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Fine Sediment Deposition at Forest Road Crossings: An Overview and Effective Monitoring Protocol

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1. Introduction

Fine sediment (< 2mm) is an integral component of naturally functioning streams but can become a pollutant when development activities increase stream concentrations beyond that of the natural regime or when the sediments carry contaminants. Watershed development activities including urbanization, agriculture, and forestry can influence fine sediment quantity, quality, and its transport and storage regime by altering the natural timing and volume of water and sediment delivered to the stream channel. These development activities increase water and fine sediment delivery to streams by removing vegetation cover, disturbing soils, and connecting these disturbed areas to streams through roads, ditch lines, and/or simplified ground surfaces that enhance runoff (Bilby *et al.*, 1989; Corner *et al.*, 1996; Keutzweiser and Capell, 2001). Although development activities can affect the transport of larger particle sizes (e.g. gravels and cobbles), fine sediments from sand to clay are emphasized here as they have a significant impact on instream biota but also because they can impair the effectiveness of potable water supply treatment and increase its costs (Gadgil, 1998). In addition, fine sediments are a transport vector for hydrophobic contaminants (Bábek *et al.*, 2008; Taylor and Owens, 2009).

This chapter provides 1) an overview of the effect that forestry generated fine sediment has on receiving stream biota and 2) an effective protocol for measuring fine sediment levels at forest road stream crossings. The routing and downstream accumulation of sediment from these stream crossing point sources is a management concern because it will affect stream biota and streambed composition at each of its temporary in-stream storage areas. This sedimentary cumulative watershed effect (CWE) is one of the most detrimental consequences of forest harvesting activities on a watershed. However, the CWE is difficult to assess because its effect is dependent upon the grain size being introduced, the number and size of streams that transport it, and the original sedimentary state of the streambed it encounters (Bunte and MacDonald, 1999). Further, while it may be possible to determine the change in fine sediment levels at a single point in the stream, it is difficult to determine which upstream land use activity instigated the change. Bunte and MacDonald (1999) suggest that to manage a watershed for cumulative sediment effects it is necessary to monitor for a minimum of 5 - 10 years pre-and-post harvesting because sediment transport is highly variable. However, this type of program is often considered cost prohibitive and of a longer reporting timeline than that required by many resource management programs.

The sampling protocol presented here can bridge the gap between a long-term study and the need for immediate information to address management needs. Application of the sampling protocol presented here will make it possible to designate sediment load increases to an identified activity on a site-specific basis. That is, by monitoring a representative number of sites for a specific type or set of disturbances (e.g. stream crossings or riparian harvest areas) the sediment contribution from those disturbances can be estimated within an affected watershed and modeled. Further, these data can be used to justify the modification of those practices found to contribute significant amounts of fine sediment. Although developed for the quantification of fine sediments generated by forest road use and crossing construction and/or maintenance, this protocol can be used at other types of stream crossings as well as for the collection of fine sediments for contaminant assessment.

The first section of this chapter provides an overview of forest road effects on stream sediment transport and storage regimes as well as its associated biological effects. Section 2 outlines the monitoring protocol, suggested here to be an effective tool for monitoring fine sediment deposition at forest road crossings. Fine sediment is collected using three fish habitat sampling techniques, namely the McNeil corer, gravel bucket, and infiltration bag. These techniques are not quantitatively compared but instead their effectiveness in a sampling protocol is verified through a field assessment using eight case studies from the central interior of British Columbia, Canada (Section 3). The number of samples required for each technique to estimate the magnitude of the road crossing disturbance was determined using field data as well as standard statistical formulas. The resultant protocol includes an outline of procedures that can be adapted to address objectives for a range of sampling programs from trend monitoring to impact assessment studies. Factors to consider before applying these procedures to other development activities and areas are summarized in section 4.

1.1 Forest roads and the sediment load

Forestry, the focus of this chapter, influences water and sediment delivery to streams through tree and understory removal, silviculture activities, as well as road construction, maintenance, and decommissioning. Vegetation removal decreases evapotranspiration, which can increase delivery of precipitation to the stream and thereby flow levels. Clearing vegetation can disturb soils, enhance soil erosion, and increase fine sediment delivery to streams if clearing locations are connected to streams and riparian buffers are absent (Corner *et al.*, 1996; Kreutzweiser and Capell, 2001; Litschert and MacDonald, 2009). Forest roads are also associated with direct stream contribution of sediment due to road surface erosion and sediment delivery at stream crossings (Bilby *et al.*, 1989; Fransen *et al.*, 2001; Lane and Sheridan, 2002) as well as increasing the frequency of landslides (Reid and Dunne, 1984; Fransen *et al.*, 2001; Wemple *et al.*, 2001). Forest road generated sediment can be transported along the road’s surface, in rivulets, or its ditches, where it can be delivered at stream crossings. Stream crossings were selected for study in this project because of their consistent occurrence in the literature and the ease in designating them as a point source for increased sediment levels downstream.

Roads can contribute fine sediment to streams during construction, use and maintenance as well as decommissioning. A range of literature from around the world provides insight into the magnitude of the disturbance. For example, Burns (1970) indicated that sediment loads in a harvested California basin were greatest during the road construction period although they were sustained for several years with continued harvesting. Beschta (1978) identified a 150% increase in the sediment load after road construction while Bilby *et al.*, (1989) identified that 680 of 2000 road drainage points directly contributed sediment to streams, and that most of those sites were found on first or second-order channels. Sediment loads can be highest during road construction and can contribute as much sediment to streams as landslides (Cederholm *et al.*, 1981). Close to 80% of the sediment eroded from tropical forestry landings and road surfaces was delivered to stream channels within 16 months of construction (Sidle *et al.*, 2004). Sediment generation can be highest the year after road construction (Megahan *et al.*, 2001) but roads will continue to deliver sediment throughout their active usage period. Reid and Dunne (1984) found that a highly active road contributed 130 times more sediment than lower usage roads. Road maintenance, including grading and ditchline vegetation removal, can increase soil erosion potential. Luce and Black (1999) identified a seven-fold increase in erosion from recently de-vegetated ditches compared to those where vegetation was left intact. Decommissioning of roads reduces the contribution of fine sediment to streams and the amount of fine sediment in streambeds downstream of previous stream crossings (McCaffrey *et al.*, 2007).

Once fine sediment enters the stream at road crossings it contributes to the sediment load, which refers to the amount of sediment passing one point within a stream over a given time period (Leopold, 1997). The sediment load is not equivalent to the rate of upstream erosion. Depending upon watershed characteristics including size, geology, and terrestrial-aquatic connectivity, 75% or more of the sediment eroded in a watershed can be stored in transitional areas such as the base of hillslopes, floodplains, and pools (Leopold, 1997). The sediment load generally consists of two components, namely suspended sediment that moves downstream through the water column as well as bedload sediment that moves downstream through streambed migration or saltation along the surface of the streambed (Leopold, 1997). Although these sediment forms are separated for ease of classification, there is transition between forms in streams as a response to hydrologic conditions. Suspended sediments can settle to the bedload when their settling rate exceeds the force of flow and bedload can be suspended when shear stress is sufficient to lift them off the bottom and they can stay suspended if turbulent flow is sufficient (Knighton, 1998). Accordingly, both sediment forms should be discussed when reviewing the effect of fine sediment contribution from forest roads to streams.

1.2 Biotic effects of increased fine sediment

Fine sediment delivered to streams will have an effect on all stream trophic levels, the scale of which is dependent upon the amount of sediment delivered and its retention period. Primary producers are influenced by fine sediments in suspension as well as settled fines that blanket the streambed surface. Increased water column turbidity or the blanketing action of settled fines will reduce light penetration and productivity. Benthic macroinvertebrates will also be affected by suspended and settled sediment. Invertebrate populations and community structure will respond to increases in suspended and streambed fine sediment concentrations. Fine suspended sediments can abrade invertebrates initiating a downstream migration, while increased streambed fines can decrease intergravel oxygen levels prompting their migration. Fish can be similarly affected by increased fine sediment concentration in streams and the streambed. Increased turbidity can reduce predatory abilities and physically damage the fish, for example by gill abrasion.

An increase in streambed fine sediment composition can reduce intergravel oxygen levels and negatively affect incubating eggs and young residing in the gravels.

1.2.1 Primary producers

Aquatic primary producers range in size from the easily visible macrophytes such as Canadian pond weed, *Elodea canadensis,* to the microscopic periphyton such as the diatom *Navicula*. While macrophytes often adhere to the streambed via roots, periphyton may attach to rocks, sand, or plants with gelatinous stalks (South and Whittick, 1987). Regardless of their size, all aquatic plants can be affected by increases in fluvial sediment loads. Sediment can affect plants by reducing light penetration via light reflection and absorption in the water column or by settling atop benthic forms. The decrease in ambient light as turbidity increases can decrease algal biomass and productivity unless the community is able to adjust efficiency to compensate for lower irradiance (Parkhill and Gulliver, 2002). Sediment can also physically damage plants through direct contact and if it deposits in high concentrations it can prevent attachment or may smother them (Newcombe and MacDonald, 1991; Waters, 1995; Wood and Armitage, 1997).

Davies-Colley *et al.* (1992) identified that clay additions from placer mining operations reduced the photosynthetic active radiation (PAR) depth in streams, which in turn reduced periphyton productivity. Further, they found that periphyton biomass decreased upon exposure to placer runoff and that remaining biomass had a high clay content, which made it a poor food source for stream invertebrates. King and Ball (1967) noted that road construction activities and sediment additions resulted in a 68% decrease in the stream's periphyton community. Brookes (1988) found that stands of the macrophyte *Ranunculus sp.* were smothered downstream of a channelization project during low flow because these species could not alter their rooting depth.

1.2.2 Benthic macroinvertebrates

Benthic macroinvertebrates form the next trophic levels above primary producers and their functional feeding groups range from the herbivorous scrapers to the carnivorous piercers (Peckarsky *et al.*, 1990). While herbivorous invertebrates may be negatively affected by the reduced food quality of clay laden periphyton (Suren, 2005), the following discussion focuses on direct effects experienced by all invertebrates. These include the alteration of substrate composition, instigation of drift due to sediment deposition or saltation, decreased respiratory rates due to sediment depositing on respiratory structures, feeding behaviour alterations, and direct mortality of immobile life stages (Rutherford and MacKay 1986; Wood and Armitage, 1997; Gibbins *et al.*, 2007).

A stream's benthic invertebrate community structure and density is strongly associated with the streambed substrate. Initially, it was believed that invertebrate diversity increased with increasing substrate size. This has been shown to be only true for the surface dwelling Ephemeroptera, Plecoptera, and Trichoptera (EPT) groups (Waters, 1995). Invertebrate community structure is positively affected by increased concentrations of stream detritus, which can increase oxygen exchange and act as a food source (Culp *et al.*, 1983). So, attempts to define community structure must consider streambed substrate composition as well as hydrology. Fine sediment deposition on the streambed can clog interstitial streambed spaces, which may reduce interstitial oxygen levels. Further, it can restrict the size of depositing detritus (Culp *et al.*, 1986). This alteration of the benthic environment can induce an escape or drift response from those organisms unable to cope with the change. Bedload movements and saltating sediments can also increase drift upon contact with surface dwelling invertebrates (Quinn *et al.*, 1992; Gibbins *et al.*, 2007). Culp *et al.* (1986) noted that during their controlled addition of sands to a surveyed stream channel, the invertebrate population was reduced by more than 50% within 24 hours of sand exposure as a result of catastrophic drift. Similarly, Larsen and Ormerod (2010) found that low-level and short term increases in particles less than 2 mm initiated drift and Gomi *et al.*, (2010) suggest that sedimentation of particles greater than 4 mm increases the rate of invertebrate drift.

Invertebrate feeding behaviour alteration and direct mortalities can also occur if sediment concentrations are sufficiently high. Filter feeders will not be able to effectively capture prey items in high concentrations of sediment (Waters, 1995). Immobile life stages such as pupae obviously cannot drift yet they require flowing water for oxygen exchange, so where sediment deposits are thick, exposed pupae may suffocate (Rutherford and MacKay, 1986).

Although invertebrate communities can be affected in several manners, it is important to recognize that exposure duration is equally important as the concentration of fine sediment (Rosenberg and Wiens, 1978). Most of the aforementioned studies determined that community structure and density often returned to pre-disturbance levels once the sediment wave had passed through the sample area. So, extreme but temporally short events such as a road washout may be less damaging than chronic sediment sources that are not as visibly extreme such as increased erosion from riparian or fire areas (Minshall *et al.*, 2001).

1.2.3 Fish

The majority of published studies have focused on sediment effects on salmonids because these fish are sensitive to increases in suspended fine sediment and sedimentation. Generally, fish can be affected at the behavioural and physiological levels (Waters, 1995). Behavioural responses are the first observable reactions to increased sediment and are also the most transitory. They are often a response to increased suspended sediments and include avoidance and increased cough frequency (Anderson *et al.*, 1996). Physiological responses are dependent upon life stage and the type of sediment encountered, suspended or depositing. As this chapter focuses on sedimentation those effects are discussed here.

Excess sedimentation, can affect fish populations by reducing habitat and directly affect individuals through increased egg mortalities and reduced fry emergence. Habitat alteration through increased sedimentation can result in a reduction of fish food resource and over-wintering sites due to in-filling of pools, as well as the alteration of spawning gravels (Waters, 1995; Anderson *et al.,* 1996; Wood and Armitage, 1997;). Further, increased bedload transport may result in deep scour or fill which can remove or bury eggs and fry (Montgomery *et al.*, 1996).

Scrivner and Brownlee (1989) documented a 50% decrease in coho (*Oncorhynchus kisutch)* and chum salmon (*O. keta)* populations of Carnation Creek, British Columbia, Canada following forest harvesting. They attribute this to high levels of fine gravel and sand transport resulting from increased streambank erosion and removal of large organic debris dams. Specifically, they noted that sands formed an impermeable layer within the streambed at varying depths depending upon previous storm flows. They postulated that these layers of sand isolated salmon redds and prevented efficient oxygen exchange or fry emergence.

Excess sedimentation has consistently been shown to affect fish communities but the biologically active grain size varies between studies. McNeil and Ahnell (1964) determined that spawning success of pink salmon (*O. gorbuscha)* was inversely proportional to streambed permeability and the concentration of sediment smaller than coarse to medium sands (less than 0.833 mm). Others have reported similar findings but focussed on grain sizes ranging between 0.25 and 6.4 mm (Chapman 1988; Reiser and White 1988; Lisle, 1989; Platts *et al.,* 1989).

2. Fine sediment monitoring protocol

Fine sediment concentration in the streambed is not commonly monitored possibly due to the lack of a standard sampling protocol and/or potentially onerous bulk sample volumes required to describe the substrate (Church *et al*., 1987; Zimmerman *et al*., 2005). The goal of this project was to develop a straightforward field-verified monitoring protocol for assessing road generated fine sediment input and corresponding streambed change that can be used in remote regions. Study areas near stream crossings are selected, which depending on the sampling design have one or more study sites. Within each study site multiple sample locations are identified. Prior to collecting sediment samples, study sites must be

Fig. 1. Laboratory photo of the McNeil corer, gravel bucket, and infiltration bag sampler.

described using site establishment procedures to verify site similarity for their future comparison. Site establishment includes the measurement of stream width and slope, streambed surface conditions using pebble count, discharge, and shear stress at each sampling location. The sampling design will vary depending on the program objectives but can include the before-after-control-impact design (BACI). A short discussion on pseudoreplication issues is also provided to ensure statistically valid results are generated. The sampling techniques used to assess sedimentation were the McNeil core which collects bulk samples to a depth of 30 cm in the streambed, the gravel bucket which captures settling sediment, and the infiltration bag which captures settling sediment and fine sediment moving through the streambed (Figure 1).

2.1 Site establishment

To assess fine sediment contributions from forest road crossings, study sites were established within the same stream reach to reduce environmental variability. A reach was defined here as two repeating units where a unit is composed of two habitat features such as riffle and run, or pool and riffle. Site establishment data should be collected at all sites and include measurements of active and bankfull channel width, discharge, mean depth, habitat units, gradient, pebble count, and sampler placement depth and overlying velocity at the time of sampling.

The active channel width of a stream is the horizontal distance over the stream channel between stream banks that is covered by water (Fig. 2a). Bankfull width is the channel width where water would just begin to spill into the active floodplain (Fig. 2b, Platts *et al.*, 1983). Bankfull indicators include changes in streamside vegetation, slope, bank material, undercuts and stain lines (Harrelson *et al.*, 1994). Measurements of these two parameters should be collected at a minimum of five points along the sample reach.

a) b)

Fig. 2. Identifying the a) active channel width and b) bankfull channel width.

Discharge data was collected at each site using the midsection velocity-area method which measures velocity for 40 seconds at 10-20 evenly spaced locations along a relatively flat channel cross section selected downstream from the sample area. Care was taken to ensure there were no obstructions to interfere with flow measurement. When water depths were less than 1 m, a single velocity reading was taken at 60% of the depth but when depth exceeded 1 m, readings were taken at 20% and 80% (Mosley and McKerchar, 1993). Discharge was calculated for each section and then summed for the channel. The mean stream depth value can be determined from the average of the depths collected during the velocity readings.

The study area was sketched in field notes with specific attention to fish habitat features (e.g. pool, riffle, woody debris, dams, etc.) and streambed sample locations. The sketch is recommended because it may be required at a later date to determine if the study area consisted of one or more reaches and to evaluate the similarity of sample replicate sample locations between and within sites. Channel gradient was measured with a clinometer but an Abney level would also be appropriate. To measure gradient, field staff positioned themselves at a distance greater than the channel width apart along the stream's edge. The clinometer was sighted from one staff to the other at the same distance from the ground. A minimum of five measurements were collected and then averaged to determine the mean channel gradient.

The streambed surface sediment was characterized using a pebble count (Leopold *et al.*, 1992). Counts were conducted at several cross-sections in the sample reach to ensure that representative portions of each habitat unit were sampled. Starting at bankfull elevation, the sampler blindly reached to their left or right foot. The first particle that was touched was removed and the intermediate axis, or width, of the particle was measured and recorded by the second staff member on a tally sheet that was divided into grain classes defined by the Wentworth Scale. The sampler then moved a standard step distance and selected another pebble at the top of the same foot used in selecting the first pebble. This continued until a minimum of 100 pebbles was counted. The pebble count procedure is widely used to assess surface sediment composition by regulatory agencies and researchers alike (Bevenger and King, 1995; Bunte *et al.*, 2009)

Overlying water depth and velocity was measured at each sample location for each technique applied. Flow measurements associated with infiltration bag and gravel bucket locations should be collected when the sampler is installed in the streambed and then again before it is removed. This information can be used to assess shear stress conditions at each sample location and to ensure that sample replicate sites are comparable within and between sites both during and over the sampling interval.

2.2 Bulk sampling: McNeil corer

Since its development in 1964, the McNeil corer has become a commonly applied technique for assessing spawning gravel composition in streams because it was a significant improvement over the previously applied techniques of visual observation or shovel sampling (McNeil and Ahnell, 1964; Schuett-Hames *et al.*, 1994). The McNeil core provides a quantitative and repeatable sampling method (McNeil and Ahnell, 1964). McNeil core samples are measures of bulk streambed composition that are collected by inserting the core tube into the streambed and removing all sediments within the tube (Fig. 3). The tube is inserted into the streambed by torquing the corer while keeping it level using the handle on top of the basin or on the sides of the basin. These handles also help staff to keep the corer from rocking during the sampling process, which would disturb the fine sediments. Once the core tube has been fully inserted, the sample is removed from the tube by hand and transferred to a sample bucket until the end of the core tube is reached. The McNeil core has been used to quantify increased fine sediment loading downstream from industrial activities such as coal mining operations (MacDonald and McDonald, 1987) and roads (Hedrick *et al.*, 2007).

The corer design recommended here differs from the original design identified in Figure 3. The original design was modified because it was both heavy and expensive to construct. The modified version was made with heavy gauge aluminum rather than stainless steel, which made it considerably lighter and inexpensive to construct. In addition, it is larger than the original, standing 0.9 m (vs. 0.45-0.6 m) tall with an outer basin diameter of 0.6 m, and the coring tube which is equipped with a replaceable ring of steel teeth, is 0.2 m in diameter and can penetrate the streambed to a depth of 0.25 m (Fig. 1). Finally, the core handles were placed on the sides of the outer basin and not along the top. Another modificiation recently presented by Watschke and McMahon (2005) is lighter still because it uses a 19 L plastic bucket as the basin instead of aluminum.

The sample procedure was also altered. The original technique required sampled sediments to be brought up through the core tube and placed in the basin. Remaining fine sediments in the tube that were kept in suspension by infiltrating water were removed by a single valve pump or the tube was capped which created a vacuum that allowed trapped water to be lifted from the stream and placed in a bucket. For this program, sampled sediment was transferred directly to a clean 4 L bucket. Also, rather than pumping out sediment laden water, the water level within the tube was measured for later volume calculation, it was then mixed to suspend settling fine sediment and a 1 L water sample was taken. This 1 L sample was analyzed for suspended solids using standard techniques (APHA, 1995) that also allowed measurement of organic and inorganic fine sediment fractions. The mass of suspended solids (SS) was calculated using the concentration of SS and the volume of water in the tube. This data was then added to silt/clay fraction measured during screening of the bulk sample.

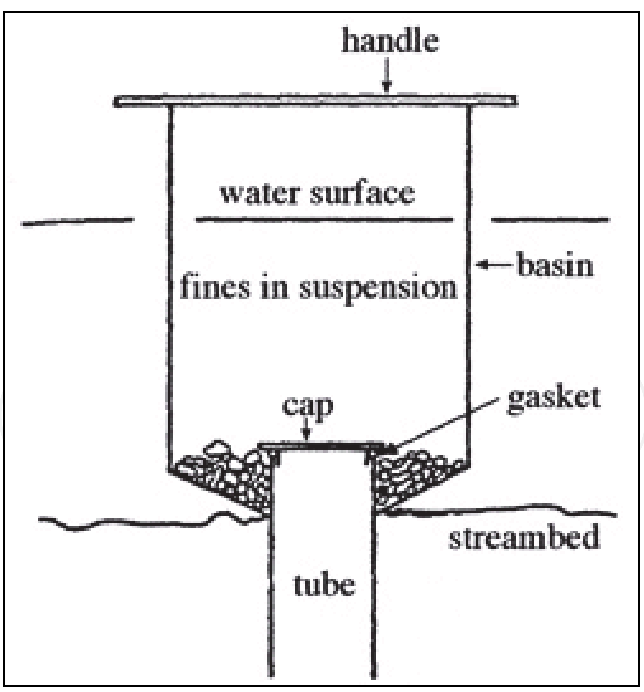

Fig. 3. The original McNeil-Ahnell corer design (McNeil and Ahnell, 1964).

McNeil core samples were collected from riffle areas near pool tail-outs as follows:

1. Sample locations were approached from a downstream direction so as to not step over the sample area prior to coring.

2. Field staff faced upstream and positioned their body over the corer and placed their hands on the handles (Fig. 4).
3. The corer was kept perpendicular to the streambed as field staff turned the corer into the streambed being careful not to use a rocking motion.
4. Once the corer was fully driven into the streambed staff checked to ensure the basin was flush to the streambed.
5. The core sample was removed by a hand to a standard depth, the top of the ring of teeth.
6. Sediment was rinsed off the sampler's hand into the bucket and a 1 L water sample from a core tube was collected to determine the mass of fine sediments.

Fig. 4. McNeil core sampling location approached from the downstream direction. The sample is taken by leaning over the core and forcing it into the streambed until it is flush.

2.3 Sediment traps: Gravel buckets and infiltration bags

2.3.1 Gravel buckets

Gravel buckets are sediment traps used to measure deposition onto and infiltration into the streambed (Fig. 5). It is not a commonly referenced sampling technique but the bucket size used and recommended here is consistent with that of Lisle and Eads (1991) as well as Larkin *et al.* (1998). These samplers consisted of a 4 L hard plastic bucket filled with washed and screened gravel from the hole dug for its placement. The screen used to remove fine sediment is the choice of the program manager but we recommend a minimum of 2 mm screen to remove sand and finer sediment from the cleaned gravel. If field collected gravels are not used and instead the sampler wants to use a standard experimental gravel, we recommend using a cleaned angular gravel with a 1.8 cm intermediate axis because it more effectively traps fine sediment than circular gravels at velocities greater than 0.4 m/s (Meehan and Swanston, 1977).

Gravel buckets can be placed in McNeil core sample locations once the core is extracted or they can be installed in runs with a stream depth less than 30 cm. Once sites are chosen, install and collect gravel bucket samples as follows:

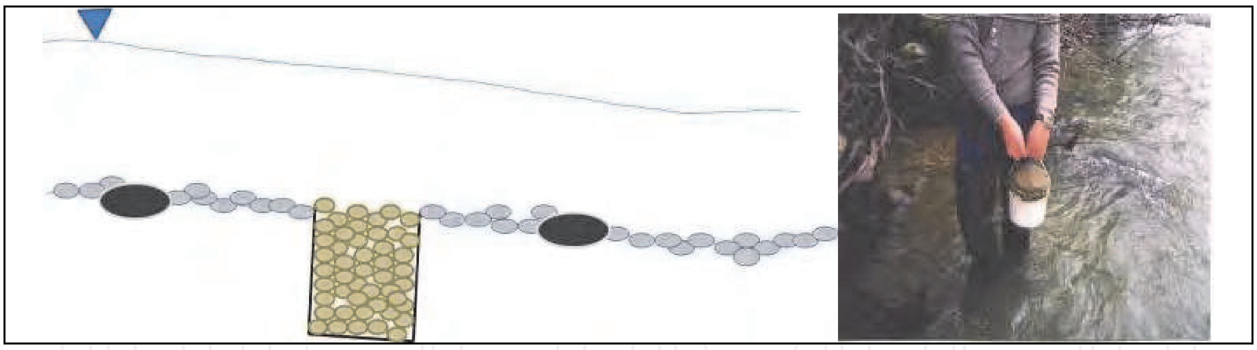

Fig. 5. Gravel bucket schematic showing flush placement with streambed (modeled after Lisle and Eads, 1991). Inset photo is a field image of an overfilled gravel bucket.

1. Identify sample locations by measuring water depth and velocity to ensure comparability between sites and locations.
2. Starting upstream, dig a hole to the approximate depth of the gravel bucket (~20 cm for 4 L buckets). Larger material should be placed to the side to refill vacant areas around the bucket once installed. If using stream sediment, screen materials to remove smaller sizes (e.g. the < 2 mm or if preferred a larger sieve size i.e. 6.3 mm).
3. Place the sealed and filled bucket level and flush to the streambed.
4. Re-measure velocity and depth to ensure replicate site similarity.
5. Move downstream to install the next gravel bucket sampler.
6. Once all upstream sampling is complete and suspended sediment generated by bucket installation has been flushed downstream or settled out, the gravel bucket lids can be removed by staff in a downstream direction. Once the final lid was removed field staff exited the channel below the last bucket.
7. During the retrieval visit, staff should enter the stream below the last bucket and replace gravel bucket lids in an upstream direction.
8. Once lids are replaced, measure the overlying depth and velocity to determine change since installation.
9. Remove buckets in an upstream direction.

2.3.2 Infiltration bags

Infiltration bags measure the amount of sediment moving vertically and horizontally through a streambed. The bags are a modified form of the wire basket retrieval system presented by Sear (1993). To prevent the loss of fine sediments when removing openwork wire baskets, Sear placed them in a collapsed polyethylene bag that was forced open with a foam collar. The bag was lifted up over the basket prior to basket removal and it prevented the loss of 26 to 40% of the collected sample. This technique has been successfully used by many including Heywood and Walling (2007) who documented sedimentation in Atlantic salmon (*Salmo salar*) redds and Petticrew *et al.*, (2007) who identified that this technique captured more fine sediment than natural gravels following a reservoir flood wave release. The infiltration bag is conceptually similar to these techniques but does not have the wire mesh or foam collars.

The infiltration bag is a waterproof fabric bag that is approximately 20 cm in diameter and 35 cm long (Lisle and Eads, 1991). It is attached by hose clamp to a brightly coloured steel ring that is also 20 cm in diameter. The bag is collapsed into the ring and is buried to a depth of 30 cm in the streambed (Fig. 6). The bag can be removed from the streambed by hand or a winch/pulley that hooks onto lines extending from the buried steel ring.

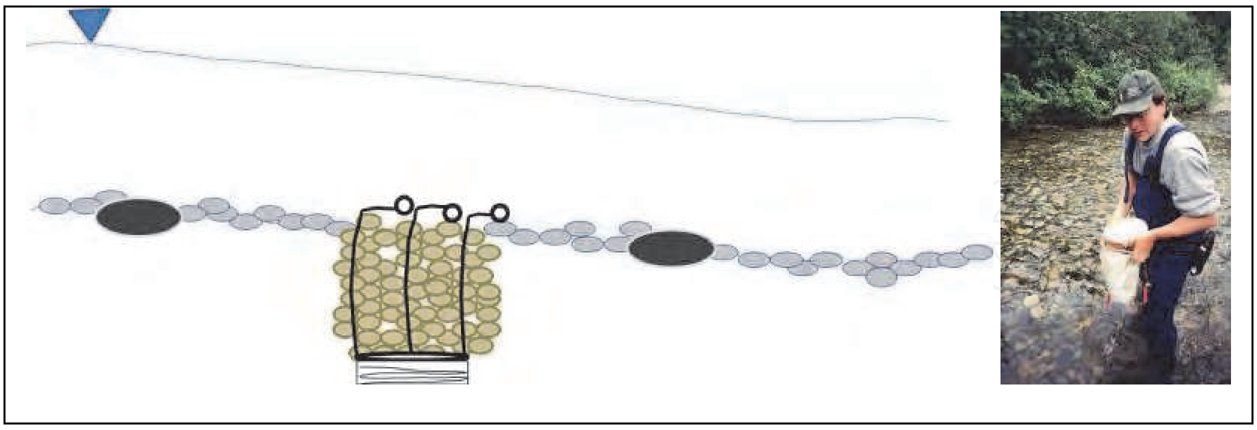

Fig. 6. Infiltration bag is shown collapsed within the steel ring and recovery lines are shown extended to the streambed surface. Inset photo shows a bag after removal from streambed.

Infiltration bags were placed in shallow runs that were less than 30 cm deep. Following the site selection process, infiltration bag samples were deployed and collected as follows:

1. Infiltration bag sites were excavated as staff moved in a downstream direction so that any suspended sediment generated by this disturbance would move downstream of the sample area.
2. Holes were dug to a depth of 35 cm and a width of 30 cm. This provided ample room for the steel ring and incorporates the 30 cm depth typically referred to in the literature for salmonid redds.
3. The collapsed bag was placed into the bottom of the hole and the reference gravel was poured into the hole until it was level with the surrounding streambed. When backfilling was a problem, a sheet metal sleeve was used to support the streambed walls during placement of the bag and reference gravel.
4. The recovery lines were held by hand so they remained on the surface after the reference gravel was poured.
5. Staff then moved downstream to the next bag.
6. To retrieve bags the sites were approached from downstream. The lines were located and attached to the winch/pulley system.
7. The bag was brought to the streambed surface and then capped with a 4 L gravel bucket lid so that upon removing it from the stream bed the overlying water was not sampled.
8. The sample was transferred to a 4 L bucket for transport. The bag was rinsed and re-deployed.

2.4 Grain size analysis

Samples can be pre-sieved in the field to remove larger grain sizes such as reference gravel or transported to the lab whole for gravimetric analysis. Case study samples were sieved using a 16, 9, 6.3, 4.0, 2.8, 2.0 mm and 500, 250, 125, 63 μm sieves. Particles above 9 mm were not included in the analysis because the focus of the study was fine sediment < 6.3 mm. Lab procedures included the following:

1. Sediment was removed from the sample container by inverting it onto a drying tray lined with a pre-weighed plastic sheet. A wash bottle was used to rinse fine sediments at the bottom of the pail and wash them onto the tray. The sample was spread in a thin layer to promote drying.
2. After the sample was air-dried to a constant weight, the weight of the air-dried sample was taken. It was corrected for the weight of the plastic sheet.
3. The sample was placed in portions in the top sieve of a stack consisting of 6.3, 4.0, 2.8 and 2.0 mm pre-weighed sieves and a bottom pan. Dry sieves were shaken by hand until particles no longer pass through to the next sieve. Each sieve was then removed and weights were recorded (corrected for sieve weight).
4. The sample collected in the bottom pan from step 3 (the 'minus 2 mm fraction') was then moved in portions to a stack containing a 500, 250, 125 and 63 μm cleaned sieves. These samples were wet sieved. The portions were limited to a maximum of 50 g because any larger may have caused the sieves to become overloaded or clogged. Sieves were often checked to ensure they were not being clogged.
5. Once the wash water ran clear the sieves were removed one at a time (i.e. from coarse to fine) and the captured sample was transferred to a pre-weighed aluminum dish. The contents were then oven-dried at 105°C. The sample weight was corrected for aluminum tray weight and recorded.
6. Because the < 63 μm (silt/clay) fraction is lost during washing it was determined by subtraction of the larger fraction weights from the total "minus 2 mm" sample weight.
7. Once tabulated, grain size classes were named according to the Wentworth size class system (Bevenger and King, 1995)

These data can be tabulated as percent less than, percent retained on sieve, and sample weight retained on each sieve. The percent retained on the sieve and those sample weights should be used in the analysis. Percent retained on sieve data can be renamed percent composition and was used for the analysis of McNeil core data because it provides a measure of streambed composition. Weight data was used for the traps because it provides a measure of sediment loading.

2.5 Study design, pseudoreplication, and data analysis

The study design selected by individual users will vary based upon the intent of the monitoring program. The case study program presented here was a compliance monitoring program (MacDonald *et al.*, 1991) to assess the effect of stream crossings on water quality. The impact-control study design was used with paired sample sites above the crossing for control and downstream of the crossing for treatment. The impact control design is a response-based study design used when the activity has already occurred but the BACI approach is recommended if temporal control samples can be collected (Manly, 2001). Findings generated from either design can be strengthened if more than one site is sampled in the control and treatment areas. Single sites were used here, but samples were collected more than once which enhances the impact-control site comparison because it can show the magnitude of the impact (Manly, 2001).

Pseudoreplication refers to the use of data drawn from studies where treatments are not replicated or replicates are not statistically independent (Hurlbert, 1984). Using replicates that are not independent artificially increases the sample size and enhances the potential for Type 1 error. Accordingly, each set of McNeil core, gravel bucket, and infiltration bag samples taken in each time interval may be considered correlated and therefore not independent or true replicates. To address this concern, we recommend that an analysis of variance (ANOVA) of mean values for each sample set be conducted. This approach was applied for case study findings where more than one data set was collected for a given technique. For example, mean values for each grain size collected with McNeil cores during each of two trips were computed. The mean values for each grain size over the two trips were grouped by site, yielding two sets of values for each grain size and location. An ANOVA of these values provides results free of pseudoreplication effects (Manly, 2001). However, this analysis was not applied across all case studies because some did not have more than one sample set.

Generally, there are two approaches for interpreting sediment data, the first is to use the raw data and the second is to generate central tendency measures. Raw data measures incorporate each grain size's weight or percent composition while central tendency measures attempt to reduce all grain size information to one number that best describes the entire particle size range. Central tendency measures include the Fredle Index, geometric mean diameter, and median particle size D_{50} (Waters, 1995; Platts *et al.,* 1983). The goal of the case study program was to quantify inputs of fine sediment from crossings so raw data was used, however when the study goal is to describe streambed composition, a wider range of raw data and/or central tendency measures may be more appropriate.

Prior to conducting a statistical analysis, the data were viewed graphically to allow for the determination of normality, designation of outliers, and to assess the potential for significant differences. Normality is a standard assumption of the parametric statistics applied and required confirmation. Data outliers were viewed in light of site establishment data to see if stream conditions at the sample location could explain data values. For example, did an outlying sample have higher or lower overlying water velocity than the other samples? Finally, by plotting sample means and their 95% confidence intervals the potential for significant differences was assessed.

Percent composition data for the McNeil core are not normally distributed. To normalize percent data arc-sin transformation was used (Sokal and Rohlf, 1995). Raw weight data for gravel bucket and infiltration bags were normally distributed and did not require transformation. To determine the presence of significant differences between sites a two-way ANOVA was applied using site and grain size as factors. Here site has two categories, identified by namely up and downstream while grain size has seven categories ranging from fine gravel to silt/clay. Tukey's post-hoc comparison or *honestly significant difference* (HSD) procedure was used to identify grain sizes that were significantly different between sites when a main effect (site difference) was observed (Sokal and Rohlf, 1995). If there was a significant interaction effect, that indicated a relationship between the two factors, i.e. grain size composition is influenced by site. Differences were identified by reviewing graphs and conducting individual t-tests, however Bonferroni adjustment should be applied to lower the risk of committing a Type 1 error if several t-tests are applied.

2.6 Sample numbers

Bulk sample estimates such as the ISO approved standards (Church *et al.*, 1987) can be used for the McNeil corer but these standards are not applicable to the trap techniques or the gravel bucket and infiltration bag. To determine the effective sample size for these techniques a short sampling program was conducted in three creeks of increasing size (5, 9, and 11 m) after the case studies were complete. Effective sample size is defined here as the number of samples after which there is limited gain in precision.

Twelve McNeil core and gravel bucket samples and 10 infiltration bag samples were collected from each stream. These sample numbers, 12 and 10, were selected because they exceeded the numbers collected during the eight case studies and also exceeded those numbers observed in the literature for McNeil coring (MacDonald and McDonald, 1987; Schuett-Hames *et al.*, 1994) and infiltration baskets (Heywood and Walling, 2007; Petticrew *et al.*, 2007). Also, the impetus of this project was to develop a protocol that will be widely used and sample numbers higher than these would likely hamper the application of this protocol in remote areas because sample weights would be too heavy to return to the lab.

2.6.1 Coefficient of variation approach

The data were subdivided into clusters ranging from 4 to 12 samples based upon similar site depth and overlying velocity. These two parameters were chosen because they are easily measured in the field and they have a substantial effect on settling environment (Knighton, 1998). Coefficients of variation (CV) were then calculated for each grouping. The CV expresses the standard deviation as a proportion of the mean (Sokal and Rohlf, 1995). As sample numbers increase, the mean and standard deviation change as does the CV. The CV is used here to represent changes in precision. Specifically, this exercise focuses on finding the sample number where the CV stabilizes. The effective sample number, defined here as that number of samples after which precision gains are small (i.e. < 5%), was determined for the three streams. The weight of sediment deposited at each site as measured by the given technique was then included in these ranked tables (e.g. Table 1) and clusters were formed starting with the largest number of similar values. For example, in Table 1 six samples have a water depth of 8 cm to represent the first cluster (CV=18.9%). The second cluster is identified by including the maximum number of samples of the depth that is most similar to the original cluster. In this case the two samples with depths of 9 cm were included (CV=16.3%). The third cluster now incorporates the single sample at 7 cm because it is more similar to the original cluster than the samples at 10 cm (CV=17.1%). The final cluster includes all samples and it has a CV of 18.4%. Note that the change in CV from six to twelve samples is less than 3%. Very little precision appears to be gained by increasing sample numbers but eight is chosen as the effective sample number because it has the lowest CV.

The results of the clustering CV analysis show the importance of maintaining similarity in site selection. Increased sample numbers are expected to improve the accuracy of the mean and the variation around the mean. However, in some cases the smallest CV was found with the lower sample sizes, which also had the narrowest range of water depth and velocity. This potentially reflects the magnitude of the change of the controlling variable used for clustering (i.e. 6 samples from the same water depth versus 9 samples that incorporate 3 depths). As depth and velocity are important controlling variables for sediment deposition it is best to maintain equivalent conditions for all replicates. This is clearly not always possible and therefore results in natural variability. The range sampled here was not expected to generate large differences but may be affecting the variation. Generally, most sample sets returned data with low variability (CV of 8-30%) with the exception of the largest creek (Young's at 11.6 m wide) where CV values were generally above 30%. Trapping techniques generally showed higher variability as measured with the CV than the McNeil core (Table 2).

Sample Identifier	Sample Depth (cm)	Sample Weight (grams)	Clusters of Samples
10	7	70.6	
9	8	74.4	
4	8	124.8	
11	8	89.7	6
3	8	81.3	8
5	8	85.2	9
1	8	78.1	12
2	9	90.4	
6	9	92.8	
12	10	76.9	
7	10	94.7	
8	10	122	
		Cluster CV	18.9(6) 16.3(8) 17.1(9) 18.4 (12)

Table 1. Gravel bucket data grouped by sample depth for the 5 m wide creek.

Sample Technique	5 m	9 m	11 m
Gravel Bucket	8 (12)	9 (13)	10 (25)
Infiltration Bag	4 (23)	8 (36)	10 (38)
McNeil Core	6 (18)	8 (24)	10 (24)

Table 2. Recommended sample number for each sample technique by stream width (CV in brackets).

2.6.2 Formula-based sample size estimates

Another approach to determine sample size was used for comparison to the sample estimates from CV alone. Sample number estimates were calculated using the following formula from Sokal and Rohlf (1995):

$$N \geq 2\,(\sigma/\delta)^2\,\{t_{\alpha\,[v]} + t_{2(1-\rho),\,[v]}\}^2 \quad (1)$$

Where: N = sample number
σ = true standard deviation (approximated)
δ = smallest true difference desired to detect
t = t-distribution
v = degrees of freedom of the sample $\sigma_{approx.}$
α = significance level
ρ = desired power (i.e. probability a difference is found if it exists)

Example Calculation for Gravel Buckets in a 4 m wide stream:

Gravel Buckets
CV = 7.6% for 9 replicates
We want to detect a 20% difference 90% of the time.
$v = 2(9-1) = 16$, $\sigma_{approx} = 7.6\ Y/100$, 20% difference is $\delta = 20Y/100$
$N \geq 2\,(7.6Y/100\ /\ 20/100)^2\,\{t_{.05\ 16} + t_{.2\ 16}\}^2$
$N \geq 2\,(7.6/20)^2\,\{1.746+1.34\}^2$
$N \geq 2.74 \sim 3$ samples

To confirm 3 is correct, re-calculate equation 1 using 3 rather than 9 replicates, which gives an answer of 5.35. When 5 is used the answer is 4, so 4 is a good approximation.
The formula based sample number requirements were typically much larger than those generated using CV alone (Table 3). As with most equation based sample estimates, these numbers ensure statistical requirements are met, i.e. in our example the ability to detect a 5, 10, or 20% difference 90% of the time (Equation 1). Note that the statistical formula approach does not consider environmental limitations. For example, can and should you collect 250 gravel bucket samples in an 11 m wide creek? The availability of similar sampling sites is implicit within the CV analysis.
The difference between the CV and formula based sample estimates can be explained. First, the CV analysis looks at the decrease in variability with increased sample numbers (based on clusters) with an upper limit of 12 samples. So, if the lowest CV is 25% at 8 replicates, this is the best sample number within the possible sample size of 12 replicates despite the high variability. Although this seems a shortfall of the method, seven of the eight case studies saw a significant difference between sites when using less samples than suggested by the CV analysis for those people interested in using the formula based approach we suggest that the 20% detection limit is most relevant as other studies have focussed on quantifying this level of difference between locations (Rood and Church, 1994).

	5 meter			9 meter			11 meter		
Detectable Difference	**20 %**	**10%**	**5%**	**20 %**	**10%**	**5%**	**20 %**	**10%**	**5%**
Gravel Bucket	4	14	56	9	40	75	250	986	1972
Infiltration Bag	30	115	450	46	176	684	83	306	1227
McNeil Core	12	43	146	11	39	143	28	108	421

Table 3. Calculated sample numbers for each technique assuming a 90% chance of finding 20%, 10%, or 5% differences between sample sites.

2.7 Case study site description

The eight sites selected for case study were located within the central interior of British Columbia in the Prince George, Vanderhoof, and Mackenzie Forest Districts (Fig. 7). All streams were fish-bearing systems with active channel widths ranging between 4 and 12 m (Table 4).

Stream	Channel Width (m)	Activity
Spruce Creek	9.0	Ditch Erosion
Government Creek	8.0	Bridge Construction
Youngs Creek	11.6	Historical Crossing
Nithi River	4.5	Bridge Construction
Big Bend Creek	7.0	Bridge Construction
Cluculz Creek	5.0	Culvert Replacement
Greer Creek	7.0	Bridge Construction
Mugaha Creek	10.0	Bridge Washout

Table 4. Summary information of the eight case studies.

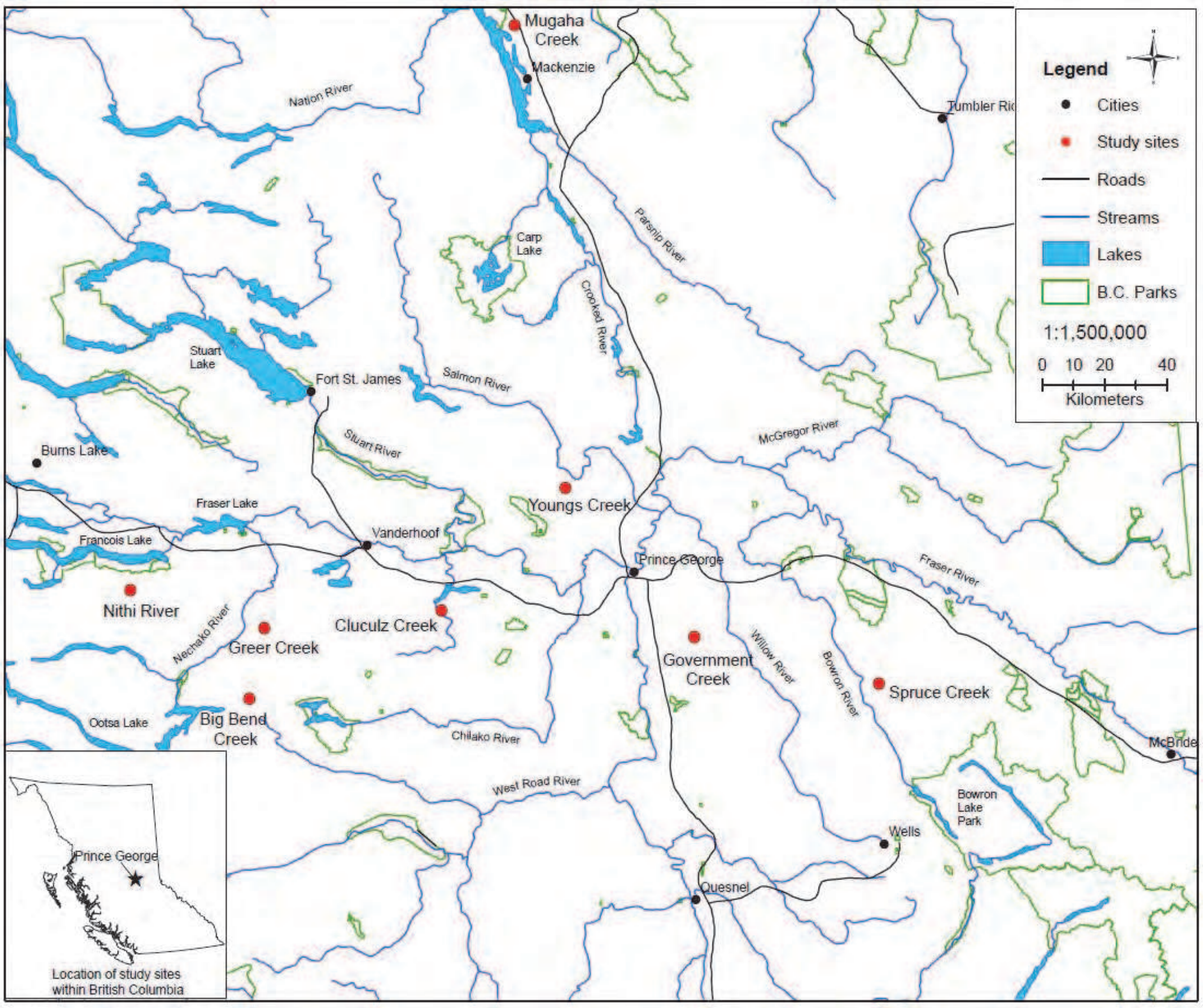

Fig. 7. Location of the eight case study sites in the British Columbia central interior.

3. Case study results

Seven of the eight case studies had significantly higher levels of fine sediment depositing downstream of the selected forest road activity for one or all of the techniques used (Table 5). The Greer Creek study did not show a significant increase in fine sediment downstream of bridge construction. This is likely the result of a decrease in discharge during our study period and the application of sediment control measures by the construction crew, which consisted of hay bales and geo-textile. For brevity the complete findings from each of the creeks will not be presented, instead details will be presented for one study site, Cluculz Creek.

3.1 Case study example: Cluculz Creek

Cluculz Creek is a 5 m wide fish bearing stream in the Vanderhoof Forest District. Its fisheries population includes the Kokanee salmon (*Oncorhynchus nerka)* and rainbow trout (*O. mykiss*). This site was selected because the crossing was undergoing road improvements consisting of culvert replacement and channel bank revetment. The culverts had repeatedly failed to accommodate spring flows often resulting in a road washout. So, the culverts were

being replaced and the channel bank was being reinforced with boulders to direct flow through the new pipe arch (Fig. 8).
The culvert replacement was a large scale disturbance to Cluculz Creek below the crossing. Baseline samples were collected on July 25 and the construction activities occurred between August 15-21. The creek was redirected through a temporary channel for several hours on August 18 while the culverts were pulled out and the pipe arch was installed. Construction period samples were collected with gravel buckets. Post-construction samples were collected with some or all techniques on September 23, October 22, and November 16. Construction activities were found to cause a significant increase in fine sediment depositing downstream of the road crossing for the total period.

Study Area	Technique	Sample Number per Visit	Results
Big Bend Creek	McNeil Core Gravel Buckets	4 and 6 4 and 6	Higher sand downstream Higher sand and clay downstream
Cluculz Creek	McNeil Core Gravel Bucket Infiltration Bag	3, 4, 6, and 6 4, 6, and 6 4 and 4	Higher sand and clay downstream Higher sand and clay downstream Higher very fine gravel upstream
Government Creek	McNeil Core	3	Higher sand downstream
Greer Creek	McNeil Core Gravel Bucket	4 and 6 4	No site differences No site differences
Mugaha Creek	McNeil Core Gravel Bucket Infiltration Bags	6, 6, and 6 6 and 6 4 and 4	Higher sand downstream Higher sand downstream Higher sand downstream
Nithi River	McNeil Core Gravel Bucket	3 and 4 4	Higher sand downstream No site differences
Spruce Creek	McNeil Core Gravel Bucket	6, 6, and 6 6 and 6	No site differences Higher sand downstream
Young's Creek	McNeil Core Gravel Bucket Infiltration Bag	3, 4, and 6 4 and 6 3	Higher sand downstream Higher sand downstream No site differences

Table 5. Sampling technique, sample number per visit, and a result summary for each of the eight case studies.

The most dramatic increase at the downstream site was observed for the construction period bucket samples, which were retrieved on August 21 three days after the creek was redirected. Bucket sample weights for each grain size were up to threefold greater at the

a)

b)

Fig. 8. Upstream view of Cluculz Creek showing a) two culverts and channel before construction and b) post-construction pipe arch and bank revetment.

downstream site (Fig. 9). Although this signal response is clearly shown in the gravel bucket samples, it is interesting to note that a similar response was not identified for the McNeil core samples. An important aspect of the sampling protocol is identified in these results because the lack of correspondence between techniques may have nothing to do with their

sensitivity but instead be a function of operator bias and/or the specific sample location. That is, the first gravel buckets were installed in McNeil core sampling locations during the July baseline 25 visit (pre-construction sampling date). Upon our return on August 21, the streambed in this area had changed from its original charcoal grey colour to tan as a result of the high amount of sediment deposited in the area. Despite this obvious increase in deposited sediment, McNeil core samples were not collected there because that area was sampled during the previous visit. Instead, samples were collected downstream of the buckets, outside of the high deposition area.
McNeil core data showed a significant difference in the sand and silt/clay fractions between the up and downstream locations four and ten weeks after the culvert replacement (Fig. 10 and 11) as the sand moved along the bed downstream from the originally effected area due to increasing fall flow volumes.

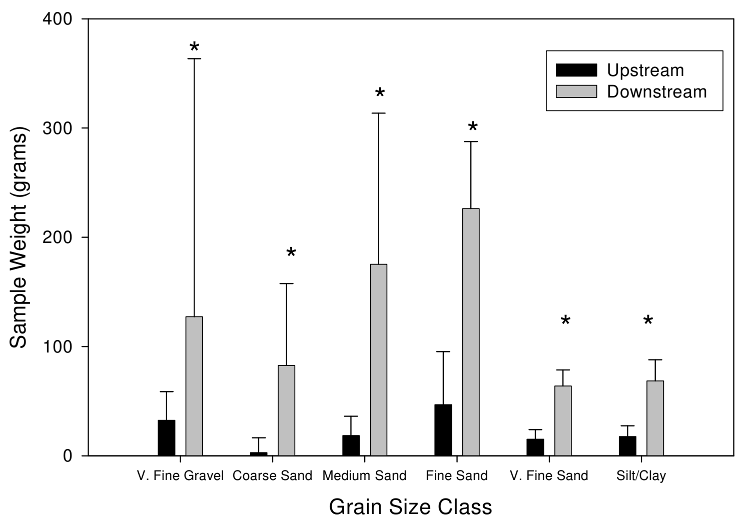

Fig. 9. Gravel bucket mean weights and their upper 95% confidence limits from samples collected at Cluculz Creek during the construction period. An asterisk highlights those grain sizes where there is a significant difference between sites.

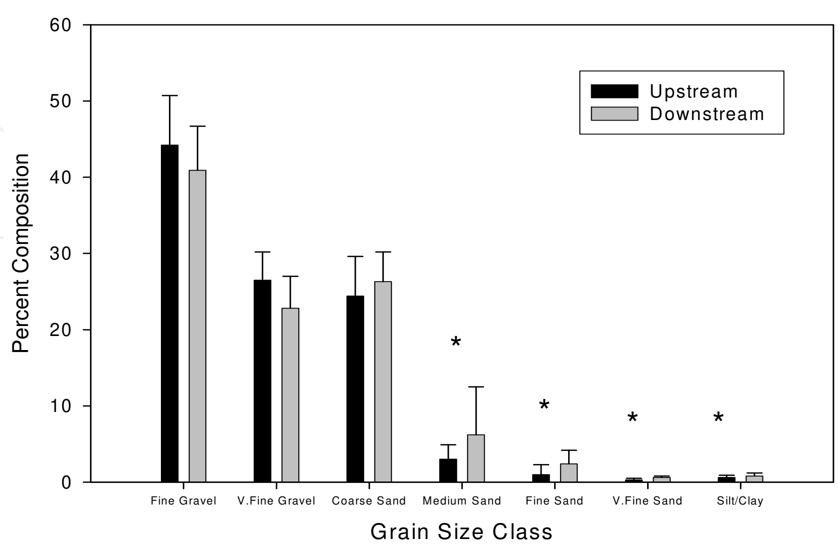

Fig. 10. McNeil core sample means and their upper 95% confidence limits five weeks after culvert replacement at Cluculz Creek. Asterisks highlight significant differences between sites.

Some of the gravel bucket and infiltration bag samplers were lost at the downstream site during October as a result of high flows. Neither the buckets nor bags show a significant difference between sites, possibly due to the low number of samples at the downstream site. Six gravel buckets were used for sampling, whereas eight are recommended for this stream width (Table 2). Eleven weeks following construction, buckets show that the crossing was still acting as a sediment source for the sand and silt/clay fractions (Fig. 12). Although the infiltration bag samples for November 16 captured higher sands and silt/clay at the downstream location, the difference was not statistically significant but it does point to an increase in infiltrating fines at that site (Fig. 13).

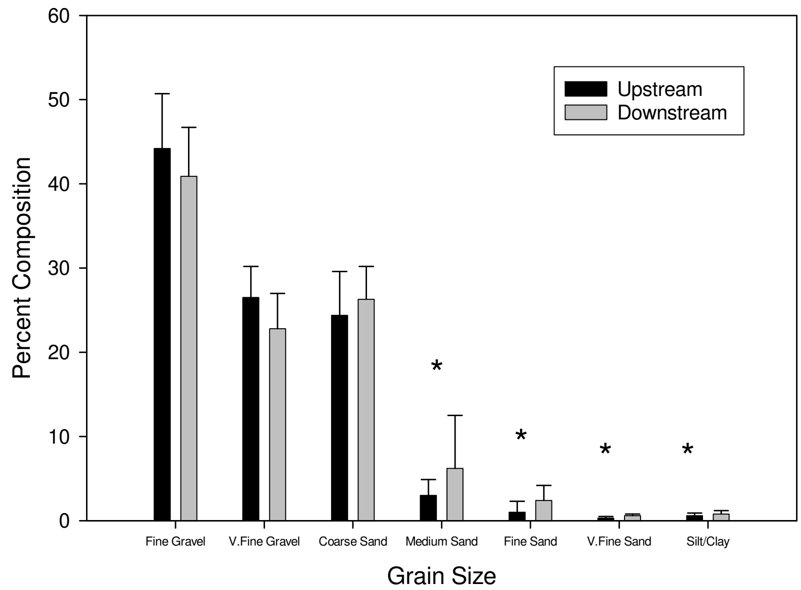

Fig. 11. McNeil core sample means and their upper 95% confidence limits 11 weeks after culvert replacement in Cluculz Creek. Asterisks highlight significant differences between sites.

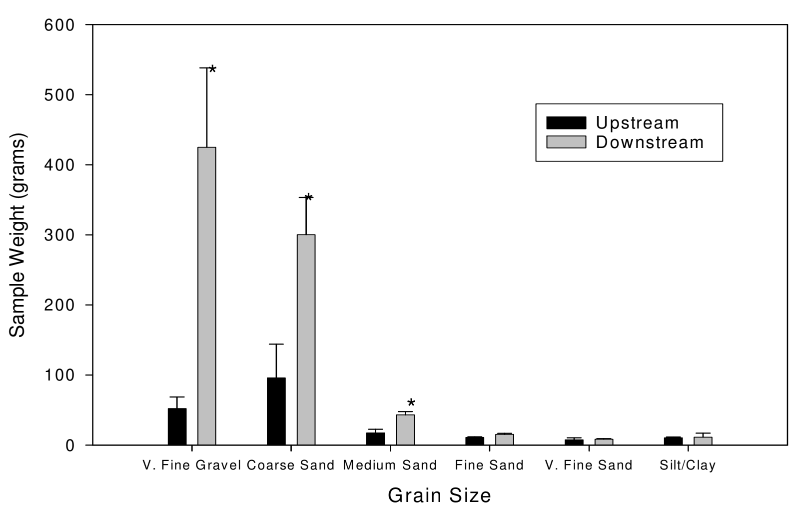

Fig. 12. Gravel bucket sample means and their upper 95% confidence limits for November 6 (11 weeks after culvert replacement in Cluculz Creek). Asterisks highlight significant differences between sites.

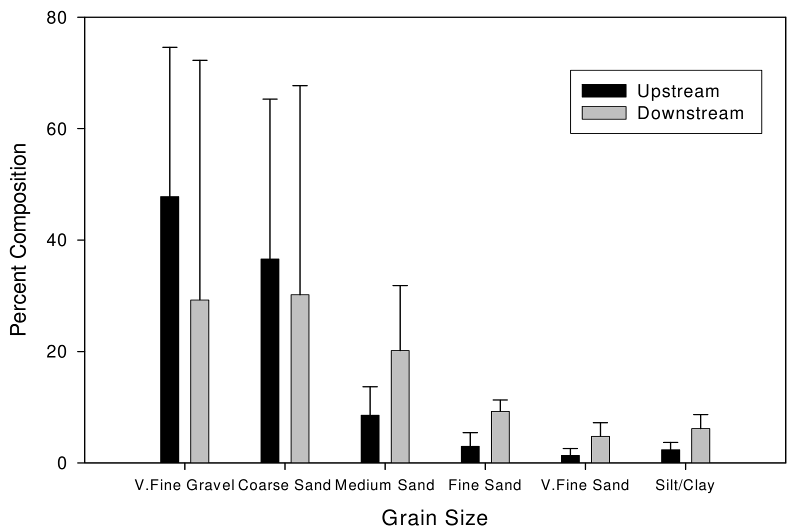

Fig. 13. Infiltration sample bag means and their upper 95% confidence limits for November 6. (11 weeks after culvert replacement on Cluculz Creek)

4. Discussion

The objective of this project was to design and evaluate a sampling protocol to quantify increases in the storage of fine sediments downstream of forest road construction and maintenance activities. Forest roads were highlighted in this study because they are the predominant type of unpaved road within the central interior of British Columbia. The study results confirm that the protocol described here is capable of detecting these increases. One or all of the techniques employed were able to detect significant increases in the fine sediment concentration for seven of the eight case studies presented.

It is suggested that this protocol would be useful for investigating unpaved roads used for other activities including agricultural development, oil and gas exploration, or mining. The latter, may be of particular interest because of high vehicular weight and traffic over wet and dry seasons during the mine's operating life. Mine haul roads support traffic with vehicular weights upwards of 290 tons and deterioration of the road can be accelerated by high traffic volumes and wear-resistance of road materials (Thompson and Visser, 2006).

Observations gathered during this study complement the literature, which often highlights unpaved roads as a major contributor of sediment to streams. Sediment delivery pathways include road and ditch runoff during road construction or following significant road bed deterioration (Cafferata and Spittler, 1998). Beschta (1978) demonstrated that road construction activities increased sediment load to a magnitude similar that of mass wasting in coastal Oregon streams. Bilby *et al.* (1989) determined in their study of a southwestern watershed that 34% of surveyed road drainage points entered streams directly. Further, in most cases fine sand (< 0.25 mm) was delivered to the streams by these roads but as gradient increased there was a shift to the larger grain sizes of sand. Sediment contribution from roads may vary based upon particle size composition of the road, with roads composed of finer sediment contributing more sediment from surface erosion. Turton *et al.* (2009) calculated that 35% of the sediment yield from Stillwater Creek, Oklahoma was generated from sandy loam to clay loam roads that comprise only 1.3% of the watershed

area. Although glacial till roads have higher erosion rates than coarser roads constructed from metamorphic rock, erosion rates are also influenced by road slope and time since the road was last graded (Sugden and Woods, 2007).
During the data analysis process and subsequent presentation of results, two other issues were identified that require more detailed discussion. These include technique sensitivity and error analysis.

4.1 Technique sensitivity

Technique sensitivity as defined here refers to the ability of a sampling technique to detect a difference in sediment storage between sites and for it to provide repeatable results. Prior to assessing sensitivity it is necessary to review the sampling protocol for each technique to highlight external influences on sample collection and to clarify each technique's strength and weakness.

4.1.1 McNeil corer

The McNeil corer is a sediment corer that penetrates the streambed and provides a bulk sample of the bed to the depth that the core is driven. It is the most environmentally representative sampling technique presented here because the natural streambed is sampled directly. Further, Young *et al.* (1991) determined in laboratory trials with known sediment mixtures that the McNeil core provided more accurate and precise samples than the single or tri-probe freeze corer and shovels.
A potential problem with the McNeil core is the under-sampling of fine sediments due to the disturbance of interstitial fines during the coring process (Young *et al.*, 1991). Similar to other coring techniques, this disturbance of interstitial fines may bias the sampler to larger grain sizes. Further, the coarser fine sediments (e.g. sands) that have settled out at the bottom of the core may not be adequately suspended or they can settle out again just prior to collection of the 1 L core water sample. However, by ensuring the consistency of sampling personnel and procedure it is defensible to compare sediment concentrations between sites using this technique.
The McNeil core has distinct advantages over other corers and the trap techniques including its ease of use, portability, and adaptability. The core tube can be exchanged for narrower or broader tubes to best suit the range of particle sizes the researcher wants to collect. It collects natural streambed material making it a better measure of streambed conditions than sediment traps.

4.1.2 Gravel buckets

Gravel buckets are impermeable walled containers that trap depositing and/or saltating sediment that settles on the reference gravel's surface. They provide a standardized measure of sedimentation within a known grain size matrix as related to a specific monitored activity. The gravel bucket is a trap and so it may not be representative of the natural environment because the bucket walls prevent exchange with the surrounding streambed. Further, if the reference gravel has a different grain size composition than the natural substrate, their trapping efficiencies will differ so bucket results may not be indicative of the retained portion of settled solids in the sample area. However, it is important to recognize that the gravel bucket is not meant to simulate the streambed. Instead, its purpose is to measure the contribution of a specific activity to the depositing sediment load within a stream. It quantifies the addition of sediment to the streambed and not streambed alteration. To assess streambed alteration the bucket should be deployed with another sampler that samples the streambed directly such as the McNeil corer.

4.1.3 Infiltration bags

Infiltration bags are also traps but unlike the buckets they are collapsed and buried at the bottom of a column of reference gravel within the streambed. They have an advantage over gravel buckets because the column of reference gravel is open to exchange with the surrounding streambed and therefore collects sediment depositing from above as well as moving vertically or horizontally through the streambed. The reference gravel is clean and its size and shape ensures that pore spaces are numerous and capable of retaining settled fines by reducing interstitial flow, all of which make it an effective sampler. Assuming that the sample collected when the bag is removed from the streambed represents the fine sediment burden at that location and time, this technique may be best applied over short periods before and after an event. When it is left for longer periods the reference gravel may come to equilibrium with the fine sediment composition of the bed but this time will be unknown.

4.1.4 Summary

Each technique focuses on sampling a different portion of the depositing sediment load and as such it can be expected that they may provide different results for the same site as shown in table 5. As previously stated, the McNeil core may be biased toward sampling of the larger grain sizes (> 1 mm) and so may not show increases in finer sediments while the traps do detect a difference in the smaller size range. This was observed at Big Bend, Cluculz, and Spruce Creek sample locations. Infiltration bags incorporate subsurface and surface sediment movement and can therefore differ from gravel buckets as shown in Young's Creek. Further, McNeil core samples and gravel buckets can show a significant increase in fine sediments due to surface loading whereas the infiltration bags can receive surface inputs but lose stored material via intergravel flows because they are open to horizontal and vertical exchange. Fine sediment can move further downstream with intergravel flow so bags may return lower fine sediment mass than buckets. This was observed at Young's Creek where both buckets and cores showed higher fine sediment loads than the bags.

Insufficient sample numbers may also explain the apparent discrepancy between the data collected by different samplers. Many of the case studies did not have sufficient sample numbers collected as was later determined by the sample number estimate program initiated in Cluculz, Spruce, and Youngs Creek. For example, four McNeil cores and three buckets were originally collected at Nithi River but according to our sample size estimates, six cores and eight buckets would have been more representative for that stream width (Tables 2 and 5). Although neither the McNeil or gravel bucket data set consistently has the appropriate number of replicates, the McNeil core sample number was often closer than the buckets, which may explain why cores determined there to be higher sand concentrations downstream and the gravel buckets did not (Table 5).

The sample size requirement information indicates that the infiltration bag will return the least variable data with the fewest number of samples for the 5 m wide stream while the McNeil core will do so for the 9 and 11 m wide streams (Table 2). Generally however, the sample numbers are comparable across techniques indicating that each is capable of returning repeatable and complementary data with relatively few replicates. Where it is not

possible to collect the suggested number of replicates due to site restrictions the sample size should be no less than three samples, which was shown in the Nithi River, Big Bend, and Government Creek site to be sufficient enough to determine a difference between sites.
To summarize, technique sensitivity is subjective because each technique was found to return repeatable data with similar sample numbers per given stream width. Further, there was general agreement between sample results for deployed techniques in each of the eight case studies. Sensitivity then is a consideration best decided upon by the sampler and the monitoring requirements of the project. For example, it is likely that the trapping techniques will be more sensitive to subtle increases in the depositing sediment load when the source is constant because their reference gravels have been cleaned and are of a size that optimizes trapping of fine sediments (Meehan and Swanston, 1977). However, while they may be more sensitive to increased fine sediments the data collected by them may not represent a similar change to the natural streambed and so the information gathered may be more relevant if partnered with the McNeil corer. Finally, the McNeil core and infiltration bag techniques may be a more sensitive measure of compositional changes with depth. The core will detect changes over the depth of the tube and the infiltration bag is open to horizontal and vertical exchange to the depth it is buried.

4.2 Potential errors

Two sources of error have the potential to affect project results, namely sampling and measurement error. Sampling error refers to errors in the sampling method, which is the selection of sites and techniques. Measurement error refers to error in sampling extraction and analysis.
Sampling error was addressed in two manners, 1) site establishment data ensured could be consistency in sample site conditions between sampling locations within the study area and 2) techniques were deployed in accordance with available standards. The site establishment data assured maximum sample site similarity given available field conditions. Although it may have been possible to find more comparable sites further up or downstream of the selected study area, there was a spatial sampling constraint. Specifically, if similar sites were chosen that were more than a couple of reach lengths from each other data interpretation is made more complex because we would have to account for the influence of tributaries, springs, or any sites of increased streambank erosion and sedimentation between the stations. Finally, where the number of sample locations within a site were limited and a sample had to be collected in a location having depth and velocity levels well outside the mean for that site, its data might have to be could be excluded from future analysis should it be shown to be an outlier.
There was limited information to draw from when developing this sampling protocol. Specifically, there was no sampling guidebook that discussed the theoretical and practical considerations necessary to design an effective sampling program. As such, the design and sampling process provided educational opportunities to improve the protocol. Starting with basic information available from the literature on how to use these sampling techniques, we were able to modify the technique to suit our specific needs and the assumptions behind these modifications were verified in the field. For example, the McNeil core has steel teeth that must be driven into the streambed by exerting pressure from above. It appears that the best approach is to torque the handles forcing the teeth to cut the streambed. When sampling in the field it is immediately obvious that when you torque the handles the core can rock, particularly on coarse substrate. This rocking results in the formation of fine

sediment plumes behind the corer due to bed disturbance. To counteract this condition two adjustments were needed. First, sampling was conducted in an upstream manner to minimize contamination of sample sites downstream with excess fines caused by streambed disturbance during the sampling process. Secondly, to maximize capture of fines during the coring process the operator had to be tall enough to rest their body on top of the core and also had to be sufficiently strong so as to force a good seal between the core tube and the streambed.

Measurement error refers specifically to sample analysis procedures and field instruments. A commercial laboratory analyzed sediment samples in accordance to ASTM standards for gravimetric sieving. In addition to the adherence of this sampling protocol 5-10% of the samples sent were re-sieved and the values compared. If the original and re-sieved values were more than 5% different from each other the sample was again re-sieved and if the difference held true, the samples from that batch were excluded. Fortunately, no re-sieved samples lay outside the acceptable level of difference.

Field instruments included a measuring tape, velocity meter, clinometer, and ruler. The same field equipment was used throughout the study to ensure consistency between sample stations within and between streams. The velocity meter was calibrated prior to the field season and its maintenance procedures were adhered to throughout the study period. The combination of these activities ensured that collected data were of good quality.

5. Conclusion and recommendations

The results of this program show that forest road construction and maintenance activities can increase downstream streambed concentrations of sediment less than 6 mm. Further, it was confirmed that these increases can be quantified with the use of the McNeil core, gravel buckets, and infiltration bags. Although each technique was found to have environmental limitations and sampling situations to which they are best applied, it is reasonable to conclude that each of them can detect forestry affected increases in depositing sediment but that they are more robust when used in combination.

Incorporating a geochemical analysis of captured sediments will enhance findings generated from the fine sediment monitoring protocol. Geochemical fingerprinting can increase the reliability of sampling results and may broaden sampling possibilities (Taylor and Owens, 2009). Fletcher and Christie (1999) used inductively coupled plasma mass-spectrophotometry (ICP-MS) to identify tracer elements for several newly formed sediment sources in six small streams (<5 m wide) in the Baptiste Watershed near Fort St. James, BC. They identified an element as useful when there are substantial differences between the sediment source being traced and the streambed sediment. Element composition differences between stream sediment and tracked sources were evaluated using the geochemical contrast (ratio) between concentration of the element within a sediment source and stream sediment above the source as well as by testing mean values of the sediment and source for significant differences.

Several elements were found to be acceptable tracers for the studied basins including calcium, chromium, iron, manganese, nickel, phosphorous, strontium, and titanium. Although not originally identified as a tracer, zinc was also found to be useful because it gave very high concentrations downstream of new stream crossings. They concluded this to be a result of sediment abrading the new galvanized culverts. Once identified, tracer elements were used to determine mixing or dilution of the new sediment into the streambed downstream. They found that within 200 m of the new sediment source the added sediment concentrations had fallen to less than 10% on these small streams. This technique would benefit assessment sampling around specified forest harvesting activities because it would be possible to designate the source material of the increased sediment. Further, by sampling at distances downstream from the investigated activity it would be possible to determine the total streambed area affected and the period of effect.

Once increases in fine sediment are documented it is possible to hypothesize biological effects with reference to water quality criteria and the available literature (Culp *et al.*, 1986; Shaw and Richardson, 2001; Cover *et al.*, 2008). Although possible to infer biotic response, it is recommended that these sediment infiltration studies be conducted in conjunction with biological monitoring programs to determine the susceptibility of monitored populations to any observed increases in fine sediment deposition. Candidate populations include periphyton and invertebrates but if fish are the resource concern it is suggested that redds, eggs, or survival-to emergence of fry be used because unlike the more transient adults these forms reside in the streambed and will be more greatly effected by temporally constrained sediment pulses. Periphyton and invertebrate populations can be collected relatively quickly and interpreted with reference to accepted techniques including the rapid bio-assessment protocols of the U.S. EPA or other biologic indices such as the index of biological integrity (Karr and Chu, 1998). When used in combination, the results of the sedimentation and biological community assessment will be more conclusive.

Finally, this protocol should not be limited to assessing forest harvesting effects alone. Instead, it should be applied to assess the effect of all unpaved roads and any land use activity that can increase fine sediment deposition in streambeds. The protocol may also prove useful where the study goal is to capture sediment for the analysis of sediment bound contaminants. This includes those programs focusing on the quantification of pesticides, hydrocarbons, heavy metals, organo-chlorines and other substances that may be released from industrial activities such as agricultural activities, mining, and pulp mills.

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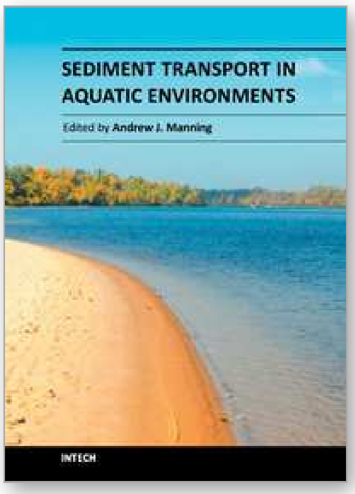

Sediment Transport in Aquatic Environments

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Sediment Transport in Aquatic Environments is a book which covers a wide range of topics. The effective management of many aquatic environments, requires a detailed understanding of sediment dynamics. This has both environmental and economic implications, especially where there is any anthropogenic involvement. Numerical models are often the tool used for predicting the transport and fate of sediment movement in these situations, as they can estimate the various spatial and temporal fluxes. However, the physical sedimentary processes can vary quite considerably depending upon whether the local sediments are fully cohesive, non-cohesive, or a mixture of both types. For this reason for more than half a century, scientists, engineers, hydrologists and mathematicians have all been continuing to conduct research into the many aspects which influence sediment transport. These issues range from processes such as erosion and deposition to how sediment process observations can be applied in sediment transport modeling frameworks. This book reports the findings from recent research in applied sediment transport which has been conducted in a wide range of aquatic environments. The research was carried out by researchers who specialize in the transport of sediments and related issues. I highly recommend this textbook to both scientists and engineers who deal with sediment transport issues.

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