reduced and diffused the inlet velocity. Compared to the beveled backstop single hole inlets of the TIPS and CPS samplers the DPS inlet was probably inefficient. McDowell and Wilcock (2004) used the Phillips et al. (2000) TIPS sampler in their measurements of FSS phosphorus load from a small dairy intensive watershed in Southland, New Zealand. Their findings related the TIPS sampler collected total weight to cumulative flow, but had poor fit and significance (r^2= 0.5, $p<0.05$) compared to the TIPS(2) results in this discussion (r^2= 0.86, $p<0.001$).

The collected FSS weight results showed that the TIPS(2) sampler assessment of flume weight variables had a stronger linear relationship to flume flow rate than the CPS(2) method. The TIPS(2) sand weight and silt/clay weight linear relationships were stronger than the organic weight relationship. There were no DPS sampler weight variables to compare to flume flow rate. The TIPS(2) results supported the hypothesis that this sampler assessment of FSS weights was reactive to the stream flow values in a more dynamic way than the other two samplers.

The collected FSS concentration results showed that, compared to the DPS assessment of flume FSS concentration variables, the CPS(2) results were strongly related to flume flow rate. There was good agreement between samplers for the assessment of mineral concentration, and less for the assessment of total and organic flume FSS concentration when related to flume flow rate. The CPS(2) assessment of organic matter concentration relation to flume flow rate was stronger than the DPS assessment. There were no TIPS(2) flume concentration variables to compare.

The collected FSS percent fraction results showed that the regression slope estimates and correlation results for all three samplers agreed that the flume percent organic fraction was negatively related to the flume flow rate while the percent mineral fraction was positively related to the flume flow rate. Thus, the greater the flume flow rate, the less organic sediments were collected as a proportion of the total sediment sample. The CPS(2) and TIPS(2) samplers agreed that the flume percent silt/clay fraction were negatively related to the flume flow rate while the flume percent sand fraction was positively related to the flume flow rate. The DPS sample size was inadequate for the assessment of sand, silt and clay class sizes. According to the CPS(2) and TIPS(2) results, the greater the flume flow rate, the less silt/clay sediments and the more sand sediments were collected as a proportion of the total sediment sample. There was consistency and agreement between all three methods when comparing percent organic and mineral fraction slope estimates. Slope estimates for percent organic of all three methods were negative and within a close range of each other. Slope estimates for percent mineral contents were opposite positive values and in close agreement as well. This is consistent with the visual results in the barcharts in Chapter 3 that showed a progressive increase in percent organic and a decline in percent mineral as the sampling season progressed. The TIPS(2) and CPS(2) percent organic matter regression results were more flow proportional than the DPS results. Furthermore, the DPS sampler results were more dispersed, and not as fit at assessing flume percent organic matter as the TIPS(2) or CPS(2). This is a significant finding, because organic matter is the focus of many water quality assessments, and automatic pump samplers are an established methodology for measuring this water quality variable.

The log-log transformed TIPS(2) and CPS(2) versus flume flow rate power equation model fit well. The log-log transformation successfully linearized the power function to determine the estimated parameters of slope and intercept. The bias-corrected exponentiated intercept was useful in the interpretation of the results and concluded that the predicted lines ran close to the origin for all models. Thomas and Lewis (1995) recommended intensive frequent discrete pump sampling or stratified sampling to improve sedi-graph curve fitting results. In this experiment the power curve relationship derived from continuous passive or pumped sampling gave better results than the frequent discrete sampling of the automatic sampler.

It appears that the TIPS and CPS samplers successfully integrated the changing FSS measurements with changing flume flow rate. The results of this experiment also validated the use of the CPS sampler in conjunction with the TIPS sampler to explore the operating characteristics of the TIPS sampler in Experiment 3.

4.3 Experiment 3: Operating Characteristics of TIPS

The operating characteristics of the TIPS were complicated by the fluid flow dynamics and sedimentation processes outside and inside the sampler. If the inlet velocity (V_i) is equal to the ambient stream velocity (V_s) then the inlet is considered to be isokinetic (Federal Inter-Agency Sedimentation Project, 2001), and likely to admit a representative FSS sample. The sampler will undersample FSS concentration if $V_i > V_s$, and oversample if $V_i < V_s$. Since particle size is a function of flow velocity, then the collected particle size distribution is affected by the V_i: V_s ratio, particularly in the sand size (> 63 μm) fraction. Thus, a non-isokinetic inlet can affect the admitted FSS concentration and particle size distribution. Inlet velocities less than ambient velocities are biased against the admission of sand sized particles.

The ramifications of using an isokinetic inlet applies to discrete pump samplers and to time integrated passive samplers. Most automatic pump samplers have a fixed peristaltic pump speed and a non-isokinetic inlet design. Pumping speed at the inlet of a pump sampler must be sufficient to balance V_i and V_s, and also to lift the FSS particles up the collection tube to the sample bottles without selective sedimentation occurring during the transit. Time integrated passive samplers balance the admission properties of the inlet design with the retention capabilities of the sampler body to determine if a representative composite FSS sample is collected over the duration of deployment. The body retention time is dependent on ambient flow velocity, the inlet velocity, and the velocity through the cross-section area and length of the body. Thus, the passive time integrated collected FSS sample is dependent on the interaction between the selective properties of the inlet and the body. The ratio of expelled to retained (E:R) FSS is of interest because it determines if the proportions of retained sediment sizes are reflective of the ambient particle size distribution. The ratio also determines the amount of FSS retained and therefore, the holding capacity of the sampler and deployment time in the field.

The TIPS(1) inlet velocities were less than the ambient flume velocities of 180 mm s^{-1} and 400 mm s^{-1} by a factor of 3.6 and 3.9 respectively; therefore, the TIPS(1) inlet design was non-isokinetic. However, these factors might be greater considering that the calibration curve of Price AA™ vs Starflow™ (Figure 3.4) indicates that the Starflow underestimated the flume flow rate.

The Phillips et al. (2000) sampler was non-isokinetic by a factor of 6.8 and 2.9 for the respective flow velocities of 180 mm s^{-1} and 400 mm s^{-1}. The inlet inside diameter was greater (25 mm), the body inside diameter was greater (155 mm), and the body length was shorter (600 mm) than the TIPS prototype. Compared to the Phillips et al. (2000) sampler, the TIPS(1) had a greater flow rate per ambient flume flow rate and a closer and narrower range of inlet to ambient velocity ratios.

The construction of the TIPS(1) inlet was a vertical opening with a 45° backstop, on top of the front cap. This is quite different from the Phillips et al. (2000) sampler and other isokinetic inlets that consist of a thin diameter pipe pointing upstream from the middle of the sampler front. These designs are not appropriate for long term sampling because they can become fouled with debris. The vertical inlet design can be justified by the pattern of movement that sediments experience as they are transported. The dominant direction of movement is up and down according to Stokes Law. There is a horizontal path as well, but a relative view of sediment movement from a position within the flow reveals a vertical occellation, according to the direction of the shear velocities that occur in turbulence. Thus, a vertical inlet, while not conventional, is appropriate for the application of collecting FSS.

The TIPS(1) E:R ratio for total weight indicated that the sampler retained approximately 1 g for every 1 g expelled. This is advantageous for the storage capacity of the TIPS(1) over periods of time if the FSS load is heavy. The silt/clay fraction was collected approximately on a balanced 1:1 basis, but the organic and sand fractions were skewed 1.61:1 and 0.02:1 respectively. The TIPS(1) was very efficient at retaining sand and inefficient at retaining organic matter. Phillips et al. (2000) discovered that their

TIPS design retained 71% of dispersed inlet sediment, but they suggested that flocculated sediments would be retained at greater percentages than primary particles.

The TIPS(1) E:R ratio varied negatively when related to flume velocity for all weight variables. At greater flume velocities the proportion retained increased. At flume velocities between 300 mm s^{-1} and 400 mm s^{-1} the E:R ration was unity for total weight and silt/clay weight. It appears that this is the most favourable flume velocity conditions for operating the TIPS(1) for measuring FSS total weight and silt/clay. Phillips et al. (2000) also examined this ratio in relation to ambient velocity based on the known mean diameter of sediments that were injected into the inlet and expelled from the outlet. The authors concluded the following: (a) that if the ambient flow was slow (300 mm s^{-1}) and the particle size distribution was coarse, that the inlet and retained mean diameters were similar, and (b) that if the ambient flow was fast (600 mm s^{-1}) and the particle size distribution was fine, that the inlet and expelled mean diameters were similar. Thus, the TIPS E:R ratio was dependent on the settling velocities of the entrained particles and the physical properties of the sampler interacting with the ambient flow. This was in agreement with the TIPS(1) sampler findings.

The TIPS(1) E:R ratio did not vary when related to flume FSS concentrations measured by the CPS(2) method. The percent silt/clay E:R ratio remained stable at approximately around 1:1 when the CPS(2) measure flume percent silt/clay was around 60%, implying that the TIPS is most appropriate for use in streams with predominantly silt/clay particle sizes.

4.4 Experiment 4: TIPS(2) Prediction of CPS(2) and DPS Measured Flume FSS Load

The time integrated passive sampler is a continuous method of collecting FSS, which is flow proportional. During the deployment period, the TIPS integrates the variation of stream flow and FSS to collect a mean discharge weighted sample. The advantage of this strategy is that the composite sample is proportional to FSS load and eliminates the work of collecting individual suspended sediment concentration and stream flow data.

The results of Experiment 4 demonstrated that the TIPS can be used to predict FSS load. This was accomplished by calibrating the TIPS to the discrete or continuous data gathered by the DPS and CPS samplers. The regression model significance and fit demonstrated that the direct linear prediction of FSS load variables from the TIPS measured weight variables were very confident. This is an advantage in calculating FSS load because there is no need to use bias corrections from log-log data transformations. These results imply that the TIPS could be used in a remote stream to estimate FSS loads (silt, sand, clay, organic and other minerals) integrated over a sampling period. This is a convenient advantage if the sampling is conducted in circumstances where continuous pump sampling is not feasible.

CHAPTER 5

CONCLUSIONS

Overall, all four objectives of this study were achieved. The study demonstrated that the time integrated strategy of sampling FSS using either the TIPS or CPS is a viable alternative to the discrete point-in-time strategy using a DPS. The two prototype sediment samplers were successfully evaluated in the ability to collect a representative FSS sample in comparison to a commercial grade discrete pump sampler. This study successfully contributes to the existing variety of TIPS and CPS sampling tools.

5.1 Experiment 1: Cross Comparison of TIPS(2), CPS(2) and DPS

All three samplers were significantly cross correlated according to the response of each sampler to flume FSS flux, particularly for the sediment mineral fractions.
The blend of flume percent organic, percent sand, and percent silt/clay fractions was measured equally by CPS(2) and TIPS(2), particularly if the TIPS(2) measured percent sand was less than 35%. This blend can be used to characterize a stream suspended sediment textural class. There was no agreement between the DPS measured percent organic and percent mineral fractions with the CPS(2) or the TIPS(2) results. The CPS(2) and DPS samplers measured mineral concentrations were in agreement. The TIPS(2) sampler appears to be more sensitive in the assessment of the sand size fraction compared to the CPS(2) sampler. Compared to the CPS(2) sampler, the TIPS(2) sampler was very effective at collecting sand fractions.

The comparison between the three FSS samplers indicated that the CPS(2) and TIPS(2) samplers had advantages over the DPS sampler. The DPS sampler was limited to one fixed pumping speed, the CPS(2) pump speed was fixed for the 24-hour period but was dynamically adjustable between observations, whereas the TIPS(2) sampler was fully dynamic and responded continuously to changing flume conditions. The TIPS(2) sampler had a greater sampling capacity and was deployable for longer periods than 24 hours. The CPS(2) and TIPS(2) samplers yielded enough sediment to conduct a more complete fractional sieve analysis of the mineral component (sand and silt/clay) than the

DPS sampler. The TIPS(2) sampler and CPS(2) samplers were time integrated and reflected the average composite changes in SSC over the sampling period. The TIPS(2) could not be used to calculate FSS concentration or load values.

5.2 Experiment 2: TIPS(2), CPS(2) and DPS Related to Flume Flow Rate

The TIPS(2) results demonstrate that this sampler assessment of FSS was more flow proportional than the other two samplers. The TIPS(2) sampler assessment of flume FSS properties had the strongest correlation to flume flow rate, followed by the CPS sampler, and the DPS sampler. The TIPS(2) sampler assessment of flume weight variables had a strong log-log linearized relationship to flume flow rate when compared to the CPS(2) method. The TIP(2) sand weight and silt/clay weight relationships were stronger than the organic weight relationship.

On a concentration basis, compared to the DPS assessment of flume FSS concentration variables the CPS(2) results were comparable and quite similar, but weakly related to flume flow rate. On a percentage basis, all three samplers agreed that the flume percent organic fraction was negatively related to the flume flow rate while the percent mineral fraction was positively related to the flume flow rate. The TIPS(2) and CPS(2) sampler results implied that, as the flow rate increased, the proportion of silt/clay fraction in suspension decreased and the sand fraction increased.

Of the three samplers' assessment of FSS percent organic matter the TIPS(2) sampler related most strongly to flume flow rate. The DPS sampler results were dispersed, and not as fit at assessing flume percent organic matter. Thus, for assessing time integrated organic matter concentration, the TIPS(2) sampler and to a lesser extent the CPS(2) sampler might be better methodologies than the DPS sampler.

This study demonstrated that, of the three samplers, the TIPS sampler was most responsive to flume flow rates. The CPS sampler had moderate to weak relationship to flume flow rate, and the DPS sampler had the weakest relationship to flume flow rate. The TIPS(2) sampler responded dynamically to the changing flume aquatic environment because the flow rate at the inlet and outlet are dependent on the ambient flume flow rate.

5.3 Experiment 3: Operating Characteristics of TIPS

The objective of this experiment was not completely achieved. The experiment gave limited insight into the relation between the TIPS(1) inlet velocity and the flume velocity, and the E:R ratio in relation to flume velocity and flume FSS concentration. The examination of the retention properties of the TIPS(1) depended on the pumping capacity of the CPS(1). The variable speed peristaltic pump was unable to balance the intake velocities between TIPS(1) and TIPS(2) for all 46 observations. Thus, with only 13 observations, there was a lack of observations to prove the technology of using TIPS outlet pressure differentials to control peristaltic pump speeds.

The TIPS(1) inlet velocities were less than the ambient flume velocity of 400 mm s^{-1} by a factor of 3.9; thus, the TIPS(1) inlet design was non-isokinetic. The E:R ratio for total weight indicates that the TIPS(1) retained approximately 1 g for every 1 g expelled. This is advantageous for the storage capacity of the TIPS(1) over periods of time if the FSS load is heavy. The silt/clay fraction was collected approximately on a balanced 1:1 basis, but the organic and sand fractions were skewed 1.61:1 and 0.02:1 respectively. The TIPS(1) was very efficient at retaining sand and inefficient at retaining organic matter.

The TIPS(1) E:R ratio varied negatively when related to flume velocity for all weight variables. At greater flume velocities the proportion retained increased. At flume velocities between 300 mm s^{-1} and 400 mm s^{-1} the E:R ration was unity for total weight and silt/clay weight. It appears that this is the most favourable flume velocity conditions for operating the TIPS(1) for measuring FSS total weight and silt/clay. The TIPS(1) E:R ratio did not vary when related to flume FSS concentrations measured by the CPS(2) method. The most favourable result was the percent silt/clay E:R ratio which was approximately 1:1, when the CPS2 measure flume percent silt/clay was around 60%.

5.4 Experiment 4: TIPS(2) Prediction of CPS(2) and DPS Measured Flume FSS Load

The TIPS design was successfully used as a predictive tool of FSS load variables including, total load, mineral load, silt/clay load, sand load, and organic load. This experiment demonstrated that the TIPS weight variables could be calibrated by establishing a simple linear relationship to make direct measurements of FSS load from a DPS or CPS.

5.5 Further Research

The conclusions of this experiment can be used to determine if further scientific investigation is warranted. Although, sizes and shapes were selected according to the availability of parts and guesswork, it is recommended that the tools be engineered using controlled flume experiments in which the flow and sediment measurements are precise. With this level of control, the inlet and pumping rates can be adjusted to find the isokinetic model which collects a sediment sample representative of the ambient stream. The CPS could be improved by adding a flow velocity meter feedback signal (0.0 to 4.0 milliamp) to the variable frequency drive control of pump speed. The CPS pumping speed would then be directly flow proportional.

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