

Flume- and field-based evaluation of a time-integrated suspended sediment sampler for the analysis of sediment properties

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ABSTRACT: Suspended sediment has been identified as a vector for nutrient and contaminant transport in the fluvial environment. A time-integrated sampler (the Phillips sampler), which emerged over a decade ago as a cost-effective tool for *in situ* suspended sediment collection, is increasingly being used to collect samples for the analysis of sediment properties such as particle size composition, and nutrient and contaminant concentrations. This study evaluates the sampler under both flume and field conditions for efficiency in the mass and grain size of the suspended sediment collected. The sampler was tested in a flume using both kaolinite and sediment samples (sieved to < 180 µm) collected from the Quesnel River, British Columbia, Canada. In the kaolinite trials, the sampler preferentially collected coarser grain sizes compared to the original sediment, probably due to finer sediment remaining in suspension and therefore passing through the sampler, and also possibly due to flocculation of the kaolinite upon introduction to the flume. Conversely, the sampler collected river sediment that was finer than the original sediment, probably due to some settling of coarser sediment observed at the bottom of the flume. Once allowance was made for these operational issues associated with the flume, maximum sediment mass efficiency for kaolinite and river sediment was 43% and 87%, respectively. Sediment collected by the time-integrated sampler during field deployment and adjacent channel bed sediment were also compared. The sampler collected sediment with a representative grain size distribution. However, there were differences in the geochemical (arsenic and selenium) concentrations of channel bed sediment and sediment collected by the Phillips sampler which may be a function of differences in the behavior of geochemical elements associated with the two types of sediment. This work suggests that further research is needed to evaluate the role of the Phillips sampler in collecting sediment for contaminant and nutrient analysis. Copyright © 2014 John Wiley & Sons, Ltd.

KEYWORDS: time-integrated sampler; suspended sediment; particle size composition; flocculation; flume evaluation; sediment-associated contaminants; channel bed sediment

Introduction

Fine suspended sediments are important in river systems for a variety of reasons including their impacts on aquatic habitats and from a biogeochemical flux perspective (Syvitski *et al.*, 2005; Owens, 2008). In addition, many trace elements tend to bind to fine-grained sediment, such as suspended material, while in the fluvial environment (Kronvang *et al.*, 2003; Jha *et al.*, 2007; Horowitz *et al.*, 2008). Martin and Meybeck (1979) and Audrey *et al.* (2004) conclude that it is not uncommon for sediment-associated metals to represent > 90% of the metal load in a river. For these reasons, there is increasing interest in collecting and studying suspended sediment in the fluvial environment. In particular, there is a requirement to collect a sufficient mass of sediment for the analysis of sediment properties such as particle size composition, organic matter and carbon content, and nutrient and contaminant concentrations. In recognition of this need, Phillips *et al.*

(2000) developed a time-integrated suspended sediment sampler (hereafter referred to as the Phillips sampler; Figure 1) in order to collect a representative sediment sample of sufficient mass for the subsequent analysis of its properties. The Phillips sampler has many advantages over previous field techniques used to collect representative fine-grained sediment samples (Wren *et al.*, 2000), which include relatively expensive automatic samplers (Gebhart *et al.*, 1998; Peart, 2003; Eaton *et al.*, 2010) and labor-intensive manual sampling methods (Collins *et al.*, 1998; Jha *et al.*, 2007). Furthermore, it is cost-effective, simplistic in design and construction, and believed to be reliable (Phillips *et al.*, 2000). It can also be deployed indefinitely in the absence of a power source and requires little to no maintenance (Russell *et al.*, 2000).

Since its inception in 2000 it has been employed in a variety of fluvial environments in many countries and its use is growing. Studies have been conducted using the Phillips sampler in the UK (e.g. Ankers *et al.*, 2003; Evans *et al.*, 2006; Hatfield

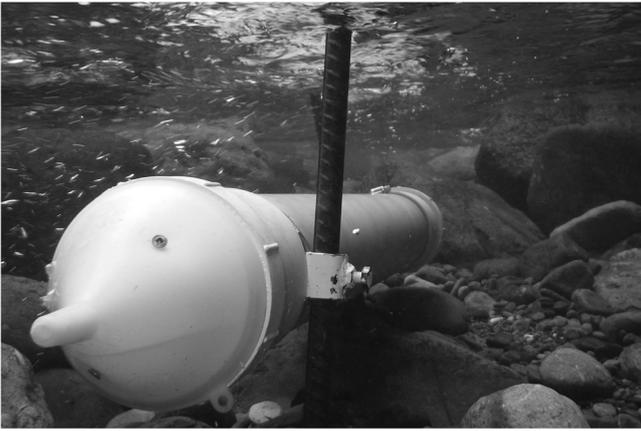


Figure 1. Phillips time-integrated sediment sampler during field deployment in British Columbia. Note the sampler is secured to the riverbed with the nose cone pointed into the direction of the current. The rebar at the downstream end of the sampler is hidden behind the rebar at the upstream end (see Figure 3 for dimensions).

and Maher, 2008; Hutchinson and Rothwell, 2008; Walling *et al.*, 2008), France (e.g. Poulencard *et al.*, 2009), Luxembourg (e.g. Martínez-Carreras *et al.*, 2012), Japan (e.g. Mizugaki *et al.*, 2008; Fukuyama *et al.*, 2010), Australia (e.g. Laubel *et al.*, 2003), New Zealand (e.g. McDowell and Wilcock, 2007), the United States (e.g. Fox and Papanicolaou, 2007, 2008; Fox, 2009; Wilson *et al.*, 2012; Huisman *et al.*, 2013; Voli *et al.*, 2013), and Canada (e.g. McDonald *et al.*, 2010; Owens *et al.*, 2012; Koiter *et al.*, 2013a).

The Phillips sampler has recently been deployed in the field by the authors in the Quesnel River Basin (QRB) in British Columbia (BC), Canada (Figure 2). The Phillips sampler was deployed at 13 sites for month-long sampling intervals during a six month period in 2008 to investigate the impact of various land-use activities (forestry, agriculture, mining, and relatively pristine, i.e. reference) on suspended sediment-associated

geochemical element (i.e. arsenic, cadmium, copper, phosphorus, selenium, zinc) concentrations (for details see Smith and Owens, 2010). Given the need to determine the effectiveness of the Phillips sampler, so as to interpret the geochemical element concentrations of the samples collected from the QRB, flume-based tests were also conducted as part of this study at the Quesnel River Research Centre (QRRC), near Likely, BC. Using an outdoor flume, the ability of the Phillips sampler to collect representative samples of suspended sediment – in terms of mass and median grain size (d_{50}) – was assessed in a simulated river environment (i.e. a flume). Comparisons were made between sampler-retained and ambient flume sediment mass and grain size at the end of each experimental trial.

Additionally, grain size distributions and geochemical (i.e. arsenic and selenium) concentrations of sediment collected by the Phillips sampler in the field were compared to bed sediment samples collected at the same sites in the QRB. When sieved to $< 63 \mu\text{m}$, the bed sediment samples were plausible surrogates for the suspended sediment transported in rivers, thus enabling an examination of the efficiency of the Phillips sampler to collect a representative sediment sample in the natural environment for the determination of particle size composition and sediment-associated geochemical element concentrations.

As the Phillips *et al.* (2000) study represents the only comprehensive flume- and field-based calibration of the sampler to date, there is, therefore, a need to evaluate the performance of the sampler further, especially given the growing deployment of the Phillips sampler in increasingly varied and dynamic applications (e.g. Martínez-Carreras *et al.*, 2010, 2012; Panuska *et al.*, 2011; Owens *et al.*, 2012).

Review of existing sampler evaluations

Assessment of the effectiveness of the sampler in the fluvial environment is essential for the interpretation of any sampler-derived

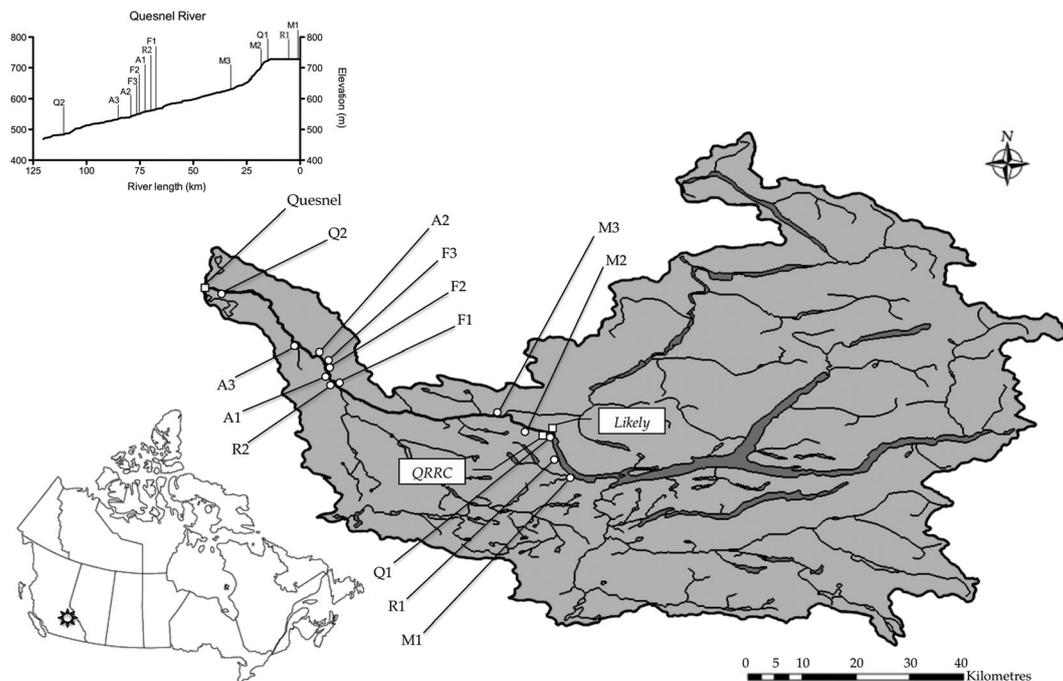


Figure 2. Quesnel River Basin, British Columbia, and location of the sampling sites: F, forestry; A, agriculture; M, mining; R, reference; Q, Quesnel River (main channel). QRRC is the Quesnel River Research Centre, located near the community of Likely. The Quesnel River flows from the Cariboo Mountains in the east to the city of Quesnel in the west, where it joins the Fraser River. Inset map (bottom left) shows location of the basin within Canada, and inset graph (top left) shows the gradient of the main stem of the Quesnel River and lower segment of Quesnel Lake downstream of site M1, and the relative location of the tributary sample sites.

data. However, few efficiency tests have been conducted. In the seminal paper by Phillips *et al.* (2000) both flume- and field-based evaluations of sampler hydraulic characteristics and sediment mass and grain size efficiency were conducted. Flow velocity in the main cylinder was determined to decrease by a factor of about 600, in comparison to external flow, due to the cross-sectional area ratio between the inlet tube and the main cylinder. It is this reduction in flow that causes sediment to settle out in the chamber. Using dye and a transparent sampler, internal flow dead-zones were noted adjacent to the inlet and outlet tubes, providing preferential locations for the settling of very fine sediment (Phillips *et al.*, 2000).

Sampler efficiency tests in a controlled environment resulted in a mass retention in the range of 31% to 71%, with greater mass efficiency associated with coarser sediment particles. Coarser median grain sizes were also retained in the sampler compared to ambient median grain sizes. Phillips *et al.* (2000) found that some of the finest grains remained in suspension while inside the sampler. Thus, some finer sediment passed through the sampler, while all coarser sediment was captured. Besides preferential selection of coarser grains, turbulence in the ambient flow of the flume, although difficult to calculate, was also suspected as a factor reducing sampler efficiency. Indeed, it was determined that flow velocity is reduced in the sampler inlet tube by frictional drag and the inertia of the comparatively stagnant water within the sampler. Thus, the inlet velocity is less than the ambient flow and the sampler is not isokinetic; this is likely to result in oversampling of coarser sediment (Phillips *et al.*, 2000). Field-based tests of the sampler were also conducted by Phillips *et al.* (2000), this time testing grain size efficiency and sediment-associated nutrient (total carbon) representation. Both the resulting grain size distributions and nutrient concentrations were statistically representative of ambient conditions.

A second appraisal of the Phillips sampler, conducted during field deployment, was undertaken by Russell *et al.* (2000). Testing determined that the sampler was able to capture a representative time-integrated sample of fluvial suspended sediment. This was determined by analyzing an array of geochemical properties of sampler-collected sediment in comparison to the ambient suspended sediment load of the test river. As in Phillips *et al.* (2000), ambient field-based suspended sediment particle size characteristics were statistically representative of those collected by the sampler. Importantly, Russell *et al.* (2000) suggested that testing and calibration of the performance of the sampler was required for each new river and/or reach (i.e. the Phillips sampler's ability to provide representative suspended sediment samples needs to be assessed for each river/study).

One of the most recent field evaluations of the Phillips sampler was conducted in Nunavut in the Canadian High Arctic by McDonald *et al.* (2010) at sites characterized by highly variable and episodic hydraulic and sediment transport conditions. Like the Phillips *et al.* (2000) evaluations, the study investigated whether the Phillips sampler could collect a representative sediment load over an extended time period. Sampler efficiency was based on daily-retained suspended sediment mass and median grain size (d_{50}) compared to equivalent values for ambient flow. However, the sampler design was modified from Phillips *et al.* (2000) to adjust for dynamic river stage variations and comparatively smaller channels (peak flow width of 10 to 15 m). To correct for sediment remaining in suspension and exiting the sampler, the outlet tube was placed at the top of the end cap as opposed to the center. Most dimensions of the McDonald *et al.* (2010) sampler were smaller than in the original design (e.g. main body length of 228 mm versus 1000 mm in the Phillips *et al.* (2000) version) as dictated by the smaller channels being

investigated. Two sampler anchorage techniques were used: (1) a fixed-depth apparatus using a boom affixed to the channel bank, as anchorage directly into the frozen riverbed was not ideal; and (2) a variable design using two parallel pivoting aluminum arms to enable automatic maintenance of 60% depth with stage variations (cf. Eads and Thomas, 1983).

McDonald *et al.* (2010) found that, when tested for the mass of sediment captured and its grain size composition, the Phillips sampler proved inefficient; that is, ambient suspended sediment concentration (SSC) and median grain size (d_{50}) were not proportionate to sampler values. Both over- and under-retention of sediment compared to anticipated values were recorded. Sediment in both sampler designs displayed significant coarsening compared to ambient flow. However, compared to each other, similar grain size distributions were recorded for both sample designs, suggesting a vertically well-mixed river. Although temporal trends were similar between sediment retention rates and flow velocity, discharge, and SSC fluctuations, sampler-retained sediment was significantly coarser and of inconsistent quantity versus ambient values (McDonald *et al.*, 2010).

McDonald *et al.* (2010) identified that factors such as organic detritus blocking the inlet tube, the potential of large composite particles, higher velocities than in the Phillips *et al.* (2000) study, and smaller sampler design (e.g. reduction of sediment capture potential due to a smaller cross-sectional area ratio than in the larger design), were all potential sources of the lower efficiency of mass retained. Perhaps the most important factor identified by McDonald *et al.* (2010) was that the relationship between water intake of the sampler and the modified inlet tube and sampler body diameters had not been examined in the laboratory to properly characterize and quantify hydraulic conditions. Had this been the case, an equation accounting for the frictional and inertial forces acting on the inlet tube could have been used in calculating the anticipated sediment retention of the sampler. Despite these potential obstacles to full acceptance of the results presented in McDonald *et al.* (2010), the introduction of the automatic variable-depth capture method may be an important improvement on sampler anchorage design.

Schindler Wildhaber *et al.* (2012) also compared information obtained from the Phillips sampler with other approaches, although their work was not a true evaluation of the sampler *per se*. They compared the mass of sediment collected by the sampler to turbidity measurements (and bed infiltration rates) for a stream in Switzerland. While they found a good correlation between the sediment load (g week^{-1}) estimated from the Phillips samplers and the turbidity data obtained from optical backscatter sensors, the samplers were not designed to determine sediment loads (Phillips *et al.*, 2000), and thus the robustness of such comparisons is uncertain. The results of Schindler Wildhaber *et al.* (2012) do, however, suggest that the sampler may provide a relative measure of the transport of fine-grained sediment in streams and small rivers. These authors also identified the need for further evaluation of the sampler in controlled laboratory conditions.

In a recent assessment of the Phillips sampler, Perks *et al.* (2013) found that the sampler under-estimated the sediment-mass flux when compared to estimates based on continuous monitoring of turbidity and discharge for several rivers in England. They therefore identified that the sampler was unsuitable for assessing absolute sediment loads. Despite this limitation, they did, however, find that there was a good relation between relative efficiency of the sampler and the reference sediment load for several rivers, suggesting that the sampler may be suitable for characterizing temporal and spatial patterns of suspended sediment flux. They also compared the properties (i.e. absolute particle size composition, organic content, carbonate content

and magnetic susceptibility) of the sediment collected by the sampler. They found that there was good agreement in property values between samplers at the same sampling location (i.e. sampler sets), especially for magnetic susceptibility, organic content and carbonate content, while there was less agreement for particle size composition. Perks *et al.* (2013) did not, however, compare properties of the sediment collected by the sampler to ambient sediment, and thus the true representativeness of the sediment collect by the samplers is still uncertain. Again, the authors call for further evaluation of the sampler in contrasting conditions.

All five sampler evaluations have furthered the understanding of the hydraulic characteristics of the Phillips sampler and its efficiency in collecting a representative suspended sediment sample. This paper provides an additional, independent evaluation of the Phillips sampler. The main objectives were: (i) to determine if the sampler collects a sediment sample that is representative of ambient conditions in term of sediment mass retained and its particle size composition; and (ii) to determine if the geochemical content of the retained sediment is comparable to fine-grained sediment stored in the channel bed.

Methods

Sampler design

The Phillips sampler is designed to collect samples of actively transported suspended sediment (i.e. clay, silt and fine-medium sand) in the fluvial environment. The main body of the sampler (Figure 3) is comprised of commercially available polyvinylchloride (PVC) pipe (9.8 cm internal diameter [i.d.] \times 100 cm length) with threaded cap seals at both ends of the cylindrical pipe. Semi-rigid nylon pneumatic tubing (0.4 cm [i.d.] \times 150 mm) provide the inlet and outlet tubes and are threaded through each end cap, and made

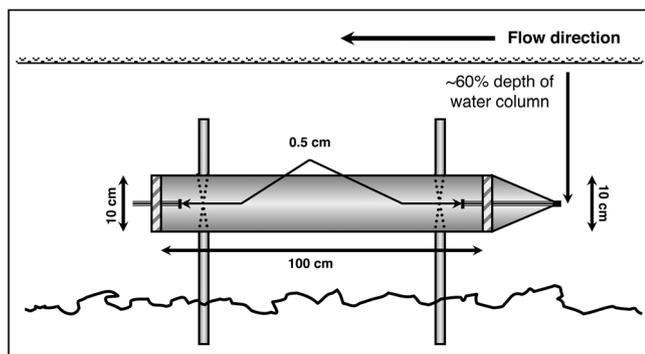


Figure 3. Cross-section of Phillips time-integrated sediment sampler. Flow velocity within the main chamber of the sampler is reduced by a factor of about 600 compared to ambient flow (Phillips *et al.*, 2000; Russell *et al.*, 2000) (figure not to scale).

watertight with silicone sealant. The tubes extend 2 cm into the internal cavity of the sampler at either end. A polyethylene funnel is secured to the upstream end of the sampler and over the inlet tube to provide a more streamlined shape and reduce ambient flow disturbance in the inlet tube region. The main body and inlet/outlet tubes have internal (lengthwise) cross-sectional areas of 754.3 cm² and 1.26 cm², respectively. Water enters and exits the inlet and outlet tubes at a velocity slightly less than ambient flow due to frictional forces in the inlet tube and inertia reduction induced by the comparatively stagnant water in the sampler's main cylinder. The main cylinder of the sampler has an internal cross-sectional area \sim 600 times larger (598.7 \times) than that of the inlet/outlet tubes and sampler internal velocity is decreased proportionally (Phillips *et al.*, 2000; McDowell and Wilcock, 2007). Thus sedimentation occurs within the main cylinder.

Some slight modifications to the original Phillips *et al.* (2000) sampler were made prior to field deployment to ensure stronger sampler anchorage. In the Phillips *et al.* (2000) version, metal eyes were screwed into the front and rear of the sampler and used to attach the sampler to steel (Dexion) uprights. In this study, cylindrical hose clamps were attached to the main body of the sampler near the upstream and downstream ends and looped through 4 cm \times 4 cm steel cylinders. A hole was drilled in the side of the cylinders and a steel nut was welded onto the hole. This modification allowed a flat-ended bolt to be screwed through the nut and into the steel cylinder to create a fastening mechanism. The cylinders were able to slide over two steel reinforcement bar (rebar) uprights, which anchored the sampler and were driven into the sediment. The sampler was easily fastened at a chosen depth within the water column and was adjustable during future sampling periods in response to changes in water level. This method of fastening the samplers to the anchorage rebar pieces ensured that there was no unstable movement of the sampler, as with the metal eye method proposed by Phillips *et al.* (2000). For increased stability and trap retention, additional hose clamps could be attached.

It should be noted that the relatively static location of the sampler (i.e. at a fixed location and depth over the period between emptying) is a limitation, particularly for small 'flashy' rivers where stage can vary considerably over a matter of hours. While it may be possible to alter the height of the sampler to allow for variations in stage, movement of the sampler to new sites should be avoided so as not to disturb the fine sediment in the channel bed.

Flume-based experimental apparatus

The Phillips sampler was suspended *in situ* in a modified flume at the QRRC in 2008 (Figure 4). The flume was U-shaped in cross-section, with a length of 640 cm, width of 70 cm and height of 49.5 cm; the depth of water was 35 cm (Figure 4).

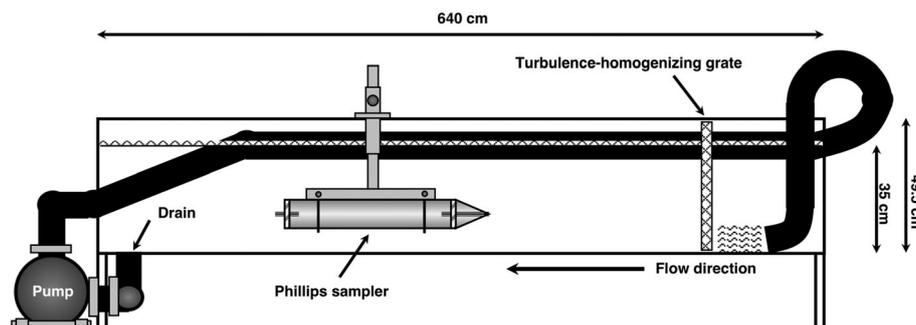


Figure 4. Flume-based calibration of the Phillips suspended sediment sampler. The pump recirculates water and sediment in the flume to maintain continuous flow. The turbulence-homogenizing grate is used to buffer the turbulent water entering the flume from the recirculation tube (figure not to scale).

The volumes of the flume and Phillips sampler were 1231.5 l and 8.68 l, respectively. An aluminum boom, capable of vertical adjustment, was fastened to the lip of the flume and used to keep the Phillips sampler pointed into the current and at 0.6 of the water depth. In an attempt to reduce the influence of turbulence on sampler efficiency (Phillips *et al.*, 2000), the nose cone of the sampler was over 1 m from a turbulence-reducing grate, where buffered turbulent flow has been measured in previous flume-based experiments at the QRRC (Rex and Petticrew, 2008). A pump was connected to the drain at the downstream end of the flume. This enabled recirculation of the water and sediment, and created continuous flow within the flume.

A Swoffer 2100 current meter (Swoffer Instruments Inc., Seattle, WA, USA) was used to determine that the average velocity in front of the Phillips sampler inlet tube was 0.28 m s^{-1} . This value is similar to the flow velocity used in the Phillips *et al.* (2000) evaluation (range $0.3\text{--}0.6 \text{ m s}^{-1}$), which was deemed representative of river flow during storm events at the UK field sites used in their study. Therefore, given the logistical problems often encountered in generating high velocities in artificial flumes, a mean flow velocity of 0.28 m s^{-1} was considered representative of the small creeks sampled in the QRB (range ~ 0.05 to $\sim 0.5 \text{ m s}^{-1}$), though not necessarily representative of the main Quesnel River, especially during peak flows.

Experimental procedures

Two sediment types were used in the calibration tests: (i) scientific-grade kaolinite ($\text{Al}_2\text{Si}_2\text{O}_5$) (Ward's Natural Science, Henrietta, NY, USA), i.e. clay-sized material; and (ii) Quesnel River sediment collected near site Q1 (see Figure 2) and wet sieved to $180 \mu\text{m}$. Kaolinite was chosen primarily to assess the sampler's efficiency in collecting sediment mass (i.e. collected mass compared to expected mass retained), while Quesnel River sediment was used to assess the particle size composition of the sediment collected by the sampler (i.e. is the collected sample representative of all particle sizes in suspension?). The results of the trials involving (ii) may have implications for the interpretation of suspended sediment data obtained from the sampler; e.g. is all sediment entering the sampler retained or do some finer particles remain in suspension and exit the sampler resulting in a coarser sampler d_{50} grain size in comparison to the ambient d_{50} ?

Both the kaolinite and river sediment samples were added to distilled water and sonication was performed using a Branson 1510 ultrasonic bath (Branson Ultrasonics, Danbury, CT, USA) for five minutes to break up any composite particles or flocs and promote homogeneous hydrodynamics of the sediment (Rex and Petticrew, 2008). Prior to the commencement of each trial, 200 g of sediment was introduced to the flume and allowed to fully disperse within the flume water, which was derived from industrial groundwater pumps at the QRRC. The Phillips sampler was then filled with water, capped at each end, and secured at 0.6 of depth, pointing into the flow. Using 200 g of sediment in the total volume of water in the flume created an ambient SSC of $\sim 160 \text{ mg l}^{-1}$, which was representative of other temperate rivers during moderate to high flow conditions (e.g. Wass and Leeks, 1999) and other rivers in BC where the Phillips sampler has been used to collect suspended sediment (e.g. Owens *et al.*, 2012, 2013).

Each experimental trial lasted six hours and three trials were conducted for each sediment type. One liter grab samples were taken adjacent to the Phillips sampler at zero, two, four, and six hours for analysis of SSC. This procedure enabled any settling of sediment during the trials to be identified and accounted for in the calibration. At the end of each trial the contents of

the Phillips sampler were rinsed-out using distilled water and collected in a 10 l plastic bucket.

Analytical procedures

Material collected by the Phillips sampler was allowed to settle (usually over 24 hours) in the buckets and the supernatant was removed by siphoning. Wet samples were then transferred to pre-weighed whirl-pak® bags and dried. After sediment dry mass was measured, subsamples were removed for particle size analysis. Subsamples underwent digestion with hydrogen peroxide prior to analysis to remove organics, and sodium hexametaphosphate was subsequently added to induce dispersion. Primary (i.e. absolute) particle size characteristics were determined using a Malvern Multisizer Hydro 2000G (Malvern Instruments Ltd, Malvern, UK) at Simon Fraser University, BC. Primary particle size was determined (i.e. after removal of organic matter and deflocculation) so that the efficiency of the sampler could be compared to other studies that have either evaluated the Phillips sampler (e.g. Phillips *et al.*, 2000; Perks *et al.*, 2013) or used it to collect sediment for property analysis (e.g. Hatfield and Maher, 2008; Huisman *et al.*, 2013); i.e. these studies have used a similar pretreatment approach. The implications of this pretreatment approach on the results of the present study are discussed further later. Grab samples collected during each trial were passed through a glass microfiber filter (Whatman GF/F; $0.7 \mu\text{m}$ mesh) to separate the sediment from water. Samples were then dried and weighed enabling an estimation of SSC.

Expected sediment retention

To evaluate the sediment mass efficiency of the Phillips sampler, the expected sediment retention for each sediment type (i.e. kaolinite and Quesnel River) was calculated. In laboratory-based experiments, the Phillips sampler was found to be non-isokinetic (Phillips *et al.*, 2000). Thus, in order to determine the comparatively slower flow velocity within the sampler, as dictated by friction and inertial forces in the inlet tube, the following equation, developed by Phillips *et al.* (2000) through laboratory-based experimentation, was used:

$$y = -2.182 + 2.074(x) \quad (1)$$

where y is the logarithmic flow velocity in the Phillips sampler inlet tube, and x is the logarithmic flow velocity of the flume.

The volume of water passing through the sampler during each trial was calculated from the inlet tube flow velocity, the inlet tube cross-sectional area, the trial duration, and the internal volume of the Phillips sampler (to account for initial SSC). The rate at which the volume of water in the Phillips sampler was replaced during each six hour trial was determined from the internal volume of the sampler and the sampler discharge (i.e. product of the inlet tube flow velocity and the inlet tube cross-sectional area).

With this information, two methods were used to calculate the expected sediment retention. The two versions were abbreviated to (1) temporal-based and (2) grab sample-based. In the temporal-based method, sediment retention in the Phillips sampler was a function of the volume of water that flows through the sampler and the assumption that all sediment was retained in the sampler during each 'flush'. As the SSC in the flume water decreased during each trial (because of sediment retention in the sampler) it was necessary to account for this reduction

based on the SSC, the volume of the sampler, and the number of times the water in the sampler was replenished. This calculation enabled the determination of the mass of sediment collected (and thus the corresponding decrease in SSC) for each sampler 'flush', enabling a more accurate calculation of the sediment retention efficiency of the sampler.

The grab sample-based method was a modified version of the temporal-based method (just described) but instead incorporated the SSC values determined from grab samples taken adjacent to the sampler at two hour intervals. This approach allowed for the observed changes in SSC due to settling (described later). The initial SSC (time $[t] = 0$ hour; SSC_i) was higher in most trials than the proceeding three values, which displayed little variation and appeared stable. Therefore, an average of the two, four, and six hour values for each trial was determined and termed the 'stabilized' SSC (SSC_s) and used in calculations for determining the sediment passing through the Phillips sampler after the initial decrease in SSC. The expected sediment retention in the sampler was then calculated using SSC_i and the volume of the sampler (iteration 1, i.e. first flush of water passing through the sampler) and SSC_s and the volume of the sampler for the remaining iterations (i.e. subsequent flushes of water through the sampler during the remainder of the trial).

Collection of bed sediment samples

As a further test of the Phillips sampler, we compared samples obtained from samplers deployed at the 13 sites in the QRB (Figure 2) with adjacent samples of channel bed sediment which were sieved to $< 63 \mu\text{m}$. As the sediment samples collected by the Phillips sampler in the QRB were also sieved to $63 \mu\text{m}$ (for subsequent geochemical analysis as part of the larger project; Smith and Owens, 2010), this enabled a comparison of the grain size efficiency of the sampler. The use of sieved bed sediment samples (i.e. $< 63 \mu\text{m}$ fraction) as suitable surrogates for suspended sediment samples has been used in numerous studies (e.g. Van der Perk *et al.*, 2007; Horowitz and Stephens, 2008), as the sediment deposited on the channel bed is mainly composed of settled (former) suspended sediment.

Instantaneous samples of the fine-grained sediment stored in the upper c. 5–10 cm of the channel bed were collected on a monthly basis during the summer of 2008 using the resuspension method (for details of method see Lambert and Walling, 1988). The channel widths of these (tributary) sites were ~ 1 to ~ 3.5 m (except the main stem Quesnel; ~ 50 to ~ 70 m) and the water depths at the locations and times of sample collection were ~ 0.15 to ~ 2 m. Sample sites were located at straight channel reaches, and were gravel-bedded with a matrix of fines. Mean discharge for the Water Survey of Canada (WSC) gauging stations on the main stem of the Quesnel River at Likely (Figure 2; $52^\circ 37' \text{N}$, $121^\circ 34' \text{W}$; area is 5930 km^2) and Quesnel (Figure 2; $52^\circ 50' \text{N}$, $122^\circ 12' \text{W}$; $\sim 11\,500 \text{ km}^2$) were 132 and $248 \text{ m}^3 \text{ s}^{-1}$, respectively, in 2007 (the year prior to sample collection) (WSC, 2009); equivalent values for the tributary creeks are one to two orders of magnitude lower.

After collection, the samples were processed in a similar way to the samples collected by the Phillips sampler (described earlier). Both the bed sediment and sediment collected by the Phillips samplers were passed through a $63 \mu\text{m}$ sieve and analyzed for primary particle size (as described earlier) and geochemical elements using inductively coupled plasma mass spectrometry (ICP-MS) (Agilent 7500cx; Agilent Technologies, Santa Clara, CA, USA) after acid (nitric and hydrochloric) and microwave digestion (Date and Gray, 1989).

Results and Discussion

Flume evaluation of grain size efficiency

In the controlled appraisal of the Phillips sampler using the QRRC flume, median grain sizes (d_{50}) of kaolinite and river sediments at the start of the experimental trails for each material type were $6.8 \pm 0.2 \mu\text{m}$ (mean \pm one standard error [1SE]) and $99.5 \pm 0.2 \mu\text{m}$, respectively. The higher value of d_{50} for kaolinite ($6.8 \mu\text{m}$) compared to what might be expected for clay-sized particles (i.e. $< 2 \mu\text{m}$) is thought to reflect some flocculation of the kaolinite particles once in the flume, due to the opportunity for particle–particle interaction and collision. The d_{50} value of $6.8 \mu\text{m}$ for the kaolinite is within the range often reported for the absolute particle size composition of fluvial suspended sediment (Walling and Moorehead, 1989; Walling *et al.*, 2000).

Assuming complete homogenization of grain sizes and continuous suspension of sediment in the flumes, these values were expected to be representative of flume d_{50} during the evaluation of the Phillips sampler. Although this was likely valid for the kaolinite trials, sedimentation was observed at the bottom of the flume during the river sediment trials, with some focusing towards the drain, suggesting that the actual flume suspended sediment sampled for the latter was finer than the above measurement.

The values of d_{50} for sampler-retained and ambient flume sediments are presented in Figure 5. The kaolinite samples retained by the Phillips sampler (i.e. $d_{50} = 15.9 \pm 0.5 \mu\text{m}$) were coarser compared to ambient flume values (i.e. $6.8 \pm 0.2 \mu\text{m}$), while the d_{50} of the material collected in the river sediment trials was finer (i.e. $47.2 \pm 1.8 \mu\text{m}$) than the measured flume suspended sediment (i.e. $99.5 \pm 0.2 \mu\text{m}$). Sediment (both kaolinite and river) was initially sieved to $< 180 \mu\text{m}$, in an attempt to determine whether grain sizes above the sand–silt boundary (i.e. $63 \mu\text{m}$), but still potentially capable of sustained suspension (Walling *et al.*, 2000), would be captured by the Phillips sampler. In the case of the river sediment trials, the flume flow velocity was probably insufficient for continued suspension or re-entrainment, and a visible portion of the sediment settled out during each trial. This is a possible explanation for the finer material collected by the sampler compared to the mean d_{50} measured in the flume.

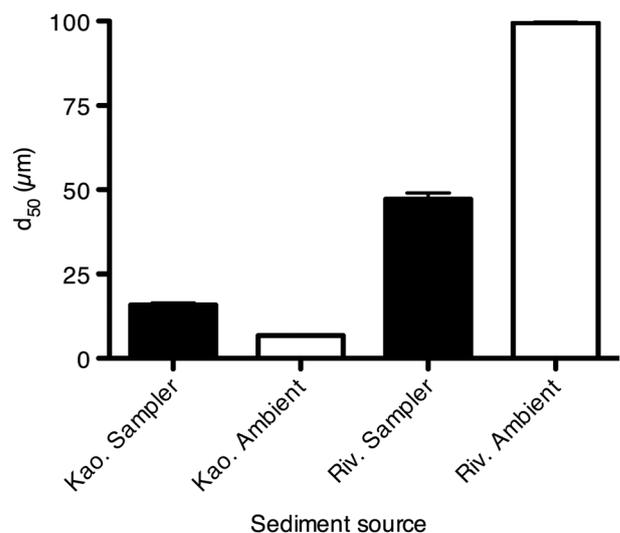


Figure 5. Comparison of median grain size composition (d_{50}) between sediment retained by the Phillips sampler and the ambient suspended sediment in the flume for both kaolinite (Kao.) and Quesnel River (Riv.) sediment types. Note that the Phillips sampler appears to oversample coarser sediment during the kaolinite trials and finer sediment during the river sediment trials. Error bars represent ± 1 SE.

For the kaolinite trials, it was apparent that some coarsening of sampler-retained sediment relative to the ambient flume suspended load occurred. Similar results were presented in Phillips *et al.* (2000) and McDonald *et al.* (2010). Preferential selection of coarser sediment by the sampler compared to flume sediment could be due to: (1) through-flow or sustained suspension of finer particles within the Phillips sampler; (2) greater retention of suspended sediment with a coarser d_{50} due to dead-zones within the sampler, as found in Phillips *et al.* (2000); and (3) the occurrence of flocculation after both types of sediment (especially the kaolinite) were introduced to the flume. The potential effect of flocculation is demonstrated by the larger d_{50} of the kaolinite measured in the flume relative to its original size, which could result in the measurement of coarser sediment particles (i.e. composite particles), and hydrodynamic alterations to the sediment particles once in the sampler (i.e. changes in size and density), which would influence settling rates and sampler retention. Thus, sediment coarsening between flume and sampler-collected samples with kaolinite can be explained by through-flow and preferential selection by the sampler for coarser particles, and perhaps by flocculation. The sediment fining observed between flume and sampler-collected samples for Quesnel River sediment was likely due to settling of the coarsest portion of the sediment within the flume due to problems with the flume set-up and a significantly finer suspended load for most of the trials.

Mass efficiency of the Phillips sampler

Two methods were used to determine the mass efficiency of the Phillips sampler. The first, the temporal method, involved a calculation of sediment retained by the Phillips sampler assuming an initial ambient SSC of 161 mg l^{-1} and accounting for ambient SSC decreases over time due to sampler retention. In the second approach, the grab sample method, the initial ambient SSC_i (i.e. SSC at $t=0$ hour) and a lower, 'stabilized' SSC_s value were based on grab sample-derived values (Table 1); thereby accounting for observed settling in the flume set-up. It should be noted that non-homogenous turbulent flow was observed within the flume despite an attempt to mitigate this using a turbulence and eddy-homogenizing grate (see Figure 4). This has also been identified by Phillips *et al.* (2000) as a potential source of error and cause of decreases in sediment retention by the sampler.

There was relative consistency among grab sample SSC values for the kaolinite trials. Actual SSC values during the trials (c. $130\text{--}140 \text{ mg l}^{-1}$) were slightly lower than the value of material introduced into the flume (161 mg l^{-1}) suggesting that there

was some settling, likely due to some flocculation within the flume. While the temporal-based method did not account for this difference in SSC, the grab-sample based method did. In the case of the Quesnel River sediment trials, not only was there a pronounced difference between the SSC of the sediment introduced into the flume and that at $t=0$ hour (c. $65\text{--}85 \text{ mg l}^{-1}$), but there was also a distinct drop in SSC after the initial ($t=0$ hour) sample collection, reflecting further settling in the early stages (0–2 hours) of these trials. Consequently, sediment retention (i.e. mass and particle size) during the kaolinite trials is expected to be more efficient than during the river sediment trials.

The temporal-based method, as a means to determine sediment retention efficiency of the Phillips sampler, is appropriate in an experiment with complete suspension and homogenization of sediment. Using this method, the kaolinite trials proved more efficient than river sediment trials in retaining sediment and the maximum efficiencies of sediment mass collected by the Phillips sampler (i.e. collected versus expected retention) were 37% for kaolinite and 15% for river sediment (Figure 6). However, this method of estimating sediment retention efficiency is clearly flawed because of the noticeable settling of sediment, especially for the river sediment trials.

Using the grab sample-based method, the sampler efficiencies were higher and arguably more representative of conditions in the flume than with the temporal-based method.

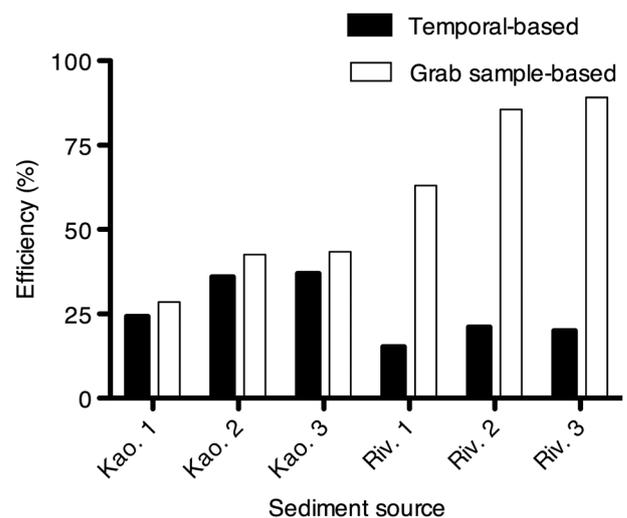


Figure 6. Efficiency of the Phillips sampler to collect sediment mass using temporal-based and grab sample-based calculation methods (see text for details on the difference of these methods); due to problems of settling, the latter is believed to be a more representative measure of collection efficiency.

Table 1. Spot (i.e. instantaneous) grab sample suspended sediment concentration (SSC) values during the flume trials for the kaolinite and river sediment runs

Sediment type	Run number	Grab sample SSC (mg l^{-1}) at time:				Mean (mg l^{-1}) 0–6 hours	Mean (mg l^{-1}) 2–6 hours
		0 hour	2 hour	4 hour	6 hour		
Kaolinite	1	141.1	137.2	131.4	132.0	135.4 (± 2.3)	133.5 (± 1.8)
	2	132.8	139.1	132.7	138.6	135.8 (± 1.8)	136.8 (± 2.1)
	3	137.0	139.6	134.8	134.6	136.5 (± 1.2)	136.3 (± 1.6)
River sediment	1	66.5	27.3	24.2	24.4	35.6 (± 10.3)	25.3 (± 1.0)
	2	84.2	19.3	18.3	15.7	34.4 (± 16.6)	17.8 (± 1.1)
	3	72.6	15.8	18.9	19.5	31.7 (± 13.7)	18.1 (± 1.2)

Note: Most sediments, except runs 2 and 3 for the kaolinite, exhibit a higher SSC at $t=0$ hour relative to 2–6 hours. Mean SSC values for 0 to 6 hours and 2 to 6 hours were calculated to highlight this initial drop-off and the stabilization of SSC values over time. Values of ± 1 SE are presented in parentheses.

What is not evident is why the evaluation for each sediment type showed lower sampler efficiencies for the first trial and similar, higher efficiencies for the second and third trials (Figure 6). The conditions were the same in all cases and the flumes were flushed of all sediment between trials. Assuming that the latter trials are more representative, the average efficiencies (trials 2 and 3 only) for kaolinite and river sediment were 43% and 87%, respectively.

When the grab sample-based method results are compared to the results from Phillips *et al.* (2000) (i.e. 46% for finer sediment and 71% for coarser sediment, at 0.3 ms^{-1}), the mean values are comparable for both kaolinite (i.e. finer; 43%) and Quesnel River (i.e. coarser; 87%) sediment. This supports the statement made by Phillips *et al.* (2000) that the sampler may preferentially select for coarser sediment and, in an environment where the ambient suspended sediment load is predominantly coarse, provides a representative sample of ambient suspended sediment mass. Conversely, the Phillips sampler is expected to be less efficient when collecting from a predominantly fine-grained suspended sediment load environment. While the suspended sediment load of many rivers is typically composed of predominantly clays and silts, with some finer sands, as most cohesive suspended sediment travels as flocs (Kranck, 1980; Droppo, 2001) then it is reasonable to believe that the Phillips sampler will effectively collect sediment in rivers dominated by flocculated fine-grained particles. Indeed, the expected role of flocculation of fine-grained sediment in rivers is one of the reasons that the Phillips sampler is an effective device for collecting suspended sediment; i.e. the flocculation helps to promote setting in the sampler – especially for finer sediment – compared to what might be expected given settling rates based on Stokes' law (Phillips *et al.*, 2000).

Comparison between sediment collected by the Phillips sampler and adjacent channel bed sediment

Values of the d_{50} associated with the sediment collected by the Phillips sampler and values for spatially comparable bed sediment are presented in Table II. Comparisons are organized by land-use activity (i.e. in-line with the approach adopted in the larger research project reported in Smith and Owens, 2010). It is important to recognize that the bed sediment (although sieved to $< 63 \mu\text{m}$) is not exactly the same as the suspended sediment during the time in which the Phillips samplers were deployed in the field (i.e. it is a surrogate). In general, there was little difference between sediment captured by the Phillips sampler and channel bed sediment. The greatest coarsening was found in the mining channels (+28.2%), and the most pronounced fining was exhibited in the samples from the Quesnel

River main channel (−38.9%). The exact reason for the coarser sediment collected by the Phillips sampler in the mining sites is not obvious, although it could reflect winnowing of fines in the channel bed sediment due to artificial flows from the mine sites during mining operations. However, it is important to note the large variability in d_{50} values for both sets of samples, and the fact that there were no significant differences between sediment types. One possible reason that samples (i.e. Phillips sampler versus bed) are noticeably different for the Quesnel River main channel is that the Quesnel is a medium-sized river (drainage area is $\sim 11\,500 \text{ km}^2$), whereas all other samples were taken from small creeks ($< 500 \text{ km}^2$). Phillips *et al.* (2000) state that the Phillips sampler is designed for small channels, and that the hydraulic characteristics and associated transport and deposition of sediment in a large channel may influence suspended sediment capturing efficiency.

There were no significant differences between samples for all land uses tested (Mann–Whitney U -test; $p > 0.05$). As with the Phillips *et al.* (2000) study, field-based grain size comparisons between sampler-retained and ambient suspended sediment are statistically similar, suggesting that for our study sites the Phillips sampler is capable of collecting a representative sample of the ambient suspended sediment load. In larger streams (e.g. the main stem of the Quesnel River) it may not be suitable in its present design configuration, and modifications may be required to increase its efficiency. Such modifications include: changes to the diameter of the inflow tube; changes in the length and diameter of the main chamber; placement of the outflow tube on the top (as opposed to the centre) of the end-cap; modifications to ensure that the sampler remains at 60% of water depth; addition of a weathervane-type fixture to ensure that the sampler is pointing directly into the current to ensure maximum inflow; and use of stronger anchorage material to ensure that the sampler remains fixed to the channel bed during high-flow events.

To illustrate the effectiveness of the Phillips sampler in providing sediment for subsequent analysis of sediment properties, Figure 7 shows the arsenic and selenium content of sediment collected by the Phillips sampler with equivalent values for adjacent bed sediment samples; again, both sets of samples being $< 63 \mu\text{m}$. In the case of arsenic, there was a good match between the two types of sediment, with differences likely to reflect difference in the particle size composition of each sediment type as well as the fact that while the values for the Phillips sampler represent samples collected over month-long intervals those for the bed sediment represent instantaneous samples collected monthly. The noticeable difference in arsenic concentrations between the samples collected from the mining sites, compared to the forested, agriculture and control/reference sites, may reflect the timing of mining operations. For example, there may have been an instantaneous discharge of mine waste products into one of the creeks draining a mine

Table II. Comparison of median particle size composition (d_{50}) for sediment collected by the Phillips sampler and for channel bed sediment samples collected from a variety of rivers with contrasting land-use activity in the Quesnel River Basin as part of a larger project (cf. Smith and Owens, 2010)

Dominant land-use activity	Phillips sampler d_{50} (μm)	(n)	Bed d_{50} (μm)	(n)	Difference (μm)
Forestry	15.9 (± 1.6) ^a	15	12.1 (± 1.5) ^a	3	3.8 (31.4%) ^b
Agriculture	14.9 (± 3.0)	18	13.4 (± 2.2)	12	1.5 (11.2%)
Mining	20.0 (± 5.6)	12	15.6 (± 6.3)	6	4.4 (28.2%)
Reference	19.0 (± 3.0)	21	21.8 (± 3.3)	12	−1.8 (−12.8%)
Quesnel River main stem	9.9 (± 1.7)	15	16.2 (± 2.3)	21	−6.3 (−38.9%)

Note: Both sets of samples were screened through a $63 \mu\text{m}$ sieve prior to analysis. The bed samples represent instantaneous samples at each site whereas the Phillips samplers were left in the field for intervals of one month over a six month period at each site.

^aValues in parentheses are one standard error.

^bValues in parentheses are percent difference between sampler and bed sediment.

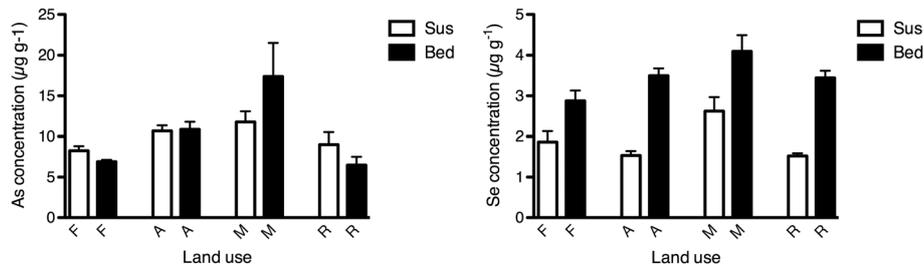


Figure 7. Comparison of the arsenic (As) and selenium (Se) content of fine-grained sediment collected by the Phillips sampler (sus) with adjacent channel bed sediment (bed) for several streams and rivers in the Quesnel River Basin draining different land uses (F, forested; A, agricultural; M, mining; R, reference; see Figure 2 for locations). Both types of sediment were passed through a 63 µm sieve prior to analysis.

site immediately before the channel bed sediment sample was collected, whereas the suspended sediment sample provided by the Phillips sampler would collect sediment over the whole month prior to retrieval, thereby diluting a short-term discharge event.

In the case of the selenium concentrations, the values for the bed sediment samples are consistently greater than those for equivalent suspended sediment collected by the Phillips sampler. The exact reason for this is not clear, but it may reflect differences in behavior between arsenic and selenium, such as differences in element–sediment interactions (e.g. differences in element speciation and sorption behavior; Salomons and Förstner, 1984; Horowitz, 1991; Carter *et al.*, 2006), again recognizing the temporal differences associated with the bed sediment (e.g. instantaneous and/or an integrated sample since the last flood event) and Phillips (i.e. integrated month-long) samples. Thus while there are no significant differences in the particle size composition between the channel bed and Phillips sediment samples, there may be differences in other properties, such as geochemical, nutrient and biological characteristics. Related, there may be issues associated with the use of sediment collected by the Phillips sampler for the determination of specific geochemical properties, such as phosphorus, that are known to be dynamic under changing environmental conditions (e.g. deposited inside the Phillips sampler and retained in a fairly quiescent environment for long periods) (Koiter *et al.*, 2013b). Further investigation is required to determine how representative such samples are of the characteristics and properties of actively transported sediment.

Conclusions

The Phillips time-integrated suspended sediment sampler was evaluated for its ability to collect a representative mass and particle size composition of sediment transported in a river system. In the case of sediment mass, once issues associated with settling within the flume were accounted for, it was estimated that the sampler retained between 43% and 87% of the mass expected if it was 100% efficient. The former value was for a fine-grained sediment sample (kaolinite, $d_{50}=6.8\ \mu\text{m}$), whereas the latter was for a coarser-grained sample (Quesnel River sediment, $d_{50}=99.5\ \mu\text{m}$). The lower value for the fine-grained sediment is consistent with observations by Phillips *et al.* (2000) that finer-grained particles may remain in suspension in the sampler and pass through it. The broader implications are that the Phillips sampler is reasonably efficient in collecting sediment mass, and thus may be used to provide some measure of relative sediment transport, as identified by Schindler Wildhaber *et al.* (2012) and Perks *et al.* (2013). However, as the particle size composition of the suspended sediment load in rivers typically changes in association with flow conditions (Walling and Moorehead, 1989; Walling *et al.*, 2000) then care is required

when the sampler is used to determine sediment fluxes (i.e. it was not designed for this use; Phillips *et al.*, 2000).

In terms of the particle size composition of the sediment retained by the sampler, a combination of flume- and field-based studies showed that the sampler collects a reasonably representative sample, especially for rivers with a coarser-grained sediment load as finer particles may pass through it. There were potential problems with the flume experiments, but most of the differences between the expected and collected particle size composition could be explained by operational issues associated with the flumes (e.g. settling or flocculation). The implications are that the Phillips sampler is suitable for collecting representative samples of suspended sediment in most small streams and rivers for subsequent physical and geochemical analysis. There were, however, some noticeable differences in the geochemical content between the sediment collected by the sampler and adjacent channel bed samples, especially for selenium. This suggests that care is required when the sampler is used to collect sediment for the analysis of some geochemical (and probably biological) properties, especially for those nutrients and contaminants which are known to be chemically mobile (i.e. adsorption/desorption) under changing environmental conditions (e.g. changing pH, redox potential), such as phosphorus. Further work is required to examine these issues. It is also suggested that it may be necessary to test the sampler each time it is used in a new environment (i.e. rivers dominated by clay-sized particles) or a new application (i.e. larger rivers, non-channel situations).

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