Assessing the Short-term Impacts on Sediment Production following Rapid Harvest and Stream Crossing Decommissioning in Rocky Mountain Headwaters

by

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Abstract

While rapid road and road-stream crossing decommissioning after forestry operations may serve to limit broader impacts of sedimentation in high value headwater streams, few studies have evaluated the combined effects of accelerated harvest operations and rapid retirement of roads on stream sediment. The objectives of this study were to evaluate the initial impacts of these management strategies on sediment production and fate during a short duration (10-month) harvesting operation in three headwater sub-catchments in the southwestern Rocky Mountains of Alberta, Canada. A multi-pronged sampling approach (automated ISCO samplers, event focused grab sampling, continuous wash load sampling, and sediment ingress measurements) was used to measure suspended sediment production and ingress in streambeds. Sediment inputs from forestry roads was generally much lower than has previously been reported with little, if any, consistent pattern of elevated sediment production during the snowmelt freshet or periodic summer rainstorms. The impact of the combined disturbance of rapid harvest (2015) and subsequent road decommissioning (2016) on total suspended solids ($p = 0.52$), wash load concentrations ($p = 0.61$), and sediment ingress ($p = 0.33$) was largely negligible. In fact, turbidity was often higher ($p < 0.001$) at the upstream sample location across both years. Minimal in-stream impacts on sediment from forest harvest and road-stream crossings was likely a reflection of combined factors including a) employment of secondary erosion control Best Management Practices to roads and bridge crossings, b) rapid decommissioning of roads and crossings to limit exposure of linear land disturbance features, and c) drier El Niño climatic conditions during the study.

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Chapter 1: Thesis Introduction

Low-order headwater catchments on the eastern slopes of the Rocky Mountain regions are critical for drinking water supplies (Emelko et al., 2011) and often contain high-priority or sensitive fisheries (Ripley et al., 2005). Today, multiple stressors including climate change, pest invasion, land-use change and extensive linear-feature disturbance (i.e., roads) associated with resource extraction threaten ecosystem values and downstream water resources provided by headwater systems. Forest harvesting, along with the construction of supporting road haul networks, is one such disturbance that is extensive across this region. In concept, although the decommissioning of haul roads immediately following harvesting activities is a recognized Best Management Practice to reduce chronic sediment input (McCaffery et al. 2007; Switalski et al., 2004), the immediate impacts on stream sediment following road decommissioning have not been well-documented. Research is currently needed to describe the efficacy of various decommissioning strategies to better inform road management policy.

Sediment production from logging roads

The effects of forest harvesting on sediment production in aquatic systems have been well-studied (Aust and Blinn 2004; Croke and Hairsine 2006; Anderson and Lockaby 2011). In particular, road networks supporting forest harvesting operations are cited as the primary source of sediment to receiving streams (Baird et al., 2012). Although road networks typically comprise of < 0.5% of the total catchment area (Ziegler and Giambelluca 1997), sediment generation from unsealed roads can be 10-times greater than from harvested cutblocks (Motha et al., 2003). Roads are often described as sediment production ‘hotspots’ (Al-Chokhachy et al., 2016) and can be significant sources of fine sediment (<64 µm). Fine sediment is of particular concern from a water quality perspective because it is easily entrained in overland flow (Bilby 1985; Kreutzweiser and Capell, 2002) and is a primary vector for contaminant transport (of nutrients and heavy metals) due to high hydrophobicity (Droppo et al., 2015). Given that mountainous headwater streams are generally oligotrophic, sediment-associated nutrient loading is especially concerning in these systems (Silins et al., 2014). Increases in both bio-limiting nutrients (nitrogen and phosphorus) as well as subsequent increases in primary production have been reported downstream due to fine sediment production from harvesting activities (Hawthorn 2014).

Many factors influence fine sediment generation on haul roads. These include the road surface condition (unsealed vs. graveled), frequency of use, and age of roads (Reid and Dunne 1984; Bilby et al., 1989; van Meerveld et al., 2014). In addition, the timing of high intensity rainfall events in relation to various road life-phases can influence the amount of sediment mobilized (van Meerveld et al., 2014; Swank et al. 2001). Inputs of sediment to streams are generally greatest during construction when soil exposure is high (Anderson and Potts 1987; Aust et al., 2011; Wang et al., 2013). Elevated levels of sediment in streams during road use (Reid and Dunne 1984; Al-Chokhachy et al., 2016) and routine maintenance have also been widely reported (Luce and Black 1999; Ziegler et al., 2001). Downstream suspended sediment concentrations can increase five-fold compared to background levels following road construction or maintenance activities (Anderson and Potts 1987; Aust et al., 2011; Wang et al., 2013; Luce and Black 1999; Ziegler et al., 2001). Maximum suspended sediment concentrations and turbidity of 1400 mg/L and 400 NTU have been respectively reported in small streams (Barton 1977; Lane and Sheridan 2002).

High-value fisheries, such as salmonids, are particularly sensitive to sediment. Large increases in suspended solids in the water column can induce a range of physiological stress responses and lead to reductions in feeding success of fish (Rex and Petticrew 2011; Anderson and Lockaby 2011; Kemp et al., 2011). Additionally, the deposition or ingress of fine sediment in the streambed have been observed downstream of haul road networks (Lane and Sheridan 2002; Spillios 1999). Sedimentation rates as high as 4,200 g/m^2 primarily comprised of coarse silt (40-63µm) fractions have been observed following road-improvement operations (Kreutzweiser and Capell 2002). Sediment production from these activities can negatively impact early-life history stages of fishes (Lisle 1989) as well as benthic communities which are prone to smothering (Descloux et al., 2013). The ingress of sediment and resultant clogging of interstitial space can also reduce oxygen exchange (Scrivener and Brownlee 1989). It has been proposed that in less than a decade between 24 to 43% of bull trout will be extirpated from various Eastern Rocky Mountain streams due to increased fine sediment production associated with regional harvesting operations and haul road networks (Ripley et al., 2005).

It is important to distinguish between suspended and deposited sediment when assessing the longevity and location of sediment impacts. Depending on flow conditions and sediment provenance from river banks and hillslopes, recovery to background levels can last from 24 hours (Tornatore 1995) to several months (Wang et al., 2013) following road-related operational phases. In contrast, sediment that deposits or ingresses into the streambed may result in longer term sediment impacts (Wang et al., 2013). For instance, Swank *et al.,* (2001) reported legacy sediment impacts over 15 years following harvesting activities due to the slow flushing rates of sediment stored within the streambed in headwater systems. The subsequent mobilization of high levels of fine sediment and associated nutrients can then present challenges for downstream drinking water treatment (Emelko et al., 2016; Marquis 2005).

Although separate studies have described the impacts on suspended (Lane and Sheridan 2002; Rex and Petticrew 2011; Wang et al., 2013; Wear 2012) and deposited (ingress) sediment (Bilby 1985; Spillios 1999; Kreutzweiser and Capell 2002) downstream of haul roads, fewer studies have concurrently investigated both modes of sediment inputs at these sites. Moreover, studies investigating fine sediment downstream of haul roads tend to investigate the particle-size characteristics of ingress sediment only (Spillios 1999; Kreutzweiser et al., 2005), with limited research appearing to describe particle-size of suspended sediments—even though fine sediment is likely to be carried in suspension.

Limiting exposure of roads and road-stream crossings

Point sources of sediment can occur when riparian buffers are compromised. Road-stream crossings are prime locations where hillslope-stream ‘connectivity’ is high simply due to its proximity to lotic environments (Croke and Hairsine 2006). Compacted and unobstructed approach slopes can produce high rates of runoff thus making road-stream crossings localized sources for sediment delivery (Burroughs et al., 1989; Croke et al., 2001). Various types of road-stream crossings including bridges, culverts and log-fills, as well as and their approach slopes, are important sites of sediment generation and delivery (Burroughs et al., 1989; Aust et al., 2011). Hence, road-stream crossings are often sites where the application of Best Management Practices (BMPs) are effective (Wear et al., 2013). While the general impact of road-stream crossings on sediment input has been addressed in the literature (Bilby 1985; Lane and Sheridan 2002; Wang et al., 2013; Petticrew and Rex 2006), field-based research is still needed to better inform road management policies and the effectiveness of specific BMPs across different spatial scales at these sites (Grace and Clinton 2007; Switalski et al., 2004; Anderson and Lockaby 2011).

The decommissioning of temporary or unused roads and road-stream crossings is generally thought to mitigate chronic sediment loading after harvesting operations are complete (McCaffery et al., 2007; Switalski et al., 2004). The ripping or roll-back of roads following harvesting operations is used to increase infiltration and reduce erosion once new vegetation stabilizes soils (Switalski et al., 2004). The decommissioning of roads may also have ecological benefits through enhancing habitat corridors, reducing wildlife poaching pressures and risks associated with traffic morality (Robinson et al., 2010).

Increasingly more unused roads are being decommissioned in North America. For example, it is estimated that upwards of 3,200 km of roads per year are being decommissioned in the United States (U.S Forest Service, 2002). Despite recognition that decommissioning operations may result in immediate impacts on instream sediment production (Switalski et al., 2004) in amounts similar to that of the crossing construction phase (Aust et al., 2011), comparatively few studies have rigorously examined the decommissioned or reclaimed life-phase of road-stream crossings (Grace and Clinton 2007).

Effectiveness of the 'get in and get out' strategy as a BMP

Old (legacy) haul road networks can be present on landscapes for decades; whether completely abandoned, left unused, or temporarily decommissioned until all forest compartment operations (i.e., silviculture) are complete. Indeed, in large harvesting compartments where harvesting operations may span decades, decommissioning is often not routinely practiced. In absence of full decommissioning strategies, soil compaction on abandoned roads can persist up to 50 years due to the slow natural recovery of soil properties (Greacen and Sands 1980; Rab 2004). This augments chronic sediment input and the risk associated with mass wasting events and utilization of haul-roads as recreational access points (Bloom 1998; Robinson et al., 2010). Such disturbances can create significant long term sediment impacts that may be inconsistent with broader landscape management objectives in high-priority or sensitive watersheds.

The 'get-in and get-out' approach, characterized by accelerated harvest timelines and rapid haul road and road-stream crossing decommissioning serves to limit chronic sediment loading. In Alberta, provincial forest management policy currently requires the decommissioning of unused Class IV roads and crossings following harvesting operations or within three years of road construction (Government of Alberta 2016). However, shorter harvesting timelines are achievable and may be preferable in sensitive systems such as high value headwater systems. While both road and road-stream crossing decommissioning after forestry operations may serve to mitigate broader impacts of sedimentation, very few studies, if any, have evaluated the combined effects of these restoration strategies following a rapid harvest. Currently, 'the get-in and get-out' approach is a BMP not described in provincial forest management regulations.

The eastern slopes of the Canadian Rocky Mountains provides an ideal setting to test the efficacy of such strategies given the steep topography, highly variable fine glacial till deposits and extensive road networks associated with natural resource extraction (i.e., forestry, mining) throughout the landscape. Additionally, as a region of high-quality provincial drinking water supplies and sensitive fisheries (Bull Trout, Athabasca Rainbow Trout, Westslope Cutthroat Trout), extensive field research is necessary to rigorously evaluate the impacts of such strategies in the context of these critical landscapes.

The broad goals of this study were to determine the overall effect of the ‘get-in and get-out’ approach across a 10-month rapid harvest and subsequent road decommissioning timeline on sediment mobilization and transport and parse out the impact on sediment across different road life-phases. Here, the rapid harvest and the subsequent road amendment timeline was the overarching or primary BMP implemented. However, as secondary BMPs (Appendix B) were also utilized during this harvest, the ‘get-in and get-out’ approach tested here reflects the overall performance of a suite of BMPs. The specific research goals were to evaluate and describe particle-size characteristics of both in-stream and road-associated sediments over the study period. The impact of road-stream crossings on suspended sediment dynamics was reported on in Chapter 2 while the downstream fate focusing on ingress sediment into streambeds was evaluated in Chapter 3. This research will provide new insights regarding the magnitude and location of immediate impacts related to the combined effect of rapid harvest and road-decommissioning disturbance on sediment source, transport and fate. An assessment of the efficacy or performance of this potential BMP may provide a scientific basis to improve forest harvesting and road management policies. This research will also help to close knowledge gaps related to forest harvesting and haul road disturbances in high-priority headwater catchments where limited linear feature disturbance is required.

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Chapter 2: Short-term effects of rapid harvest and road-stream crossing decommissioning on suspended sediment production in receiving streams

2.1 Introduction

Sediment delivery to waterways from haul road networks is one of the well-documented impacts of forest harvesting. Sediment production from these linear features to streams can deteriorate water quality (Bilby 1985; Anderson and Potts 1987; Lane and Sheridan 2002) and aquatic habitat (Gomi et al., 2010; Maitland et al., 2016). Following conventional harvesting operations, the greatest suspended sediment impacts generally occur within 1 to 2 years after initial road disturbance (Croke et al. 2001). Recovery to background water quality generally returns an additional 2 to 5 years following the decommissioning of roads (Aust and Blinn 2004; Anderson and Lockaby 2011).

The impacts on suspended sediment in streams are often related to various road life-phases of forestry operations that include road construction, hauling/harvesting activities and road decommissioning (Aust et al., 2011). The greatest impacts on sediment production occur during the construction of road networks and crossing structures, where a five-fold increase in TSS and turbidity following construction has been reported (Anderson and Potts 1987; Kreutzweiser and Capell 2002; Aust et al., 2011). During bridge construction, elevated concentrations of suspended sediments have been linked to either mechanical introduction of soil backfill (Wang et al., 2013; Aust et al., 2011), or with runoff following large storm events preceding crossing installation (Swank et al., 2001; Wang et al., 2013). Increased sediment production also occurs during hauling periods (Al-Chokhachy et al., 2016; Reid and Dunne 1984) when finer-grained materials (<64 μm) on unsealed road surfaces are exposed and mobilized (Bilby 1985; van Meerveld et al., 2014). Due to their large surface area and high cation exchange capacity, fine sediment is of particular concern because it is a the primary vector for the transport of sediment-associated contaminants such as nutrients (Stone and English 1993) and heavy metals (Legret and Pagotto 2016). During active haul periods, sediment concentration in streams can increase by one to two orders in magnitude (+11.5 – 132.2 mg/L; Tornatore 1995, Aust et al., 2011). While the relative magnitude of sediment loss during hauling has been reported, few studies have rigorously described the physical characteristics (particle-size) and instream transport dynamics of fine material produced during hauling.

Knowledge gaps also remain in regards to the decommissioned road life-phase. Comparatively few studies have specifically examined the effects of road removal and road-stream crossing decommissioning life-phase on sediment production, even though temporary increases of suspended sediment during amendment activities are recognized (Switalski et al., 2004). The decommissioning of roads and stream crossings following harvesting activities is a mitigation strategy employed to reduce chronic sediment loading and restore wildlife habitat in public and private lands across Canada and the United States (Switalski et al., 2004). Additionally, while both rapid harvest and road/road-stream crossing decommissioning (i.e., ‘the get-in and get-out approach’) after forestry operations may serve to mitigate broader impacts on sediment in high value headwater streams or sensitive watersheds, few studies have evaluated the combined effects of these management strategies following a rapid harvest.

The broad objective of this study was to assess the impact of the ‘get-in and get-out’ approach of forest management on sediment losses at road-stream crossings. This was done over a two-year (ice free) period that included a 10-month rapid harvest followed by road decommissioning operations. In an effort to thoroughly determine the overall effect of rapid harvest and road stream crossing decommissioning on suspended sediment production a number of parameters (representing various particle-sizes) were investigated, including TSS, turbidity, wash load concentration. A secondary objective of this chapter was to assess the relative contribution of suspended sediment to streams during various operational road life-phases (Non-Haul, Haul and Post Haul), as sediment availability (supply) and transport mechanisms (energy) would vary across road life-phases. This multi-pronged sampling approach provides key insights into the magnitude of impacts related to rapid harvest and road-decommissioning and the efficacy of such strategies for future harvesting operations in high-value and sensitive watersheds.

2.2 Materials & Methods

2.2.1 *Study Area*

This study was conducted in the Star Creek watershed which is located in the headwaters of the Oldman River Basin along the eastern slopes of the Rocky Mountain front-range in southwestern Alberta (Figure 2.1). Star Creek is a fourth order stream that drains 1865 hectares (49° 37’ N; 114° 40’ W). Natural sub-regions in the watershed are classified as montane, subalpine and alpine regions (Silins et al., 2016). Forest stands consist primarily of conifer species (92%; *Pinus contorta, Pseudotsuga menziesii*, and *Picea glauca*) (FHP 2014). The surficial geology is largely comprised of Cretaceous shale and sandstone deposits, overlain by Eutric or Dystric Brunisolic soils (Bladon et al., 2008). The flow regime of Star Creek is primarily influenced by snow-melt during late spring, storm runoff and groundwater inputs (Macdonald et al., 2014). The average annual precipitation for the region ranges from 800-1360 mm (Silins et al., 2016). Mean elevation of the three sub-catchments of Star Creek range from 1700-1930 m and the mean slopes range from 25 to 59% (Table 2-1).

2.2.2 *Harvest/Road Design*

In 2015, three harvest treatments (Clear-cut, Strip-cut, Partial-cut) were applied in three headwater sub-catchments of Star Creek (Figure 2-1, Table 2-1). The largest sub-catchment, Star West (4.63 km^2) consisted of a (0.68 km^2) clear-cut with patch and single tree retention. Star East (3.89 km^2) consisted of a strip shelterwood cut alternating 35-m wide harvested strips (0.44 km^2) with 35-meter wide retention (uncut) strips. McLaren, the smallest sub-catchment, (0.95 km^2) comprised of a group selection shelterwood harvest resulting in 50 percent (overall) stand retention with 28% stand retention within harvested area (5 x 5 m target residual tree spacing). Single-span bridge crossings consisted of two-girders and open timber decking wrapped in geotextile fabric laid upon concrete footings, spanning 9-15 m and designed to withstand a 1:25 year flood event (FHP 2014; Figure 2-2). Temporary road networks were constructed during winter 2015 to a Class IV standard with primary use in winter and summer seasons, in accordance with the operating ground rules (Spray Lakes Sawmills 2011). Slopes of road approaches to stream crossings ranged from 2.3 to 11.9% grade (Table 2-1). All harvesting operations in Star Creek, from initial road grading through to harvesting, hauling and final road roll-back and crossing decommissioning, took place over 10 months (Jan-October 2015; Appendix A). In addition to the short timeframe in which harvesting took place, other secondary BMPs incorporated during this harvest included the use of silt fences, ditch dug outs to trap sediment during periods of ditchflow, swamp mats (12-ft timber beams) for crossing streams during construction, as well as the installation of a seasonal water-bar diversion network and cessation of hauling/harvesting activities during spring and summer wet conditions (Appendix B).

2.2.3 *Precipitation & Streamflow*

Star Creek watershed is the location of a broader hydrological and meteorological monitoring network managed by the Southern Rockies Watershed Project (Silins et al., 2016). Annual precipitation (mm) was measured at a gauging station (Star Main) downstream of all three sub-catchments (Figure 2-1) during 2015 and 2016. High frequency (10-minute interval) precipitation data (mm) was recorded using a tipping bucket rain gauge (Jarek Rain Gauge, Geoscientific Ltd.) and pendant logger (HOBO pendant, Onset Computer Corp.). Streamflow (Q) was measured using standard area-velocity current metering techniques with a Swoffer velocity meter (Model 2100, Swoffer Instruments Incorporated, Seattle, WA, USA) or a Sontek acoustic doppler velocity meter (Flow Tracker ADV, Sontek/YSI, San Diego, CA, USA) at the confluence of Star West and Star East sub-catchments. Measurements of Q occurred approximately every 14-days throughout the snow free period, with the frequency increased to every 7-days during peak snow melt. Stage readings were measured simultaneously from staff gauges to derive stage-discharge relationships for each stream. Continuous Q was then determined from continuous stage measurements recorded at 10-minute intervals on recording pressure transducers (HOBO U20, model U20-001-01, Onset Computer Corporation, Pocasset, MA, USA). A compound 120° V-notch weir below a larger rectangular throat was used to measure Q at the McLaren Creek confluence with 10-minute time interval stage recorded in the weir stilling pond. Streamflow was calculated using the standard rating equation for a 120° V-notch weir (Eq.1). (Eq.1)

$$Q = 2391\, H^{2.5}$$

Q= Streamflow (m^3/s)
H=head, in meters, within the V-notch weir throat

Stage remained within the V-notch throat section during 2015 and 2016 (i.e. compound rating equation including the rectangular section was not needed).

2.2.4 *Total Suspended Solids & Turbidity Sampling*

Water samples were collected upstream (US) and downstream (DS) of three bridge crossings using paired ISCO automated water samplers (Teledyne Model 6712) for total suspended solids (mg/L) and turbidity (NTU) analyses (Figure 2-3). Downstream ISCO samplers were previously installed approximately 200 to 600 m below each of the three road-stream crossings, while the upstream ISCO samplers were installed for this study approximately 20 m above each crossing. Daily composite samples (1L), consisted of one-250 ml sample every 6 hours collected during the ice-free seasons in 2015 (harvest) (n=366) and 2016 (1-year post-harvest) (n=244). Intakes for the automated samplers were installed at 0.6 of total depth at locations where turbulence was low. Installation of samplers took place after initial road construction and water-bar cross drainage installation, before summer hauling commenced (approx. July 16th 2015).

2.2.5 *Wash load Sampling*

The concentration of fine sediment in suspension (herein referred to as wash load) was also measured using a ‘siphonator’ which is a passive, flow-through sampling device specifically designed for this study (Figure 2-4). This fine sediment sampler consists of a 25-ft polyethylene intake tube (1/4 in.), attached to 19L pail. Total flow through the siphonator was determined using direct measurements, or from volume totalizers (DigiFlow 6710M-32, Savant Electronics).

Paired siphonators were installed directly upstream (25 m) and downstream (25 m) of crossings where sufficient hydraulic head was present (log-steps, meanders, bank collapses etc.)(Figure2-3). Siphonators were deployed for 2 to 3 weeks during baseflow conditions (July-August), which provided comparable conditions between the harvest (2015) and 1-year post-harvest (2016), as well as melt freshet conditions in 2016. Slight differences in hydraulic head resulted in changing flows conditions across siphonators (~20-250 ml/min). Upon retrieval, excess water in settling basin was decanted and the ~1.5L sediment slurry was collected. Buckets were cleaned with a spatula to ensure that fine sediment was detached from the walls. Samples were stored in a cool dark location prior to processing.

2.2.6 *Road-Associated Sediment Sampling*

Collection of road-associated sediment during the harvest (2015) were obtained using: sweep (EPA 1995), dust deposition, and storm-culvert (ditchflow) samples (Bilby 1985) to assess the physical characteristics (particle-size) of each sediment source. Dust deposition samples were collected twice over two-week sampling periods in 4L pails placed streamside, adjacent to the active haul road. Road-associated sediments following road amendment (2016) were collected as surface (~15cm) grab samples (methods adapted from Pagotto et al., 2000). Following collection, particle-size distributions of road-associated sediment were determined (see below).

2.2.7 *Event Sampling*

Grab samples were collected during two storm events in 2015 (Julian Day 146 and 153), that produced 28.8 mm and 50.5 mm of rainfall, respectively. These two events were the largest events over the duration of the study. Sediment samples were collected at stream crossings, as well as nearby flowing culverts. Storm grab samples during the largest storm event (Julian Day 153) were collected twice, once during the peak and the other during the falling limb of the storm hydrograph. Particle-size characteristics of sediment collected from grab and culvert storm samples (Julian Day 153) were determined (Bilby 1985). No rainfall events in 2016 were large enough to cause runoff from road surface (see pg. 50).

2.2.8 *Water and Particle-Size Analysis*

Total suspended solids (mg/L) and turbidity (NTU) of US/DS daily composite samples were determined using gravimetric methods (Stednick 1991) and a bench-top turbidimeter (Model 2100N IS, Hach Co.), respectively. Method detection limits for these techniques were 0.25 mg/L and 0.01 NTU. Within each processed sample set, calibration filters were used to account for changes in relative humidity and ambient conditions in the laboratory. Gravimetric methods were not ideal for event-based samples or wash load samples, due to high sediment loads requiring repetitive filtration of subsamples. Instead, event-based grab samples and wash load samples were left to settle for three days, decanted then subsequently oven-dried at 107°C overnight (Klute 1986) to determine total sediment mass.

Particle-size distributions of road-associated, wash load, and event-based sediment samples were measured with a laser particle analyzer (LISST Type C, Model 100X, Sequoia Scientific) in conjunction with a full path mixing chamber (SAA-L100X-CHMX, Sequoia Scientific). Dry sediment samples were mechanically sieved (Ro-tap Model RX-29, WS Tyler) to < 250 µm, a conservative threshold for samples analyzed with a Type C LISST device (2.5-500 µm), that ensured concentration maximum for the instrument was not exceeded. Sieved samples >2 grams were subsampled using 'cone and quartering' techniques (EPA, 1995) before applying a dispersing solution consisting of 0.05% sodium hexametaphosphate $(NaPO_3)_6$ and diluted up to 1L (Bouyoucos 1962). A 150 ml subsample was used to measure median particle-size, particle-size distribution (D10,16,50,60,84,90) and silt density (<64 µm, Eq.2) based on an average of 30 measurements.

(Eq.2)

$$sd = \frac{svc\ (n)}{vc\ (n)}$$

sd= Silt Density (%)
n= Total number of 1-sec measurements
svc= Total silt volume concentration (<64 microns, µl/l))
vc= Total volume concentration (µl/l)

2.2.9 *Statistical Analysis*

Post-hoc descriptive statistics were used to evaluate sediment data at road-stream crossings. A paired-site approach was employed to control variability and account for non-independence of observations between up and downstream sites. Analyses of TSS, turbidity, and wash load concentration data were first investigated across the three streams individually, as well as combined, to determine overall combined disturbance effect (2015 and 2016). Due to low sample numbers in McLaren Ck., the overall disturbance effect for wash load concentrations could not be evaluated. Accordingly, the stream data were pooled. Pooled stream data was then utilized to determine the effect of various life-phases (Non-Haul, Haul and Post-Haul periods) of rapid harvest and road decommissioning. Impact on wash load concentration during the Haul and Non-Haul was inferred by pooling site data and examining US/DS differences, followed by differences across life-phases. As neither raw data nor Box-Cox transformed data met assumptions for normality (Shapiro-Wilk test; α=0.05), non-parametric tests were conducted. Wilcoxon signed-ranked test were performed on paired upstream and downstream samples. To reduce a Type I error rate with multiple comparisons, an overall experimental wise error rejection level of α=0.05 was used. Individual pairwise comparisons values of α=0.016 and α=0.025 were utilized for such tests.

All data analyses were computed with using R statistical software (RStudio, Version 0.99.896, 2016). Particle-size data were analyzed using MATLAB R2016a (MathWorks, 2016).

2.3. Results

2.3.1 *Precipitation and Streamflow*

Total annual precipitation for the harvest year (2015) was 703.8 mm, while the annual precipitation 1-year post-harvest (2016) was considerably lower at 568.0 mm. The difference in precipitation was due to a greater number of storm events (>10 mm) and longer average storm durations observed during 2015 than in 2016 (Table 2-2). Precipitation during both study years fell within the range of historic records (2004-2014) for the Star Main gauging station (average: 646.7 mm/yr and range: 381.9-863.6 mm/yr). The annual hydrographs differed substantially between the 2015 and 2016 across all three streams (Figure 2-5). In 2015, large spring rainfall events and a large snowmelt freshet contributed to a single steep rising limb and rapid post-peak recession, while fewer spring/early summer events and a small snowmelt freshet in 2016 resulted in a flashier and muted peakflow signature. The difference in hydrologic response across years was especially evident in Star West and Star East Creek. (Figure 2-5). In general, differences in discharge reflected differences in precipitation, and resulted in comparatively higher average annual streamflow (mm) observed during 2015 than in 2016 across all streams (Table 2-2 & 2-

3).

2.3.2 *Effect of the overall combined disturbance (2015 and 2016)*

Impact of the combined rapid harvest (2015) and road-stream crossing decommissioning (2016) disturbance on TSS was largely negligible where median TSS upstream of all three bridge crossings was 1.49 mg/L compared with 1.62 mg/L downstream of these bridges ($p = 0.52$, Table 2-4). While variation in TSS production existed across sites, the increase in median TSS concentrations (upstream to downstream of bridges) was below the analytical detection limit for TSS (0.25 mg/L) in Star East and Star West Ck. ($p = 0.001$ and 0.29, respectively; Table 2-4, Figure 2-6). Median sediment concentrations were slightly lower below the bridge crossings at McLaren Creek ($p = 0.15$; Table 2-4, Figure 2-6).

There was no significant difference in turbidity between upstream and downstream locations from the combined harvest related disturbances. In fact, turbidity was often higher at the upstream sample location across both years ($p < 0.001$; Table 2-4). Within sites, this trend was observed at Star East (+0.25 NTU (US-DS)) and Star West Ck. (+0.16 NTU, $p < 0.001$; Table 2-4, Figure 2-6). McLaren Creek was the only site that showed a small but significant increase in turbidity downstream of the bridge crossing (+0.14 NTU (DS-US), $p = 0.002$; Table 2-4, Figure 2-6).

Differences in wash load concentrations between up and downstream locations were also negligible ($p = 0.61$; Table 2.5, Figure 2-7) with no significant differences in median particle-size ($p = 0.53$; Table 2-5, Figure 2-7) or median silt density ($p = 0.56$; Table 2-5) of wash load between up and downstream locations.

2.3.3 *Effect across individual road life-phases*

Individual road life-phases (Non-Haul, Haul and Post-Haul) were assessed by pooling data across streams for up and downstream locations. Across Non-Haul, Haul and Post-Haul periods, there was no significant increase in either sediment concentrations or turbidity downstream of any of the three bridge crossings (Table 2-6, Figure 2-8).

During the Non-Haul period (May - June 30th), negligible upstream-downstream differences in median TSS concentrations ($p = 0.40$) were observed while median turbidity was significantly higher at upstream locations ($p < 0.001$; Table 2-6). The two largest storm events and the greatest average daily precipitation (2.5 mm/d; Table 2-2) occurred during the Non-Haul period. Although event-based grab samples showed increased TSS concentrations of +10 mg/L at the downstream sites, these increases were not statistically significant ($p = 0.59$; Table 2-7). Moreover, no significant pattern in median particle-size or silt density was observed either upstream or downstream of bridge crossing for event-based grab samples collected during the largest precipitation event (Julian Day 153) (Table 2-7). During the Haul period (July-October 30th), sediment sources on the road were abundant but no increase in median TSS or turbidity was observed during this period. Indeed, median TSS and turbidity were marginally lower downstream of all three bridge crossings ($p=0.034$ and 0.050, respectively; Table 2-6) during this period. Similarly, no significant difference in median TSS ($p = 0.59$) between upstream and downstream locations was observed during the Post-Haul period, while there was a significantly higher median turbidity was again greater at upstream locations of bridge crossings ($p < 0.001$, Table 2-6).

Differences in fine sediment fractions as reflected in wash load concentrations were assessed during Haul and Post-Haul periods when road-use and road-amendment occurred, respectively. No increases in wash load concentration at downstream sites were observed for either Haul ($p = 0.25$) or Post-Haul ($p = 0.79$) periods (Table 2-8). However, when up and downstream data were pooled and compared for Haul and Post-Haul periods, some differences in wash load and particle-size characteristics were observed. During the Post-Haul period following road amendment, slight increases in median wash load concentrations (+0.23 mg/L; $p = 0.03$), median particle-size (+13.3 μm; $p = 0.016$), as well as a 3% decrease in median silt densities ($p = 0.016$; Table 2-9) were observed. The data show that the road stream crossings were not significant sources of sediment input during any of these road life-phases evaluated in this study.

2.3.4 *Road-associated sediment sources*

Particle-size characteristics of road sediment varied temporally across each of the road life-phases (Table 2-10, Figure 2-9). Finer fractions were present on road surface during the Non-Haul and Haul periods (means: 17.2-18.9 μm) relative to Post-Haul period in 2016 (mean: 75.0 μm) (Table 2-10). The highest proportion of silt-sized fractions (< 64 μm) was observed during 2015 culvert storm sampling where 82% of the sediment (by volume) consisted of clays and silts (Table 2-10). During the Haul season, stream side dust deposition rates varied from 0.2-2.1 mg/m^2 day, with mean particle size of 45.0 μm.

2.4 Discussion

2.4.1 *Effect of the overall combined disturbance (2015 and 2016)*

The overall combined effects of road construction/bridge installation, harvesting and decommissioning on TSS and turbidity were negligible. However, minor variation in this general finding was evident across the three road stream crossings in this study. For example, at both

Star East and McLaren Creek slight increases in both TSS and turbidity downstream of the crossings suggest that these road-stream crossings did contribute small amounts of sediment to these two streams. However, in Star East Creek, higher downstream TSS (+0.13 mg/L) fell under the analytical detection limit for TSS and was minor in comparison to increases previously reported for periods following newly constructed forestry roads (5.2-13.8 mg/L; Anderson & Potts, 1987; Wang et al., 2013). Similarly, very small increases in turbidity (+0.14 NTU) were measured downstream of the bridge crossing in McLaren Creek. These value were also small in comparison to what has previously been reported following a newly constructed road-stream crossing (+5.6 NTU; Wang et al., 2013). In the case of McLaren Creek, field observations suggest increased turbidity was not associated with the road-stream crossing as no obvious points of sediment connectivity were observed during large storms. This included backhoe cat tracks present on stream banks off McLaren Creek that were created during road construction (Figure 2-10). Rather, increased turbidity was thought to be attributed to natural variability in stream sediment dynamics related to the scour of thirty-five in channel sediment sources visually identified along the 600 m reach between up and downstream measurement locations. Log steps and log slides were especially prevalent in McLaren Creek due to historic logging where the stream channel and immediate river valley were used as a skid trail (Figure 2-11). Large woody debris can retain fine sediment in disturbed high-gradient systems (Benda et al., 2005; Little 2012), and when destabilized, can act as a persistent in-channel sediment source during high flow events (Lisle 1989; as seen here following a storm event on Julian Day 146). All of the streams examined in this study are classified as step-pool systems, which have previously been shown to play a vital role in sediment dynamics (Montgomery 1995). The minor impact of bridge crossings in this study on TSS and turbidity reported here may also be a reflection of both primary and secondary BMPs applied to the road-stream crossings. In contrast to Star Creek, sediment control measures were not applied in the harvested headwater study described by Wang *et al.,* (2013). Here, authors cite that the increase sediment input attributed to road-stream crossings (1.8 times the annual load) could have been easily mitigated with the employment of BMPs.

In general, greater turbidity was observed upstream compared to that observed downstream of the road-stream crossings. Turbidity (measure of the optical properties of water) is widely considered a proxy measure for TSS. Factors that influence turbidity measurements include variations in water colour, dissolved organic matter, particle-size and shape, dissolved air (bubbles), and solute concentration (Anderson & Potts, 1987). It is hypothesized that reach-scale differences in some of these factors may have influenced upstream turbidity measurements; however, I have no tangible evidence for this. Greater upstream turbidity may also reflect the natural variability in reach-scale sediment flux present in high-gradient gravel bed streams. Sediment flux can be influenced by variations in cross sectional area, flow dynamics and availability of sediment sources. In Star Creek, in-channel sources were prevalent across all study tributaries and included overturned trees with exposed root balls, bank undercuts and animal crossings.

The complex role of hyporheic flow pathways in creating a more variable fluvial geomorphic environment may also reflect higher turbidity upstream. Evidence of this occurred in Star East Creek, where higher upstream turbidity exhibited greater variability (unrelated to precipitation events) in mid-summer (July-August; Figure 2-12). As Star East Creek exhibits evidence in of sub-surface/groundwater flows additions (unpublished data), theoretically, upwelling flows pathways near the upstream site could incorporate water with different optical properties (i.e., solute concentration) or potentially mobilize fine bed sediments, giving rise to differences in reach-scale sediment flux.

There are numerous reasons why upstream turbidity may be greater than at downstream locations. This apparent ‘noise’ in the turbidity data makes parsing out the impacts of the overall combined harvest and decommissioning disturbance at the road-stream crossing difficult. This is especially true when upstream and downstream sample sites are separated by large distances (in this case upwards of 600 m). Foreseeing this issue, continuous wash load concentration samplers (siphonators) were installed immediately upstream and downstream (20 m) of road-stream crossing to ‘pinpoint’ impacts of crossings. As a time-integrated sample method, continuous wash load concentration data have the ability to capture the episodic nature of sediment transport (Phillips et al. 2000). However, even with this robust sample method, results of wash load concentration data upstream and downstream show a similar trend and indicate that the overall effect of the combined rapid harvest and road-stream crossing decommissioning were negligible. In regards to particle-size data, it would be expected that if crossings were a persistent source of fine sediment to receiving streams finer suspended loads would have been observed downstream (Bilby et al.,1989). However, no significant changes in wash load particle-size distributions (median particle-size, silt density) suggests that road-stream crossings were not a point-source of finer sediment fractions. To the best of my knowledge, few if any studies have used time-integrated sampling methods to assess upstream-downstream differences in wash load concentration or particle-size of stream suspended sediment at road-stream crossings. Moreover, a limited number of studies also exist regarding characterizing particle-size data for mountainous environments making cross study comparisons in particle-size data difficult (Grangeon et al., 2012), and an area for future research efforts.

2.4.2 Effect across individual road life-phases

Previous work examining disturbance impacts of linear features on stream sediment dynamics show that the period including the road installation phase, upwards of 1-year following installation is when sediment mobilization is typically greatest (Anderson and Potts 1987; Aust et al., 2011). However, results presented here suggest that no significant increases in TSS or turbidity were evident downstream in the 1.5 years following initial road construction, or the road life-phases examined in this study. Although sediment was not monitored during crossing installation, monitoring commenced only five months after crossing installation. It is reasonable to expect that sediment impacts would be the greatest during the ice-free monitoring period as the construction of bridge crossings took place in January 2015 when the stream riparian soils were frozen.

Non-Haul

No significant increases in TSS or turbidity occurred downstream of the road-stream crossing during the Non-Haul life-phase. This is somewhat surprising given the exposure of new sediment sources following installation and occurrence of larger rainfall events, often leads to high erosion rates (Megahan et al., 2001) and the greatest downstream impacts at road-stream crossings (Wang et al., 2013). The Non-Haul life-phase (May-June 30th 2015) coincided with spring melt conditions which temporarily postponed hauling and harvesting activities. During this time the road network was deactivated when a temporary water-bar diversion network was installed. Two large rainfall events (28.9 mm, 50.5 mm) occurred during the Non-Haul period, yet no significant increases in TSS downstream from storm samples were measured during either of these two storm events. In addition, maximum concentration of sediment in ditchflow was <

2.2 mg/L, a relatively low value in comparison to ditchflow concentrations previously reported (19,500 mg/L: Bilby et al., 1989; 2-15 mg/l: Croke et al., 2005). Median particle-size data from the largest storm event (50.5 mm, Julian Day 153) showed no increase in silt density, as the portion of silt fractions upstream-downstream were comparable (Table 2-7). Given that road surface material had a mean particle-size 17.1 µm, silt density (< 64 µm) is thought to be a valid indictor for the input of road-associated sediment to stream. However, it should be noted that infrequent or intermittent measurements of particle-size characteristics are not representative of an entire storm event (Williams et al., 2007) because of sediment hysteresis. In particular, it is possible that the timing of grab samples, one set taken during the rising limb and one during the falling limb, may have missed the initial fine sediment pulse (i.e., first flush effect; van Meerveld et al., 2014), as the finest fractions would be expected to be easily mobilized and transported to stream at the beginning of a storm hydrograph (Bilby et al., 1989).

Sediment transport regimes after land disturbance are often described in terms of supply (sediment) and energy/power (flow) dependencies (Rice et al., 1979; Wang et al., 2013). Here, the Non-Haul life-phase is suggested to be both *supply and energy sufficient*, as there was evidence of the mobilization of fine sediment (supply) in runoff during two relatively large storms (energy). However, negligible increases in TSS or turbidity downstream of stream crossings were attributed to the careful and rapid implementation of various secondary Best Management Practices (BMPs) across the Non-Haul life-phase. Two co-occurring secondary BMPs that likely mitigated sediment delivery during storm events and across the Non-Haul phase were the suspension of hauling/harvesting operations during wet periods, and secondly, the creation of a temporary water bar diversion network during the spring wet season (Lynch et al., 1983). The use of unpaved roads during wet conditions increases road-sediment production through the detachment, redistribution and mobilization at newly incised overland flow pathways (van Meerveld, et al., 2014). Accordingly, it is necessary to avoid harvesting and hauling activities during these conditions (Government of Alberta 2016; van Meerveld et al., 2014). The installation of temporary water bars likely reduced runoff rates and diverted sediment away from streams. In Star Creek, a field inventory of 28-water bar structures following a small overnight rain in 2015 confirmed that 79% of these features were effective at diverting ditch flow onto hillslope with none exhibiting evidence of hydrologic connectivity to the stream (unpublished data). This contrasts similar site assessments done by Sidle *et al.,* (2004) who reported 100% of road-drainage nodes showed evidence of hydrological connectivity in forest headwaters. From my observations, in cases where large flow diversion was evident, sediment deposition generally occurred just off the fill slope (Figure 2-13), in places where woody debris retained sediment on hillslope (Sidle et al., 2004).

Haul

During the Haul period (July - October), over 100 fully loaded logging trucks hauled timber out of Star Creek. This road traffic produced fine-grained material throughout the Haul period. Mean particle-size (18.9 µm) of sampled road surface sweep sediment reported here was larger than previously reported (80% < 4 µm; Bilby 1985), possibly due to the lower-limit sampling range of the laser analyzer (2.5 µm). Also evident during hauling were large rates of streamside dust deposition (~0.2 - 2.1 mg/m^2 day) attributed to dust mobilization from traffic and wind disturbance, and was most obvious on surrounding streamside vegetation during Haul periods. Despite the fact that fine sediment generation on the road-surface is often greatest during hauling and harvesting activities (Reid and Dunne 1984), and that fine sediment was available on the road surface and streamside throughout the Haul period, no significant increases in TSS, turbidity or washload concentration occurred downstream of the road-stream crossing.

Negligible increases downstream of crossings during hauling were primarily related to the low number of high-intensity rainfall events that occurred during this life-phase. Rainfall intensity is often cited as a dominant factor controlling the amount of sediment generated from a road surface (Bilby et al., 1989; van Meerveld et al., 2014). During the Haul period the largest intensity event occurred on Julian Day 263, producing only 28 mm across 8-hours, with a maximum rainfall intensity of 3.3 mm/hr (10-minute interval). This was the first event to coincide with hauling activities, prior to which conditions were remarkably dry. Fines generated during hauling throughout an extended intra-storm period would likely be readily flushed in the early stages of an event (Ziegler et al., 2001). This was observed in TSS, turbidity, and wash load data surrounding Julian Day 263 when slight increases downstream (+3.8 mg/L, +0.65 NTU, +0.11 mg/L, respectively) of road-stream crossings occurred; a phenomenon sometimes referred to as 'first flush effects' (van Meerveld et al., 2014). However, generally no significant increases in any sediment parameter were observed at the downstream location during hauling operations. Hence, results from the Haul period suggest that this road life-phase was primarily *energy limited* by the low frequency of high-intensity rainfall events. The cessation of hauling activities during wet-periods (Julian Day 226-228, 256-264 and 283-284) was also expected to mitigate road-sediment generation during the Haul period (van Meerveld et al., 2014; Ziegler et al., 2001).

These results differ substantially from the 25-fold increase in TSS downstream previously reported during harvest activities in drought conditions (Aust et al., 2011). In part, such large increases observed in this study was due to the different type of road-stream crossings examined (i.e., bridges, culvert, fords, log-fills). In Star Creek, increases in downstream sediment inputs would be expected to be lower than the value reported by Aust *et al*. (2011) simply due to the use of bridge crossings, as these structures are often cited to contribute the least sediment to receiving streams (Aust et al., 2011; Witt et al., 2013).

Post-Haul

Similarly, no significant increases in TSS, turbidity or wash load concentrations occurred downstream of the road-stream crossing during the Post-Haul life-phase following crossing amendment. Again, this differs from increases in TSS noted as high as +317 mg/L in the months following road-stream crossing decommissioning (Aust et al., 2011). In addition to type of crossing, sediment impacts are also dependent on specific restoration strategies employed during decommissioning (Wear et al., 2013; Witt et al., 2013). In this study, this included the use of swamp mats to cross streams during decommissioning as well as the installation of silt fences at toe slopes following crossing removal which likely promoted streambank protection minimizing impacts on water quality.

A lack of response in sediment production (TSS, turbidity and wash load concentration) downstream during the Post-Haul, may also be reflective of the limited availability of fines sediments during this life-phase. In comparison to the Non-Haul and Haul period, coarser road-associated material was present following road roll-back during Post-Haul period. Larger mean particle-size (75µm) was reflective of a fully decommissioned road site, where fine sediments were redistribution and reworked into soil matrices. From a sediment delivery perspective, mobilization of coarser material at the toe slopes would only occur during large storm events. Such substantial event did not occur during the Post-Host period; hence the Post-Haul being described as *supply and energy limited*. The largest intensity event during Post-Haul occurred on Julian Day 199, producing 18.8 mm in over an hour, with a maximum rainfall intensity of 7.6 mm/hr likely leading to minimal increases (+0.10 mg/L) in wash load concentration downstream during trial surrounding this storm event.

In comparison to the Haul life-phase, significantly greater wash load concentrations (+0.18 mg/L) were observed during the Post-Haul period. This appears to be driven by greater median particle-size. Even though coarser road-sediment was available in the Post-Haul period there was no evidence of sediment delivery, as generally no upstream-downstream differences in particle-size of wash load were noted at the crossings. Greater wash load concentrations and coarser material present during Post-Haul were not attributed to higher ambient baseflow discharge, as baseflow rates in 2015 and 2016 were comparable (Table 2-3). However, this pattern could be the result of greater maximum peakflows exhibited in 2015 (Figure 2-5), that had the power to mobilize fine cohesive sediment fractions following armor layer breakup (as addressed in Chapter 3).

2.5 Conclusion

1. Temporary road-stream crossings were not significant point sources for suspended sediment input as the result of the overall combined disturbance of the rapid 10-month harvest and subsequent road decommissioning (the ‘get-in and get-out approach’). Although variation existed in suspended sediment parameters (TSS and turbidity) across sites, generally no large increases occurred at downstream sites. Higher turbidity levels at the upstream sample sites across both years were likely related to the natural variation in sediment and flow dynamics in each stream reach. Particle-size distributions (median particle-size, silt density) of suspended

sediment were also comparable between locations upstream and downstream of road crossing.

2. No significant increases in washload concentration, or changes in particle-size characteristics of wash load were noted downstream of the road-stream crossings as the result of the rapid harvest and road decommissioning. However, minimal increases (~10 mg/L) in wash load concentrations, interpreted as first flush effects (van Meerveld et al., 2014), were observed following trials encompassing larger rainfall events during the Haul and Post-Haul periods.

3. Unlike previous research, my results suggest that no single road-crossing life-phase contributed sediment to stream, as negligible inputs (TSS, turbidity, wash load concentration) during the Non-Haul, Haul and Post-Haul periods were observed at the downstream site. This included negligible impacts on sediment during the Post-Haul/decommissioning life-phase which has not been well addressed in the literature,

4. Despite two relatively large storm events during the Non-Haul life-phase, no significant increases in daily-composite or storm event grab samples occurred at downstream sites. In large part, this reflects secondary BMPs employed during Non-Haul, particularly the prohibition of hauling activities during the wet season coinciding with the temporary installment of a water bar network. These practices were thought to be effective at mitigating event-related sediment delivery during this period. In contrast, the Haul and Post-Haul period were primarily energy (rainfall) limited by the occurrence of few large-intensity rainfall events.

Table 2-1. Basin, harvest and road characteristics for three study sub-catchments of Star Creek

Basin Characteristics	i) McLaren	ii) Star East	iii) Star West
Location[a]	49°35' 56.932"N; 114°33' 38.796" W	49°35' 44.772"N; 114°34' 16.392"W	49° 36' 18.927"N; 114° 34' 3.487"W
Basin area (km^2)	0.95	3.89	4.63
Mean elevation (m)	1693	1869	1928
Mean basin slope (%) (±SD)	25.38 (11.7)	52.66 (37.3)	58.68 (57.9)
Stream slope (%)	10.93	12.53	11.87
Drainage density (km/km^2)	3.03	1.40	1.49
Stream wetted-width (m)	1.2	2.3	3.0
Stream Classification	Ephemeral	Permanent-small	Permanent-small
Harvest & Road Characteristics			
Harvest treatment	Group selection shelterwood harvest	35 m-Strip cut harvest	Clear-cut harvest with green patch retention
Harvested area (km^2)	0.56	0.44	0.68
Percent harvested (%)	59	11	15
Block Road Length (km)	4.8	3.7	3.8
Road density (km/km^2)	5.1	0.95	0.82
Approach slopes (upslope/downslope %)	9.1 2.5	2.3 4.8	11.9 4.8
Crossing type	Two-girder bridge	Two-girder bridge	Two-girder bridge
Length	15 m	12 m	9 m

[a] UTM (NAD83) Zone 11

Table 2-2. i) Precipitation records and ii) storm-event characteristics at Star Main gauging station (49°36' 36.560" N; 114° 33' 21.747" W) during harvest (2015) and 1-year post-harvest (2016) and for iii) across road life-phases (Non-Haul, Haul and Post-Haul).

i. Total precipitation (mm) ±(SE) across study period and hydrograph flow components

Period	Duration	N	2015	2016
Study Period	May 1st - August 31th	123	285.8 (0.6)	214.8 (0.3)
Stormflow and melt freshet	May 1st - June 30th	61	149.6 (1.0)	101.9 (0.5)
Baseflow	July 1st - August 31st	62	136.2 (0.7)	113.3 (0.2)
Total Annual	Jan1st - Dec 31st	365	703.8 (0.3)	568.0 (0.2)

ii. Storm event characteristics across study period

Descriptor	2015	2016
Number of storms (>10 mm)	8	4
Maximum rainfall intensity (mm/hr)[b]	5.6	7.6
Average rainfall intensity (mm/hr)[b]	0.53	0.43
Average storm duration	9.3 hours	8.5 hours

iii. Total precipitation (mm) ±(SE) and daily averages (mm/d) across road life-phases

Road Life-Phase	Duration	N	Total Precipitation (mm)	Daily Average PPT (mm/d)	Max. Rainfall Intensity (mm/hr)[b]
Non-Haul	May - June 30th 2015	61	149.6 (1.0)	2.5	5.6
Haul	July - October 15th 2015	107	253.1 (0.4)	2.4	3.3
Post-Haul	May - August 22nd 2016	123	214.8 (0.3)	1.7	7.6

[a] N, refers to the number of days, [b] 10-minute interval

±SE= Standard Error

Table 2-3. Average daily streamflow (mm) ±(SE) for McLaren, Star East and Star West Ck. during 2015 (harvest) and 2016 (1-year post-harvest).

			McLaren		Star East		Star West	
Period	Duration	N	2015	2016	2015	2016	2015	2016
Study period	May 1st- August 31th	123	0.83 (0.09)	0.49 (0.06)	2.21 (0.24)	1.67 (0.11)	2.86 (0.27)	2.42 (0.15)
Stormflow and melt freshet	May 1st-June 30th	61	1.56 (0.10)	0.97 (0.09)	3.64 (0.40)	2.66 (0.11)	4.65(0.44)	3.64 (0.20)
Baseflow	July 1st-August 31st	62	0.12 (0.02)	0.01(0.01)	0.81 (0.03)	0.70 (0.03)	1.10 (0.04)	1.21 (0.06)
Annual	Jan 1st-Dec 31st	365	1.15 (0.04)	0.58 (0.03)	1.27 (0.08)	1.18 (0.04)	1.87 (0.10)	1.59 (0.06)

±SE= Standard Error

Table 2-4. Median Total Suspended Solids concentrations (TSS; mg/L) and ii) Turbidity (NTU) for daily composite 1L samples taken upstream (US) and downstream (DS) at each stream crossing. Probabilities reflect Wilcoxon-signed rank tests between US and DS locations. Boldface indicates significance.

		i. TSS (mg/L)			ii. Turbidity (NTU)		
Stream Crossing	N	Median US (±SE)	Median DS (±SE)	P value	Median US (±SE)	Median DS (±SE)	P value
McLaren	109	2.17 (1.14)	1.5 (1.15)	0.149	0.30 (0.06)	0.44 (0.18)	**0.0022**[a]
Star East	250	1.10 (0.22)	1.15 (0.18)	**0.001**[a]	0.50 (0.22)	0.25 (0.04)	**< 0.001**[a]
Star West	251	1.82 (2.39)	2.03 (1.08)	0.289	0.63 (2.15)	0.47(1.96)	**< 0.001**[a]
Combined (All streams, Both years)	610	1.49 (0.99)	1.62 (0.50)	0.52	0.50 (0.45)	0.37 (0.41)	**< 0.001**

[a] Significantly different at an overall (experimental wise) rejection level of 0.05 (p=0.016)
±SE= Standard Error
NTU=nephelometric units

Table 2-5. Median wash load concentration (mg/L) and particle-size characteristics for continuous wash load samples collected upstream (US) and downstream (DS) pooled for all stream crossings across harvest (2015) and 1-year post-harvest (2016). Probabilities reflect Wilcoxon-signed rank tests between US and DS locations.

	i. Wash load concentration (mg/L)			ii. Particle-size characteristics				
Site	N	Median (±SE)	P value	N	Median Particle-Size (μm) (±SE)	P value	Median Silt Density (%) (<64 μm) (±SE)	P value
US	16	0.28 (0.11)	0.609	15	70.0 (5.1)	0.530	39 (3)	0.562
DS	16	0.36 (0.07)		15	78.9 (5.3)		37 (3)	

±SE= Standard Error

Table 2-6. Median Total Suspended Solids concentrations (TSS; mg/L) and Turbidity (NTU) for daily composite 1L samples taken upstream (US) and downstream (DS) of stream crossings across different road life-phases (Non-Haul, Haul, Post-Haul) during the harvest (2015) and 1-year post-harvest (2016). Probabilities reflect Wilcoxon-signed rank tests between US and DS locations. Boldface indicates significance.

			i. TSS (mg/L)			ii. Turbidity (NTU)		
Year	Road life-phase	N	Median US (±SE)	Median DS (±SE)	P value[a]	Median US (±SE)	Median DS (±SE)	P value[a]
2015	Non-Haul	131	1.47 (4.56)	1.99 (2.24)	0.402	0.78 (2.09)	0.44 (1.91)	**< 0.001**
	Haul	235	0.60 (0.14)	0.32(0.10)	0.034	0.41 (0.06)	0.37 (0.03)	0.050
2016	Post-Haul	244	2.12 (0.15)	2.07 (0.09)	0.593	0.53 (0.11)	0.36 (0.04)	**< 0.001**

[a] Significantly different at an overall (experimental wise) rejection level of 0.05 (0.016)
±SE= Standard Error
NTU=nephelometric units

Table 2-7. Median i) Total Suspended Solids (TSS; mg/L) from grab samples taken upstream (US) and downstream (DS) during two storm events (Julian Day 146, 153) pooled across streams. ii) Particle-size characteristics of grab samples from largest storm event (50.5 mm, Julian Day 153) at three road-stream crossings during the Non-Haul period. Probability reflects Wilcoxon-signed rank tests between US and DS locations.

i. Total Suspended Solids (mg/L)

Period	N	Median US (±SE)	Median DS (±SE)	P value
Non-Haul	10	25.0 (67.8)	35.0 (71.4)	0.59

ii. Particle-Size Characteristics

Stream Crossing	N	Site	Mean Particle-Size (µm)(±SE)	Mean Silt Density (< 64 µm)
McLaren	2	US	27.15 (47.8)	79%
	2	DS	29.3 (43.0)	78%
Star East	2	US	27.9 (38..7)	80%
	2	DS	43.8 (58.3)	68%
Star West	2	US	29.52 (52.4)	75%
	2	DS	24.79(49.6)	79%

Table 2-8. Median wash load concentration (mg/L) during baseflow conditions (July-August 31st) upstream (US) and downstream (DS) of stream crossings across Haul (2015) and Post-Haul (2016) life-phases. Probabilities reflect Wilcoxon-signed rank tests between US and DS locations.

		Wash load concentration(mg/L)		
Road Activity	N	Site	Median (±SE)	P value
Haul	4	US	0.19 (0.10)	0.250
	4	DS	0.17 (0.06)	
Post-Haul	4	US	0.40 (0.51)	0.789
	4	DS	0.41 (0.06)	

±SE= Standard Error

Table 2-9. Median wash load concentration (mg/L) (n=8) and associated particle-size characteristics (n=7) for samples during baseflow conditions (July-August 31st) across Haul (2015) and Post-Haul (2016) life-phases. Data is pooled across all three road-stream crossing sites. Probabilities reflect Wilcoxon-signed rank tests between US and DS locations. Boldface indicates significance.

	i. Wash load concentration (mg/L)			ii. Particle-size characteristics				
Road Activity	N	Median (±SE)	P value[a]	N	Median Particle Size (µm) (±SE)	P value[a]	Median Silt Density (%) (<64 µm) (±SE)	P value[a]
Haul	8	0.18 (0.06)	**0.03**	7	74.7 (9.7)	**0.016**	37 (5)	**0.016**
Post-Haul	8	0.41 (0.18)		7	88.0 (10.0)		34 (3)	

[a] Significantly different at an overall (experimental wise) rejection level of 0.05

±SE= Standard Error

Table 2-10. Particle-size characteristics of road-associated sediment sources during harvest (2015) (road sweep, dust deposition. culvert storm sample) and 1-year post-harvest (2016) (road surface sample).

Year	Sample	Road life-phase	N	Mean Particle-Size (µm) (±SE)	Mean Silt Density (%)	D10	D50	D90
2015	Culvert storm sample	Non-Haul	5	17.2 (26.9)	82	2.9	15.9	111.0
	Road sweep	Haul	3	18.9 (39.9)	78	2.6	19.0	126.3
	Dust deposition	Haul	6	45.0 (37.6)	60	9.1	47.6	206.8
2016	Road bulk	Post-Haul	6	75.0 (41.2)	43	16.6	91.5	250.1

±SE= Standard Error

D10, D50, D90: Three point particle-size distribution. i.e., D50 (median) particle size in which 50% is under diameter

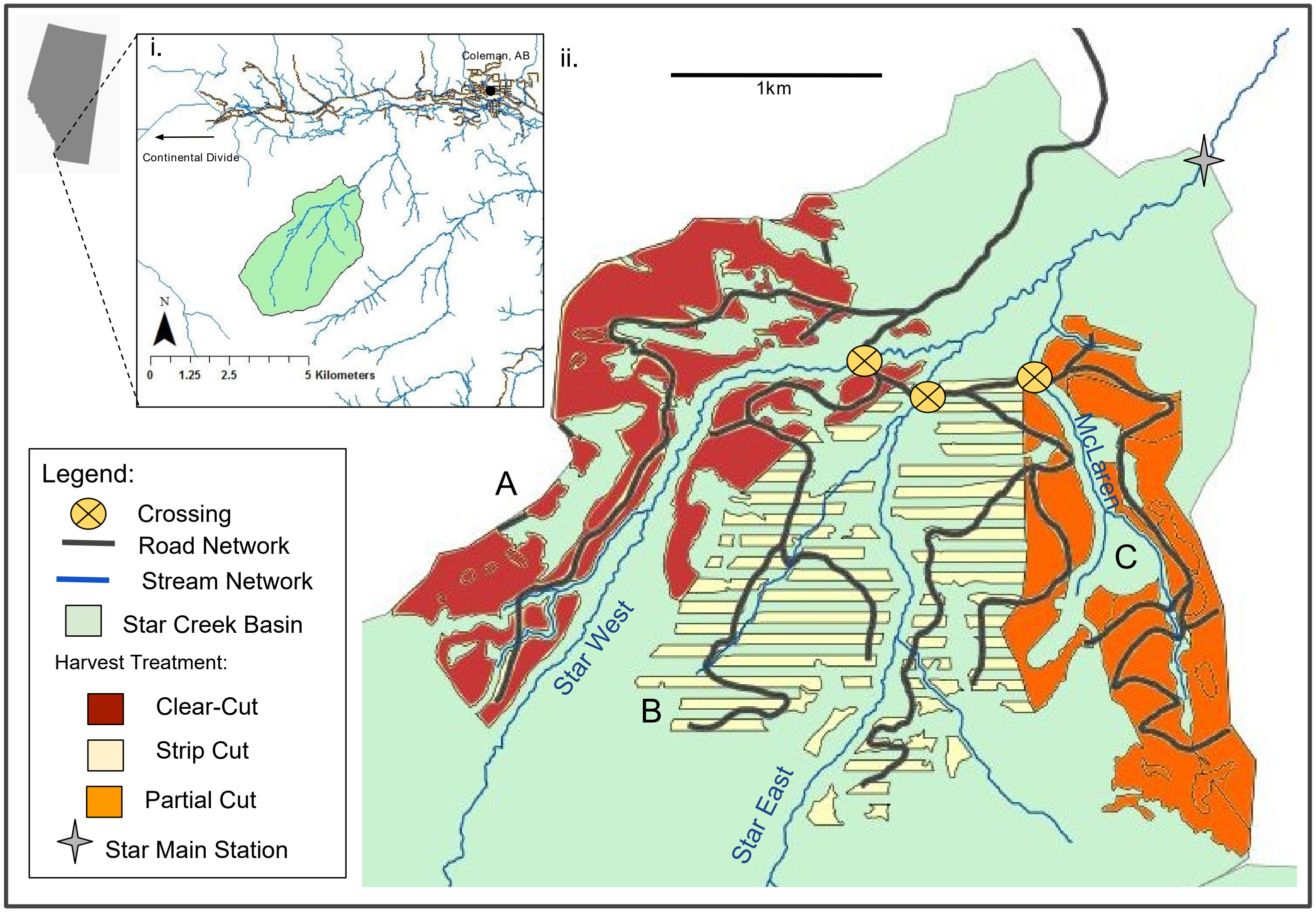

Figure 2-1. i) Map of Star Creek Basin which is located in the headwaters of the Oldman River Basin, Alberta, Canada. ii) Map of three harvest treatments applied to Star Creek. Harvest treatments included a 68-hectare variable retention clear-cut harvest (Star West, A); a 44-hectare 35-m strip harvest (Star East, B); and a 56-hectare group selection shelterwood harvest with 50% retention (McLaren, C). Temporary road network (black), bridge crossings (yellow circle), stream network (blue) and Star Main Gauging Station (grey star) also shown.

Figure 2-2. Single span two-girder bridge crossings in Star West (9 m, top), Star East (10 m, middle) and McLaren Ck. (15 m, bottom). Bridges were wrapped in geotextile fabric.

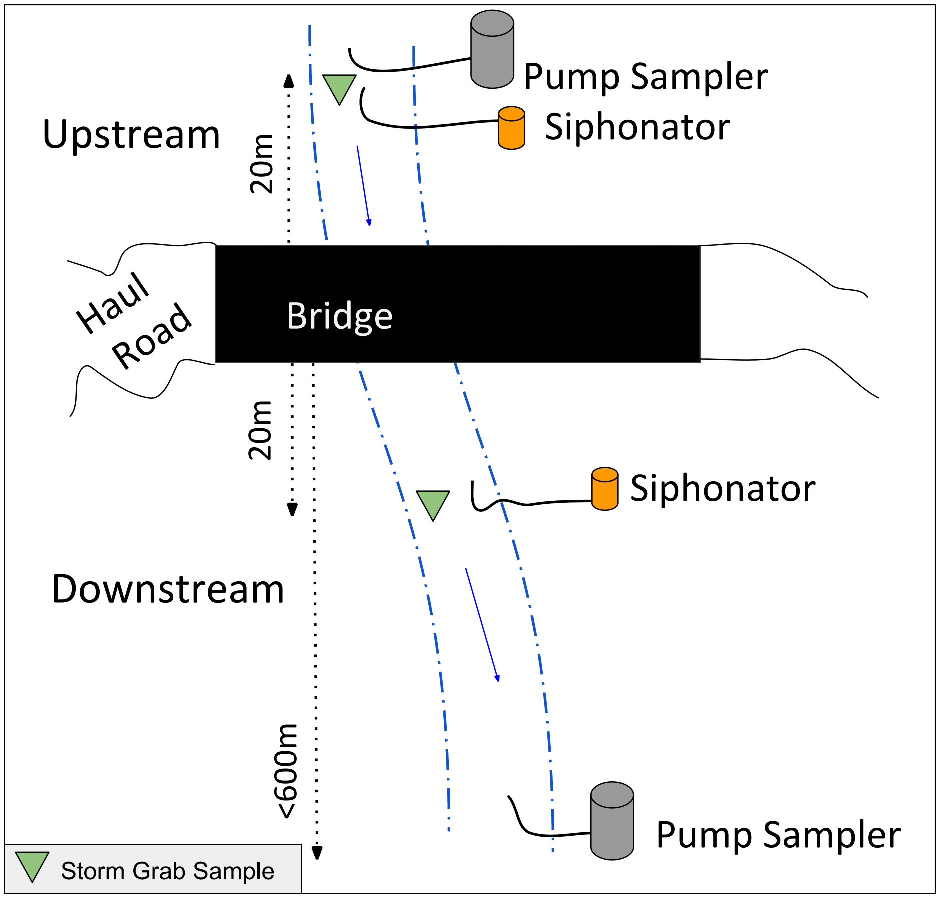

Figure 2-3. Experimental design to capture suspended sediment production at road-stream crossing sites (not to scale). Control (upstream; US) pump samplers were located 20 m above bridge crossings, while downstream samplers (DS) were less than 600 m below bridge crossings. Location of storm grab samples also highlighted.

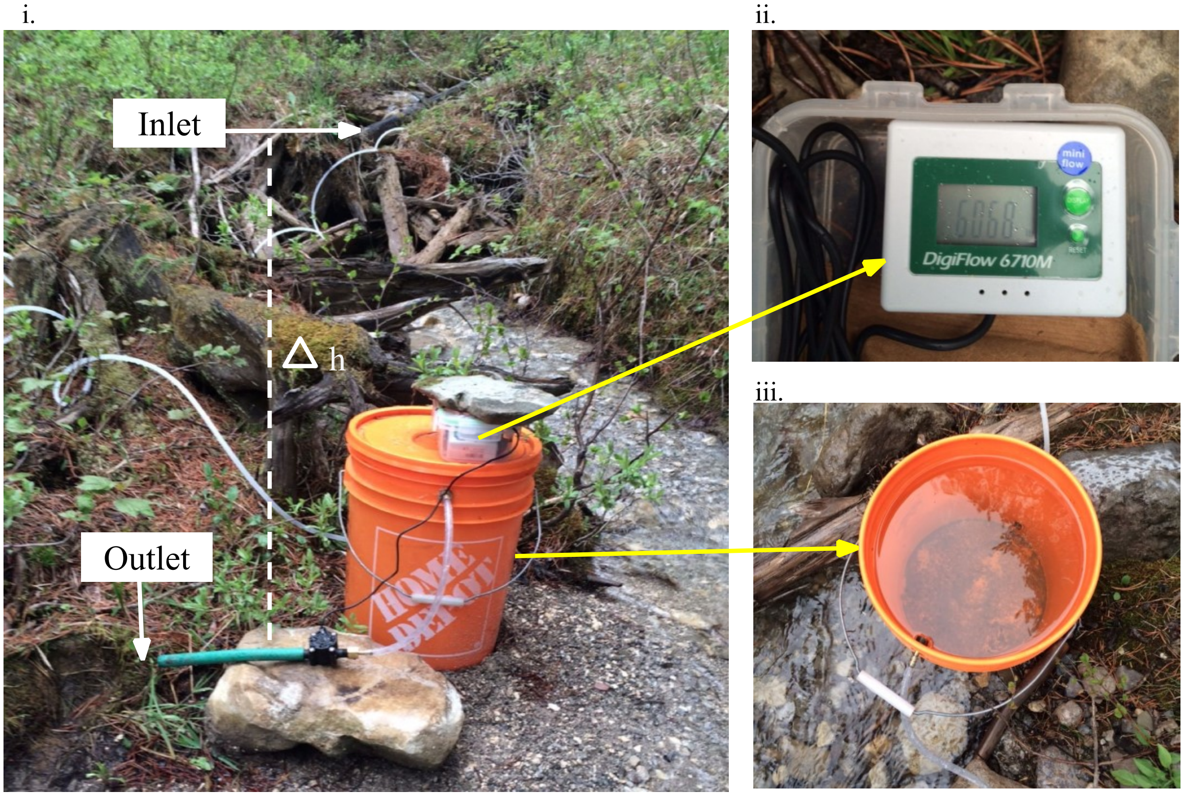

Figure 2-4. The ‘siphonator’ sampling device used to measure continuous wash load concentration (mg/L) up and downstream of road-stream crossing in areas of i) sufficient hydraulic head (meanders, log-steps etc.). Siphonators were deployed for 2-3 weeks, during which ii) total volume (L) was recorded using a DigiFlow volume totalizer (Model 6710M-32, Savant Electronics), while iii) settling basin accumulated sediment.

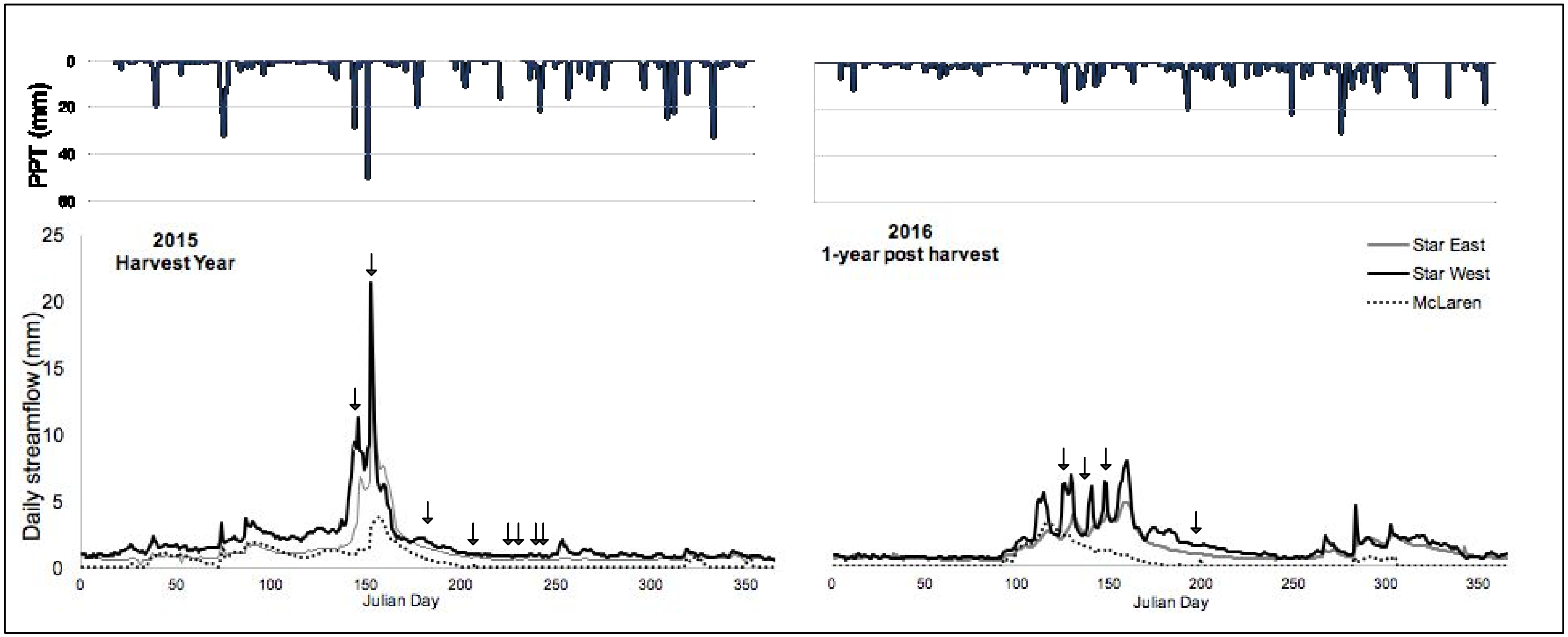

Figure 2-5. Daily precipitation (mm) and daily streamflow (mm) during harvest (2015) and 1-year post-harvest year (2016). Streamflow for McLaren (dotted), Star East (solid grey) and Star West Ck. (solid black) are shown. Arrows indicate rainfall events > 10 mm.

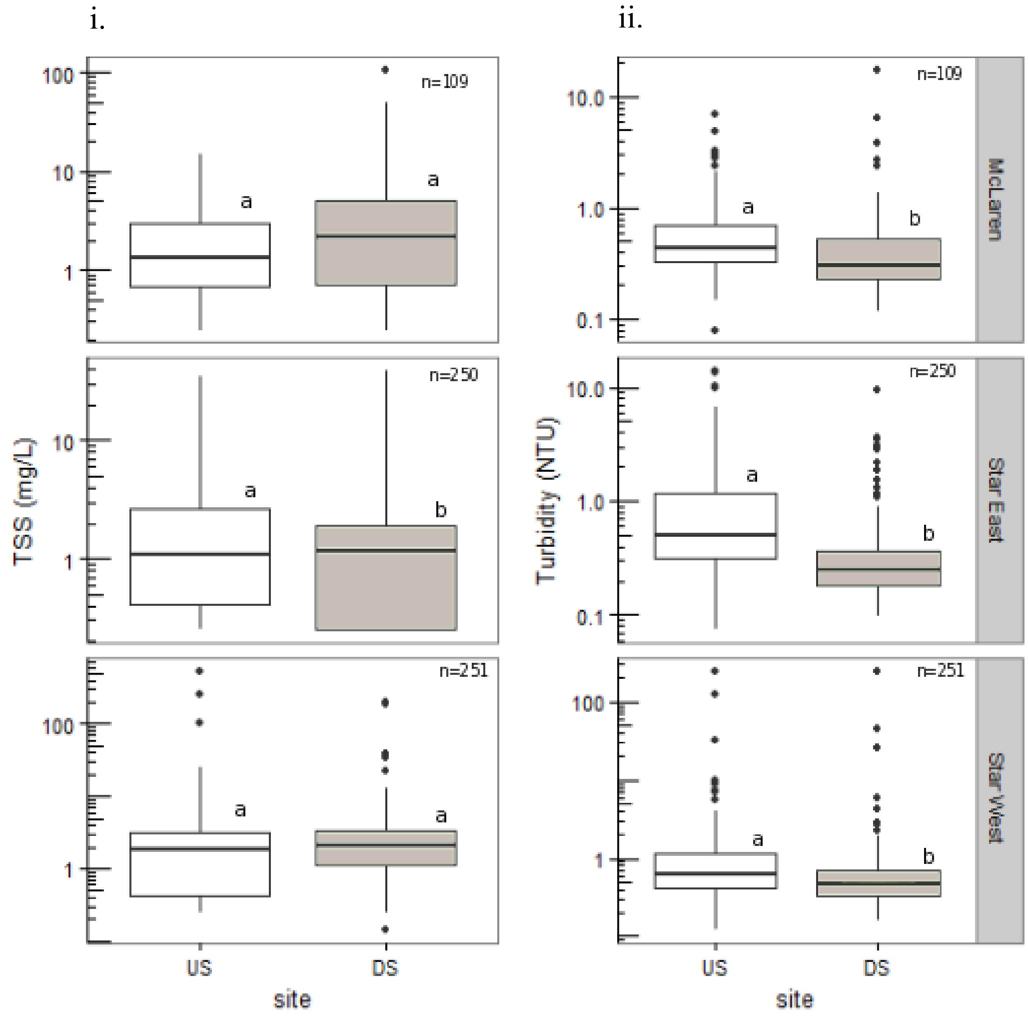

Figure 2-6. Distribution of Total Suspended Solids concentrations (TSS; mg/L), and Turbidity (NTU) upstream (US; white) and downstream (DS; grey) at three stream crossings: McLaren (top), Star East (middle), and Star West (bottom). Horizontal lines represent median, while upper and lower limits of boxplots indicate 75th and 25th percentile, whiskers indicate the 95th and 5th percentile, solid dots indicate outliers. Different letters are significantly different (Wilcoxon-sign ranked, $p < 0.016$).

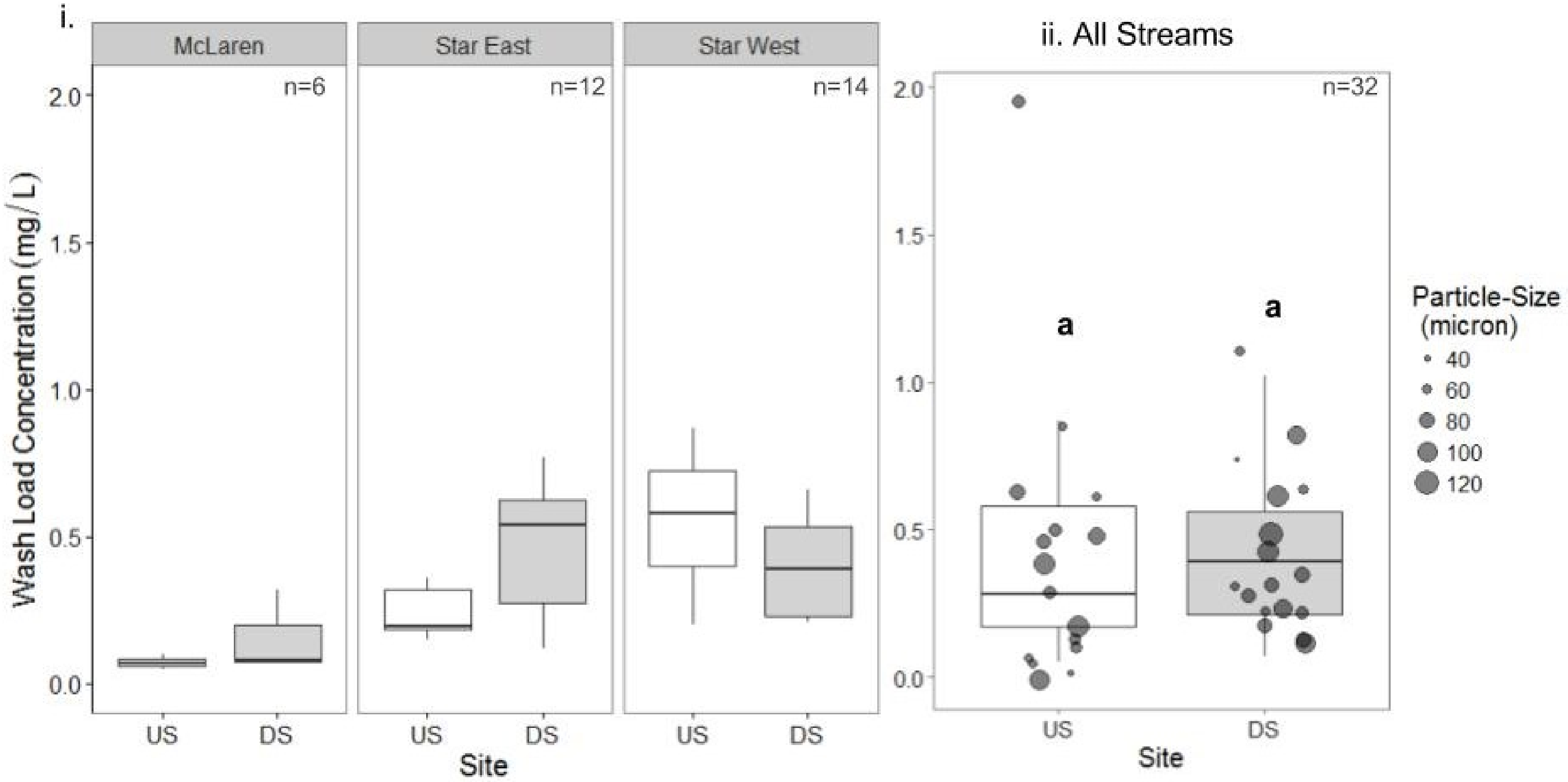

Figure 2-7. Boxplots displaying the distribution of wash load concentrations (mg/L) upstream (US;white) and downstream (DS; grey) of individual stream crossings and pooled across stream crossings. Dotplots represent median particle-size (µm) of wash load. Horizontal lines represent median, while upper and lower limits of boxplots indicate 75th and 25th percentile, whiskers indicate the 95th and 5th percentile. Different letters are significantly different (Wilcoxon-sign ranked, $p<0.05$).

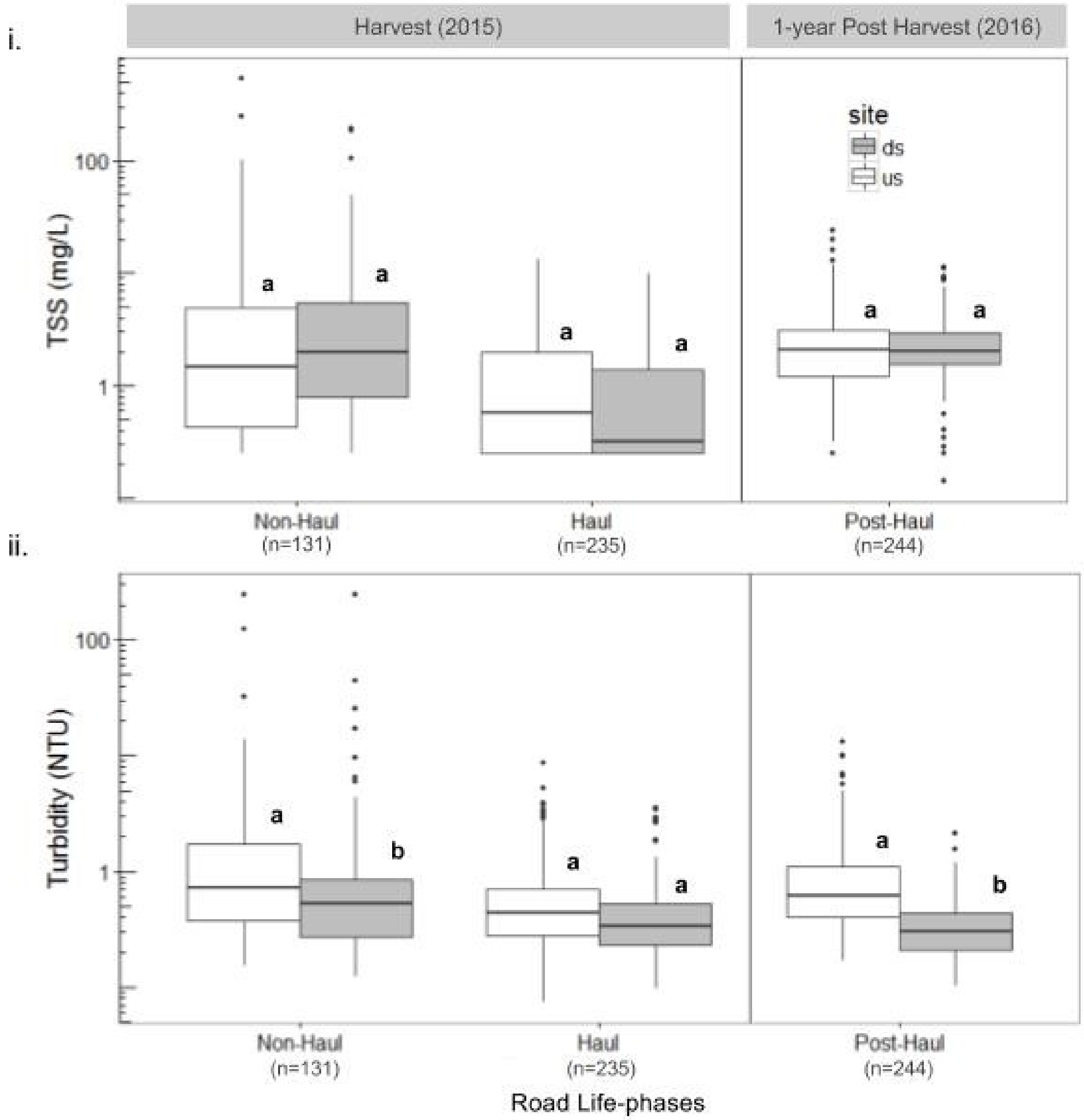

Figure 2-8. Distribution of Total Suspended Solids concentrations (TSS; mg/L), and Turbidity (NTU) upstream (US; white) and downstream (DS; yellow) of road-stream crossings across road life-phases (Non-haul, Haul, Post-Haul). Horizontal lines represent median, while upper and lower limits of boxplots indicate 75th and 25th percentile, whiskers indicate the 95th and 5th percentile, solid dots indicate outliers. Different letters are significantly different (Wilcoxon-sign ranked, $p < 0.016$).

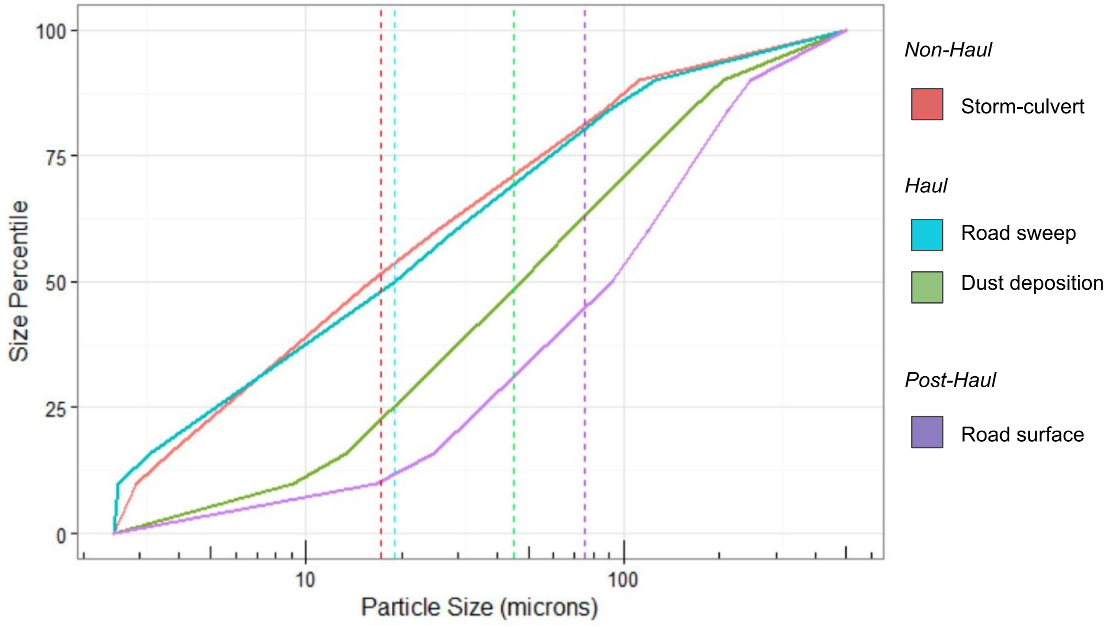

Figure 2-9. Particle-size distributions and mean particle-size (μm; dotted vertical line) of road-associated sediment in 2015 during Non-Haul (Storm-culvert), Haul (Road sweep 2015, Dust Deposition) and in 2016 during the Post-Haul (Road surface 2016) road life-phases.

Figure 2-10. Photograph of backhoe cat tracks present on valley banks in McLaren Creek.

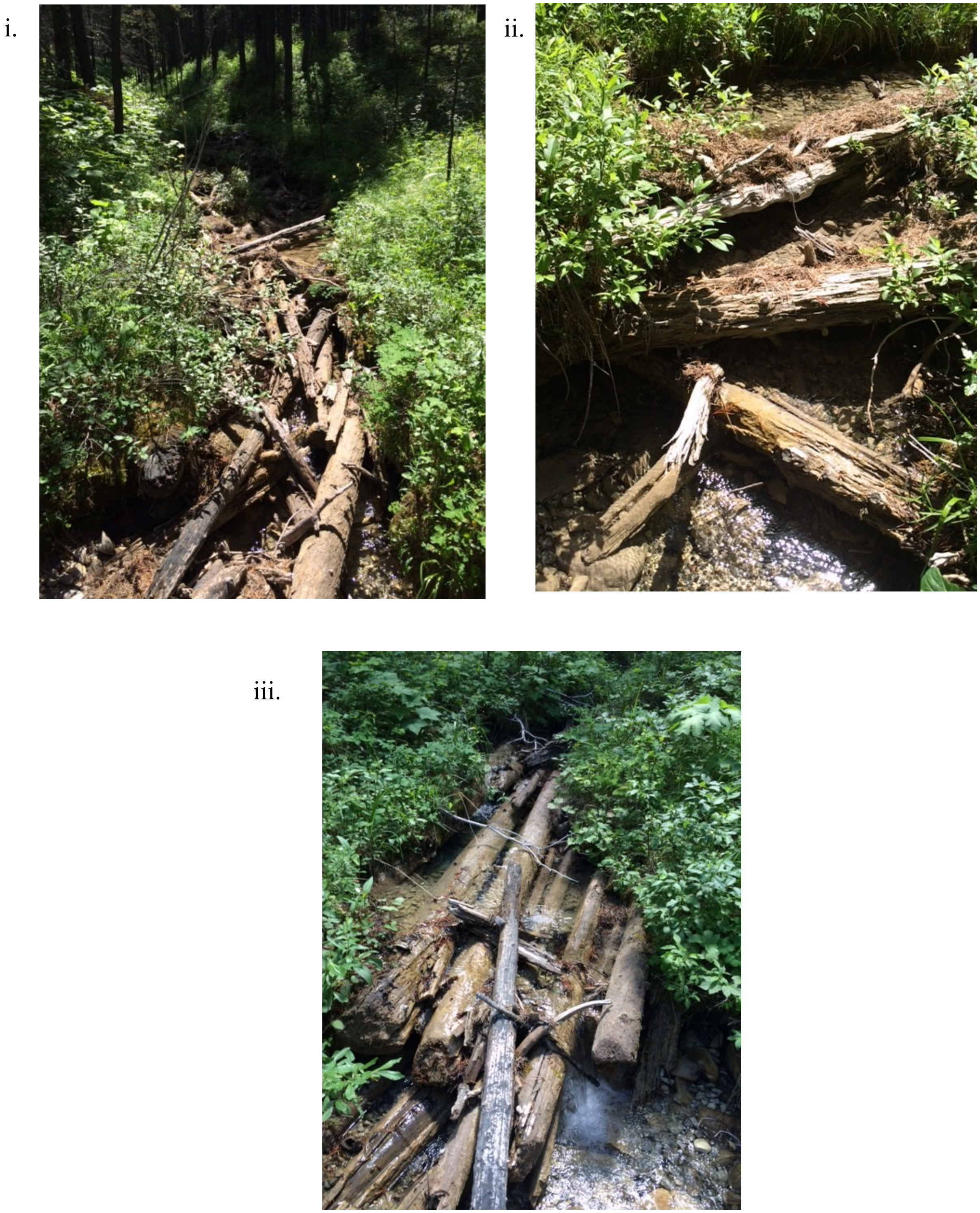

Figure 2-11. Examples of log slides (i., iii.) and log step (ii.) features located between upstream and downstream sample sites in McLaren Ck.

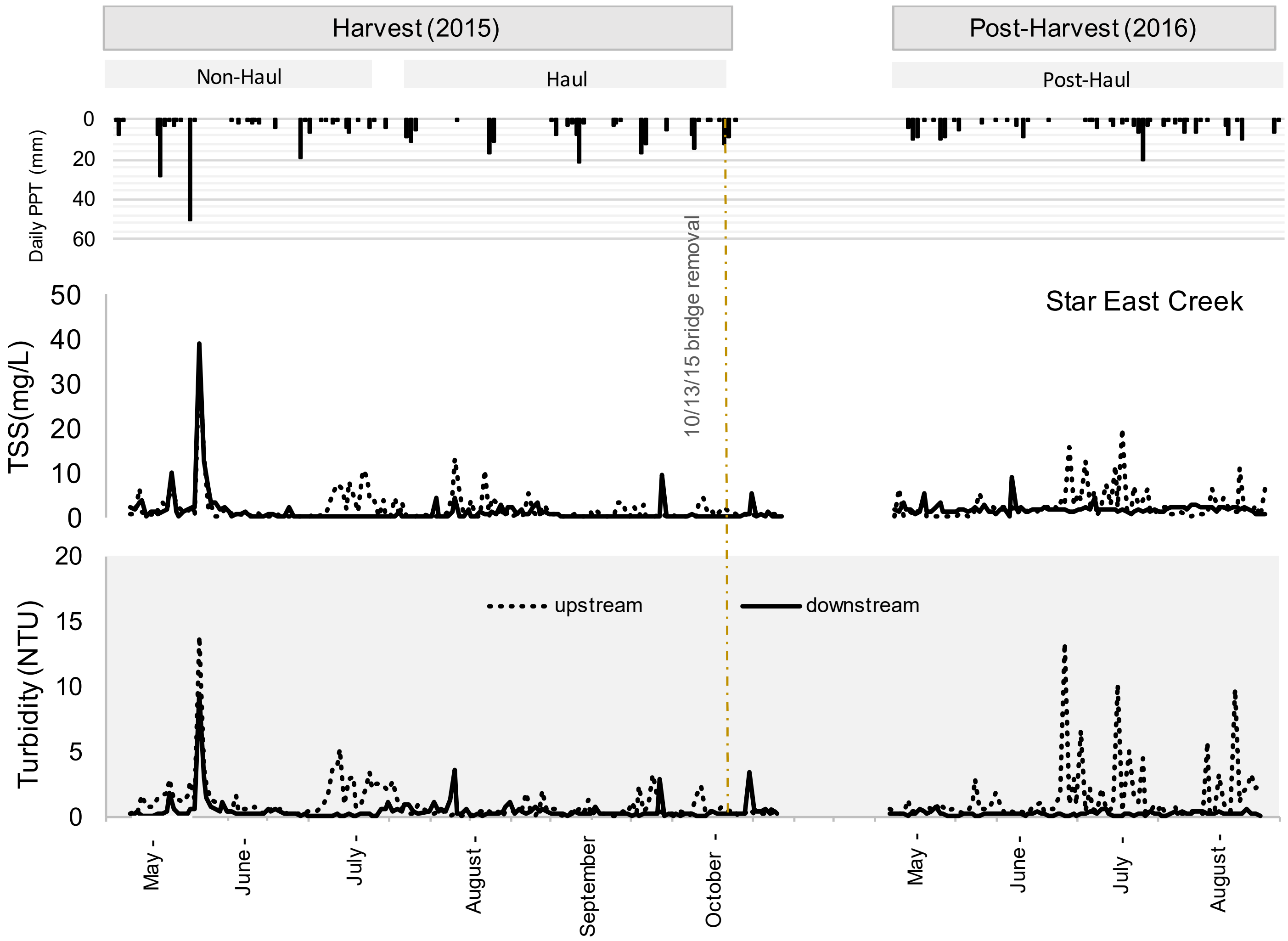

Figure 2-12. Times series of Total Suspended Solids (TSS, mg/L) and Turbidity (NTU) upstream (US; dotted) and downstream (DS; solid) at Star East stream crossing during harvest year (n=366) and 1-year post-harvest (n=244). Daily precipitation (PPT, mm; inverted black bar) recorded at Star Main gauging station.

Figure 2-13. Hillslope woody debris retaining sediment–laden runoff from temporary water-bar network.

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Chapter 3: Short-term effects of rapid harvest and road-stream crossing decommissioning on sediment in gravel bed streams

3.1 Introduction

The effects of forest harvesting on increased sediment production and delivery to waterways has been well-documented (Anderson and Lockaby 2011) including elevated rates of sediment deposition (ingress) in gravel bed streams that can impact aquatic habitat and influence the fate of sediment-associated pollutants (Scrivener and Brownlee 1989; Descloux et al., 2013; Droppo 2001). In headwater catchments, the impacts of deposited sediment following initial road disturbance may also be long-lasting due to lags in timing of sediment transport because of sediment storage in streambeds (Swank et al., 2001; Benda et al., 2005; Hawthorn 2014). While the ingress of sediment < 2 mm is of general concern for benthic habitat quality (Lisle 1989; Soulsby et al., 2001), the ingress of fine cohesive sediment (< 64 μm) is of concern regarding long-term contaminant storage and transport (Ongley et al., 1992; Droppo 2001). Indeed, in harvested systems fine sediment ingress (< 64 μm) is of particular interest as this the size fraction often generated on haul roads (Bilby 1985).

As point sources for sediment pollution, road-stream crossings are the sites where the impact of road-related sediment production is frequently reported (Lane and Sheridan 2002; Bilby 1985; Spillios 1999; Petticrew and Rex 2006; Kreutzweiser et al., 2005). Increases in sediment ingress are reported typically 25 m downstream of crossing sites (Lane and Sheridan 2002); however, increased sediment deposition as far as 200-300 m below crossing sites have also been reported (Kreutzweiser and Capell 2002; Maitland et al., 2016). The spatial extent of deposited sediment downstream of forest related disturbance would be dependent on several physical mechanisms including flow conditions, sediment conveyance, particle-size, and bed composition. However, few field studies have rigorously investigated the ingress of fine sediment progressively downstream of crossings.

Increases in sediment ingress downstream of road-stream crossings is often attributed to specific road life-phases. The greatest impacts often occur following construction at stream crossings or crossing upgrades (Lane and Sheridan 2002; Rex and Petticrew 2011). Increases of sediment to receiving streams during construction or upgrading are often associated with the mechanical introduction of coarser material. Road ripping and the decommissioning of road-stream crossings is another road life-phase that can potentially affect the rates and magnitudes of sediment production (Switalski et al., 2004); however, the impacts of these activities on sediment ingress rates following decommissioning activities have been largely unexplored.

Despite the short-term impacts on sediment linked to road and road-stream crossing decommissioning activities, the employment of this strategy immediately following harvesting operations is broadly recognized as a Best Management Practice (BMP) to mitigate chronic sediment sources (Switalski et al., 2004). While limiting the exposure of chronic sediment pollution from forestry roads is extremely important in high-value headwaters streams that are sources for drinking water supplies (Emelko et al., 2011) or inhabited by at-risk fisheries (Ripley et al., 2005), the efficacy of various decommissioning strategies is largely undocumented and is required to better inform forestry road management policy (Grace and Clinton 2007).

The broad objective of the study was to assess the impact of the ‘get-in and get-out’ approach of forest management on sediment ingress in gravel bed streams across a 10-month period of rapid harvest and road decommissioning operations. Specific objectives included assessing how sediment ingress rates and particle-size characteristics vary across operational road life-phases (Haul and Post Haul) and across two spatial scales (site (immediate location of road crossings) vs. broader reach scale). This multi-scale sampling approach may provide key insights into the impacts to streambed sediment ingress related to rapid harvest and road decommissioning at road-stream crossings as well as quantify the efficacy of such strategies for future forest harvesting in high-value or sensitive watersheds.

3.2 Materials & Methods

3.2.1 Study Area

This study was conducted in the Star Creek watershed in the headwaters of the Oldman River Basin along the eastern slopes of the Rocky Mountain front-range in southwestern Alberta, Canada (Figure 2.1). Star Creek is a fourth order stream that drains an area of 1865 hectares (49° 37' N; 114° 40' W). A detailed description of the basin characteristics, biogeochemical and hydrological setting, as well as the harvesting operations in Star Creek can be found in Section 2.2.1. and Section 2.2.2., respectively. In brief, three road-stream crossings were monitored for the duration of the 10-month rapid harvest, as well as the year following decommissioning in McLaren, Star East and Star West sub-catchments. As presented in Chapter 2, fine-silt material (18µm) was generated on the active road-surface during the Haul life-phase while fine-sand material (75µm) was observed at the decommissioned site during the Post-Haul (Table 2-10). Additionally, during the Haul period (July-August 2015) large stream side dust deposition rates were observed (0.2-2.1 mg/m^2 day).

All streams studied were first-order headwater streams with step-pool morphology (Macdonald, 2008). Star East and Star West Creek are small permanent streams, while McLaren Creek is an ephemeral watercourse often drying up completely in early to mid-July. All three sites can be described as well-armored gravel bed streams with variable substrate particle-size

(Figure 3-1). Previous freeze-coring done in Star Creek has shown that bed sediment is dominated (42% by weight) by fine gravel (4-8mm) sized fractions (Hawthorn, 2014).

3.2.2 Precipitation and Streamflow

Star Creek watershed is the location of a broader hydrological and meteorological monitoring network managed by the Southern Rockies Watershed Project (Silins et al., 2016). Annual precipitation (mm) was measured at a gauging station (Star Main) downstream of all three sub-catchments (Figure 2-1) during 2015 and 2016. For Star East and Star West Ck. streamflow (Q) was gauged using 10-minute stage recordings (Model U20, Onset Computer Corp.) combined with bi-monthly on-site field measurements of both manual stream stage and discharge (Swoffer Model 2100, Swoffer Instruments Inc.; Sontek Flowtracker, YSI Inc.). Streamflow in McLaren Ck. was gauged using a 120° V-notch weir. A full description of precipitation and hydrometric monitoring methods can be found in Section 2.2.3.

3.2.3 Study Design

This study was designed to measure the rates of sediment ingress in gravel bed streams at three temporary road-stream crossings. Study sites were located upstream (US) and progressively downstream (DS1, DS2, DS3) of the road-stream crossings in Star East and Star West Creek (Figure 3-2). Only one upstream and one downstream transect was constructed in McLaren Creek due intermittent flows in this stream. Typical distances between transects ranged from 30 to 50 m. The furthest transect was located approximately 120 m downstream of the crossings. Transects were located in relatively straight stream reaches with roughly similar cross sectional areas. Each transect consisted of five sediment ingress traps, based on recommendations of Rex and Petticrew (2011) (Figure 3-3). Sediment ingress trap were installed after initial road grading, in mid-spring of the harvest year just before summer hauling began. Impacts on ingress sediment were examined for baseflow conditions during active hauling (Haul; 2015) and 1-year following road-stream crossing decommissioning (Post-Haul; 2016) (Appendix A).

3.2.4 Ingress Traps

Sediment ingress traps were deployed to measure the rate of Total Ingress Solids (TIS; mg/cm^2 day, < 2 mm) (Figure 3-3). Such techniques are useful when measuring sediment ingress attributed to a given point source (Rex and Petticrew 2011). The traps consisted of a plastic food container filled with pre-washed native reference gravel (2-70 mm). Larger traps were installed in Star East and Star West Creek (Volume: 1125 ml, Surface Area: 156.3 cm^2, 13 x 13 x 9 cm), while McLaren Creek transects consisted of smaller traps (Volume: 880 ml, Surface Area: 145.0 cm^2, 12 x 17 x 8 cm) to accommodate the narrower stream channel (Figure 3-4).

Traps were deployed to plywood-based anchors that were secured to the streambed with rebar (Figure 3-3). Plywood anchors were installed prior to trap deployment and left to overwinter between study years. Trap anchors also proved useful in minimizing the mobilization of sediment during sample collection. The anchors were buried to a depth of 15 cm to insure that the traps were installed flush with the streambed. The same anchor sites were used for all trials, and were selected to represent variation in microsite streambed topography and bed structure that is found in riffle habitat. Prior to deployment, pea-sized reference gravel was placed at the bottom of the trap and overlaid with larger gravel sized reference material to prevent washout. Also to prevent excavation of reference gravel during high streamflows, plastic mesh coverings

(1 inch. mesh squares) were installed during the collection period (Figure 3-3). The mass of reference material in each trap ranged from 1.2 to 1.5 kg.

3.2.5 Ingress Sediment Sampling

Ingress traps were deployed during ice-free periods (May-August) in 2015 (harvest) and 2016 (1-year post-harvest). Due to high sample loss during large 2015 rain events, ingress trap data were only analyzed for baseflow conditions (July1st - August 30th) across both years. Sediment ingress traps were deployed in the upstream to downstream direction and left in the stream for a period of 2 to 3 weeks (Table 3-1, 13-19 days). Short duration trap deployments (trials) were based on sampling timelines for continuous wash load trials (Chapter 2), but also ensured that the capacity of trap void space was not exceeded—a common problem with longer deployments (Rex and Petticrew 2011). Upon retrieval, trap removal started at the furthest downstream site, working upstream. Samples from sediment ingress traps were collected then passed through a 2mm sieve (Fisher Scientific, U.S Standard No.10) and flushed with a 500 mL nalgene squirt bottle. Sediment ingress rates were normalized by the amount of time deployed to the stream. Any samples lost due to high flows, or cracks in the traps were also recorded. Samples were stored in a cool dark place prior to processing.

3.2.6 Sediment and Particle-Size Analysis

Sediment ingress samples were allowed to settle for three days, decanted, and oven-dried overnight at 107 °C (Klute *et al.,*1986). Particle-size distributions were determined from a subset of ingress sediment samples (n= 94) using a laser particle analyzer (LISST Type C (2.5-500 µm), Model 100X, Sequoia Scientific, Section 2.2.8) in conjunction with a full path mixing chamber

(SAA-L100X-CHMX, Sequoia Scientific). Measurements of particle-size distribution (D10,16,50,60,84,90) and silt density (<64 μm, Eq.1) were based on an average of 30 measurements per sample. In this study, silt density (%) was considered as an indicator of road-associated impacts because road derived material was generally observed in this particle-size range (18-75 μm).

3.2.7 Statistical Analysis

The variation of sediment ingress rates downstream of road-stream crossings was investigated separately across two spatial scales. Site-scale effects were first examined directly downstream (20 m; DS1) of road-stream crossing, followed by reach-scale effects examined further downstream (up to 120 m; DS1, DS2, DS3).

Site-scale impacts - Post-hoc descriptive statistics were used to evaluate sediment ingress data at road-stream crossings. At the site scale (i.e., US, DS1), a paired-site approach was employed to control variability and non-independence between upstream and downstream sites. Variation of sediment ingress rates across the three streams were investigated individually then pooled across streams, to determine the overall combined disturbance effect (rapid harvest (2015) and 1-year following road decommissioning (2016)) upstream and immediately downstream (DS1) of the road-stream crossing. After Box-Cox transformations were unsuccessful at normalizing the data, nonparametric methods (Wilcoxon signed-rank test) were employed for statistical comparisons of ingress sediment data. In contrast, particle-size data (i.e., median particle-size, silt density) conformed to normality assumptions, therefore a parametric paired t. test approach was conducted. However, due to low sample numbers in McLaren Creek, particle-size data were pooled and evaluated across all streams to determine an overall disturbance effect. To reduce Type I error rate with multiple comparisons, an overall experimental wise error rejection level of $\alpha=0.05$ was used. Individual pairwise comparisons values of $\alpha=0.016$ were utilized for such tests.

Reach-scale impacts- Linear mixed-effects models (LMEs) were used to determine the impacts of road crossings on both coarse (TIS; <2 mm) and fine (Silt density; <64 μm) ingress sediment at the road-stream crossing, while blocking for the unplanned variation attributed to specific streams and trials. The main effects of site (US, DS1, DS2, DS3) and road life-phase (Haul and Post-Haul) were individually tested, followed by their interaction (Table 3-2). Reach-scale impacts were only determined for Star East and Star West Ck. because McLaren Ck. had only one downstream sampling site. Significance of site as a main effect would indicate differences in responses across the reach-scale, while significance of road life-phase as a main effect would suggest differences in responses between Haul and Post-Haul periods. Significance of the interaction term (site X road life-phase) would indicate differing responses 'within-life-phase' across the stream reach. Given the nested structure of data (i.e., trial nested within stream), the random intercept term for specific stream-trial effects (i.e., ~1|stream/trial) were accounted for in the mixed model. The two-level mixed model approach was validated using Akaike's Information Criterion (AIC) which represented the best fit for the data (Akaike 1974). Normality and homoscedasticity of model residuals, as well as for random effect term, were visually examined to ensure model assumptions were met. A significance level of $\alpha=0.05$ was maintained for all tests. Comparison of means was assessed using Least Square Means where P values were adjusted using Tukey HSD methods.

All data analyses were done using R statistical software (RStudio, Version 0.99.896, 2016) with packages nlme (Pinheiro et al., 2015). Particle-size data were computed using MATLAB R2016a (MathWorks, 2016).

3.3 Results

3.3.1 *Precipitation and Streamflow*

Across ingress trap deployment periods (July-August), total precipitation was less during the Haul (2015) than in the Post-Haul life-phase (2016)(Table 2-2). Late-spring events and snowmelt in 2015 produced a steep rising limb and rapid post-peakflow recession in the annual hydrograph, while fewer spring events and a smaller freshet response in 2016 resulted in a more muted peakflow signature. Although base flow (Q) conditions during ingress trials was generally similar in Star East and Star West Creek across both Haul and Post-Haul road life-phases, streamflow in McLaren Creek was 15-fold greater during base flow conditions during Haul life-phase in 2015 (Table 3-1, Figure 3-5).

3.3.2 *Site-scale effects of the overall combined disturbance*

A total of 373 sediment ingress samples (TIS; mg/cm^2 day) were collected during the study. A subset (n=132) of these samples were analyzed for baseflow conditions and the particle-size distribution for 54 samples was determined. Rates of sediment ingress during stormflow and melt freshet periods (May-June) were substantially higher than for baseflow conditions (24.4 and 1.7 mg/cm^2 day, respectively; Table 3-3). Across streams, the highest measured ingress rate during baseflow occurred in Star West Creek (mean: 2.5 mg/cm^2 day) followed by Star East Creek (mean: 0.95 mg/cm^2 day) and McLaren Creek (mean: 0.55 mg/cm^2 day) (Table 3-3, Figure 3-6).

The combined disturbance effect of the rapid harvest and road-stream crossing decommissioning was first examined at the site-scale (US, DS1). Sediment ingress data revealed slightly higher baseflow ingress rates downstream (+0.21 mg/cm^2 day (DS-US)) due to the impact of the combined disturbance. However, these increases were not significant (p = 0.33, Table 3-4, Figure 3-6). McLaren Creek was the only stream where median rates of TIS were slightly higher downstream of the road-stream crossing (+0.64 mg/cm^2 day (DS-US); p = 0.019, Table 3-4, Figure 3-6). Across all streams, median particle-size (p = 0.95) and median silt density (p = 0.91) of ingress sediment showed no differences at downstream locations as a result of combined rapid harvest and road decommissioning disturbance (Table 3-4, Figure 3-6).

3.3.3 *Reach-scale effects across sites and road life-phases*

In this study the reach-scale was defined as the 140 m stream reach between US to DS3. Reach-scale effects on TIS (< 2 mm, n=229) and silt density (< 64 µm, n=94) across sites (US, DS1, DS2, DS3) and individual road life-phases (Haul and Post-Haul) were assessed using mixed model approaches. For TIS, rates of sediment ingress did not differ significantly across sites in the study reach (p = 0.32), nor across road life-phases (p = 0.65; Table 3-5). Moreover, rates of TIS did not vary by the interaction of site and road-life phase (p = 0.86; Table 3-5, Figure 3-7).

In contrast, differences in percent silt ingress (i.e., silt density) were observed. Across road life-phases, silt density was significantly greater during the Haul (mean: 45.2 %) than the Post-Haul (mean: 33.8%) period (p = 0.001; Table 3-5, Appendix C). Percent silt ingress also varied significantly across sites within the 140 m study reach (p = 0.005; Table 3.5, Figure 3-7). In part, significance across 'sites' reflects a significant interacting effect (p = 0.05; Table 3-5) observed within the road-life phases, specifically during the Haul period. However, in comparison to the upstream site (US), silt density was 6-7% lower at these downstream sampling sites (DS2, DS3) during hauling activities in 2015 (Figure 3-7, Appendix C).

3.4 Discussion

3.4.1. *Site-scale effects of the overall combined disturbance*

The highest sediment ingress rates were measured during high flow conditions that occurred throughout spring freshet and stormflow periods (May-June). This observation is generally consistent with patterns reported for similar ingress trap samplers (Petticrew and Rex 2006). Greater rates of sediment ingress are likely related to greater shear stress and turbulence acting on streambed materials during high flow conditions (Powell and Ashworth 1995). In particular, increase ingress rates observed here is thought to reflect the saltation/ingress of medium and coarse sand fractions (250µm - 2mm) intruding into the interstitial storage space. A noticeably larger amount of this fraction was present when sieving material prior to particle-size analysis.

In general, baseflow ingress rates reported here (1.7 mg/cm^2 day) are substantially less than previously reported in the literature (Barton 1977; Krein et al., 2003; Petticrew and Rex 2006; Table 3-6). The one notable exception to this was reported by Kreutzweiser *et al.,* (2005), who observed relatively low rates of sediment deposition in a forested headwater stream in Ontario (Table 3-6). This is comparable with the lower rates reported here, and may be reflective of the smaller headwater streams investigated which exhibit overall lower sediment production than larger rivers downstream (Church et al., 1989; Macdonald et al., 2003). The general lack of high-intensity convective storms during baseflow periods (July-August) across both years also likely contributed to the lack of in-channel sediment mobilization and ingress.

Rapid harvest and road-stream crossing decommissioning in Star Creek had very little impact on sediment ingress. However, variation in sediment ingress did exist across sites. McLaren Creek was the only site where sediment ingress was significantly higher (+0.64 mg/cm^2 day) downstream of the road-stream crossing. Again, it is hypothesized that increases in sediment ingress rates downstream was due to the remobilization of fine sediment from behind in-channel woody debris (i.e., log-steps and slides) following higher flows (as observed in McLaren during baseflow conditions in 2015)(Little 2012). Despite routine field observations that suggested the McLaren Creek crossing was not connected to the stream during large events, the delivery of sediment from heavy equipment track ruts that were created during construction cannot be ruled out as a pathway for sediment to enter the stream (Figure 2-10). Unlike Star East and Star West Creek, where temporary swamps mats were utilized for initial equipment crossing during construction, it is assumed that steep river valley banks in McLaren Creek prevented their use.

Pooled across streams, slight increases (+0.21 mg/cm^2 day) in overall sediment ingress were observed downstream of the road-stream crossings. However, these increases were not significant and marginal in comparison to the 7 to 10-fold increases other researchers have reported following road-stream crossings amendments (Barton 1977; Kreutzweiser et al., 2005). The observed ingress rates are likely insignificant from an ecological perspective. It has been reported that negative ecological impacts in streams (i.e., increased frequency of invertebrate drift response) generally occur with a 6.5 to 10% increase (by weight) in sediment ingress (Culp et al., 1986; Suren and Jowett 2001). The results of these studies are equivalent to 78 to 150g per trap which is considerably higher than ingress rates observed in the three tributaries of Star

Creek. Negligible increases of ingress material downstream of road-stream crossings compares favourably with results reported by Rex and Petticrew (2011) for Greer Creek. At their site, negligible differences in sediment ingress observed downstream of bridge construction was due to the high efficiency of erosion control measures employed (i.e., hay bales and geo-textile fabric). Similarly, secondary erosion control measures were implemented in Star Creek throughout the rapid harvest and road-stream crossing decommissioning phases (Appendix B). These secondary BMPs likely mitigated sediment inputs to the stream as well as ingress rates in downstream reaches.

Particle-size data also suggest that road-stream crossings did not contribute to the ingress of fine material, as no significant differences in median particle-size or silt density were observed downstream of road-stream crossings. Although not significant, the 3% increase in silt and clay sized fractions downstream of road-stream crossings observed in this study are comparable with results of Spillios (1999) where similar portions of silt (8%) and clay (4%) sized fractions ingress were reported downstream of crossings.

3.4.2 *Reach-scale effects across sites and road life-phases*

At the reach scale, no differences in sediment ingress were observed during the Haul or Post-Haul season across sites. Although not significant, minor increases in the 75th percentile of ingress sediment rates directly downstream (DS1) may reflect minor road-stream crossing impacts during hauling (Figure 3-7). This observation is comparable to studies that generally report the greatest impacts on sediment deposition downstream at < 25 m below road-stream crossing (Lane and Sheridan 2002). This result suggests that the ‘site-scale’ is a sufficient scale to investigate impacts on sediment ingress downstream of road-stream crossings.

This study was one of the first studies (to my knowledge) to document impacts of road and road-stream crossing decommissioning on sediment ingress. The very low increases in ingress sediment during Star Creek decommissioning are comparable to the negligible effects reported by other studies during hauling and following crossing upgrading (Bilby 1989; Rex and Petticrew 2011). No differences in ingress sediment within road life-phases suggests that neither the Haul or Post-Haul period disproportionately contributed ingress sediment to the streambed. Similar to results of Rex and Petticrew (2011), the application of secondary Best Management Practices in Star Creek employed throughout the Haul (2015) and Post-Haul periods (2016) provided an added measure of sediment control at these sites (Appendix B). In addition, the lack of large mid-summer convective storms during both the Haul and Post-Haul period likely limited road-associated sediment input. In the absence of large rainfall events, as seen here during baseflow conditions, ingress sediment rates likely reflected in-channel processes rather than terrestrial sediment input (Krein et al., 2003). Unfortunately, ingress sediment data for higher flow conditions could not be analyzed due to high sample loss on Julian Day 154.

In contrast to total ingress sediments (< 2 mm), ingress of silt-sized fractions (< 64 μm) varied both across and within road life-phases. Silt density of ingress sediment was greater during in the Haul than the Post-Haul period. These differences in silt and clay ingress across years is not believed to be related to ambient baseflow conditions during the deployment periods, as baseflow was comparable in Star East and Star West Creek (Table 3-1). It is hypothesized that the higher proportion of ingress silt and clay sized sediment fractions measured during the Haul period reflects the greater peaks in maximum streamflow exhibited earlier in 2015 (Figure 2-5). Larger flows and greater critical erosion velocities exhibited during the 2015 freshet may correspond with greater availability of fine sediment following armor layer break up, and the ‘legacy’ flushing of fines during trap deployment. This finding is consistent with particle-size characteristics of wash load concentration (as addressed in Section 2.4.2) across road life-phases where a 3% increase in silt density was also observed during the Haul period (Table 2-9).

Within road life-phases, a lower proportion of silt and clay sized fractions were detected at the furthest downstream sites during hauling (DS2, DS3). Decreased silt density observed downstream during the Haul period suggests that the road-stream crossings were not a point source of fine sediment. Given that sediment from the road-stream crossing primarily consisted of fine–silt fractions (18 µm), it would be expected that a higher—not lower—proportion of silt and clay ingress downstream would be observed downstream of road-stream crossings.

3.5. Conclusion

1. Relatively low overall sediment ingress rates observed in Star Creek tributaries were likely due to the low sediment production in headwater systems as well as the lack of summer convective storms that could mobilize streambed sediment. Rates of sediment ingress during melt freshet and storm periods were 24-times higher than during baseflow conditions (July-August). This finding is thought to reflect the mobilization and saltation of medium and coarse sand fractions (250µm - 2mm) during periods of greater shear stress.

2. The combined impacts of rapid harvest and road-stream crossings removal (i.e., ‘the get-in and get-out approach’) on ingress sediment downstream of road-stream crossings was largely negligible at both the site (20 m) and reach scale (120 m). Neither the rates of total ingress (<2 mm) or percent fine sediment (<64 µm) showed significant increases in the 120 m reach downstream of the road-stream crossings. The minor increases (+0.21 mg/cm^{2}day) in total

ingress observed were statistically (and likely ecologically) insignificant and small in comparison to the large rates of ingress sediment previously reported in the literature.

3. McLaren Creek was the only site where significant increases of ingress sediment was detected downstream of road-stream crossing. Increased rates of ingress are thought to be due to in-channel log-steps and slides, in combination with higher baseflow in 2015 destabilizing retained fines behind large woody debris. Although not field verified cat scars present from construction could have also contributed to these minor increases of ingress downstream.

4. Neither the Haul or Post-Haul period disproportionally contributed to sediment input, despite sediment impacts often being attributed to periods surrounding road and road-stream crossing amendments. The combination of secondary BMPs employed across road life-phases in addition to the lower number of high-intensity convective storms during the Haul and Post-Haul period likely mitigated sediment ingress related to road-stream crossings.

Table 3-1. Meteorological and hydrometric data across sediment ingress trials. i) Average daily streamflow (mm/day) for McLaren, Star East and Star West Creek during Haul (2015) and Post-Haul (2016) road life-phases and ii) average total precipitation (mm) at Star Main gauging station (49°36' 36.560" N; 114° 33' 21.747" W) across life-phases is shown.

						i. Total precipitation (mm)			ii. Average daily streamflow (mm)		
Year	N	Road life-phase	Trial	Date	Duration (days)				McLaren	Star East	Star West
Harvest year (2015)	68	Haul	1	July 1st-14th	13		20.0		0.446	1.220	1.629
		Haul	2	July 29th- August 11th	14		1.0		<0.001	0.641	0.901
		Haul	3	August 27th-Sept 9th	13		45.5		<0.001	0.607	0.967
						Total	**66.5**	Av.	**0.15**	**0.82**	**1.17**
1-year post-Harvest (2016)	64	Post-Haul	1	June 29th-July 15th	16		12.7		0.002	1.021	1.895
		Post-Haul	2	July 15th-August 3rd	19		57.4		0.036	0.723	1.307
		Post-Haul	3	August 8th-August 22nd	14		25.4		<0.001	0.531	0.885
						Total	**95.5**	Av.	**0.01**	**0.76**	**1.36**

[a] excludes day of deployment

N= number of ingress sediment samples

Table 3-2. Model terms used to test whether the ingress of coarse (TIS, <2mm) and fine sediment (Silt density, <64 microns) vary across sites and road life-phases.

Term	Effect	Number and level descriptor	Description	Interpretation
Site	Fixed	4 (US, DS1, DS2, DS3)	Test the site level effect of ingress sediment at the control (US) progressively downstream of crossing	A significance term would suggest impacts across sites varied; resulting from increased rates downstream in comparison to control.
Road-life phase	Fixed	2 (Haul, Post-Haul)	Test the effect of road-life phase	A significance would suggest differences between road-life phases, perhaps owing to hydraulic conditions (whole-stream scale).
Site x Road life-phase	Fixed	8 (four sites in each road life-phase)	Interaction to test whether responses within each road life-phase vary across sites	A significant interaction term would suggest potential impact across sites varied within-road life-phases. A pattern that could be driven by particle-size of road-associated material, as finer material was available during hauling, verses during post-haul periods (18 vs. 75 microns, respectively)
Stream/Trial	Random	12 (6 trials (T1-T6) in two streams (Star East, Star West)	Accounts for random error (variation) associated across individual trails which were nested within streams	

Table 3-3. Average total sediment ingress rates (TIS; mg/cm^{2}day) during stormflow/melt freshet and baseflow conditions. Rates were pooled across study sites (US, DS1, DS2, DS3) and study years (2015, 2016).

Flow conditions	N	Stream	Average TIS (mg/cm^{2}day)
Stormflow & melt freshet			
(May-June)	30	McLaren	5.01
	49	Star East	21.55
	46	Star West	40.12
	125	**Mean**	**24.40**
Baseflow			
(July-August)	10	McLaren	0.55
	114	Star East	0.95
	124	Star West	2.52
	248	**Mean**	**1.72**

Table 3-4. i) Median total ingress solids (TIS; mg/cm^2 day, < 2mm) and ii). Particle-size characteristics during baseflow conditions (July-August) upstream (US) and downstream (DS) of each stream crossing (McLaren, Star East, Star West) as well as pooled across all streams. Probabilities reflect Wilcoxon-signed rank tests and Paired T. tests between US and DS sites. Boldface indicates significance.

		i. Total Ingress Solids					ii. Particle-Size Characteristics					
		TIS (mg/cm^2 day, <2 mm)					Particle-Size (µm)			Silt Density (%, <64 µm)		
Stream Crossing	N	Site	Median	(±SE)	P-value[a]	N	Median	(±SE)		Median	(±SE)	
McLaren	10	US	0.97	(1.9)	**0.019**[c]	4	74	(7.7)		0.4	(0.04)	
	10	DS	1.61	(1.6)		4	63.5	(2.3)		0.44	(0.01)	
Star East	27	US	2.22	(1.6)	0.03	11	68.1	(4.9)		0.39	(0.02)	
	27	DS	2.07	(3.1)		11	68.8	(4.7)		0.41	(0.02)	
Star West	29	US	6.29	(8.7)	0.46	12	75	(4.8)		0.42	(0.03)	
	29	DS	5.60	(6.7)		12	72.6	(4.5)		0.42	(0.02)	
									P-value[b]			P-value[b]
Combined (all streams x both years)	66	US	2.74	(5.3)	0.33	27	74.4	(3.0)	0.95	0.4	(0.02)	0.91
	66	DS	2.95	(4.2)		27	68.6	(2.8)		0.43	(0.02)	

[a] Reflected in Wilcoxon-signed rank test

[b] Reflected in Paired T.test.

[c] Significantly different at an overall experimental wise rejection level of α=0.05 (0.016)

Table 3-5. Results from linear mixed effects model (LME) testing the fixed effects of site (US, DS1, DS2, DS3), road life-phase (Haul and Post-Haul) and the interaction of site and road life-phase. Boldface indicates significance at α=0.05.

Response	Variable	DF	F-value	P value
TIS (< 2 mm, mg/cm^2 day)	Intercept	1	0.07	0.792
	Site	3	1.187	0.316
	Road life-phase	1	0.216	0.653
	Site X Road life-phase	3	0.26	0.855
Silt Density (< 64µm, %)	Intercept	1	113.848	**<0.001**
	Site	3	4.619	**0.005**
	Road life-phase	1	19.732	**0.001**
	Site X Road life-phase	3	2.675	0.053

Table 3-6. Summary table of previously reported sediment ingress rates.

Citation	Location	Trap	Stream Description	Disturbance/impact	Sediment fraction	Reported ingress rate
Petticrew & Rex (2006)	Hogem Range, British Columbia	Infiltration Bag	Large mountain streams	post-spawning salmon die-off	< 2 mm	~12.0 g/day
Krein *et al.,* (2003)	Germany	Bulk tube corer	Small rural streams	n/a	< 64 microns	20-25 mg/cm^2
Barton (1977)	Guelph, Ontario	Tin cans	Small urban streams	road-crossing upgrading	all	60 mg/cm^2
Kreutzweiser *et al.,* (2005)	Turkey Lakes Study Area, Ontario	Centrifuge tubes	Forest headwater	road-crossing upgrading	< 250 microns	~15 g/m^2 day
This study:	Rocky Mountain Region	Bucket traps	Mountain headwaters	road-crossing decommissioning	< 2 mm	1.7 mg/cm^2 day

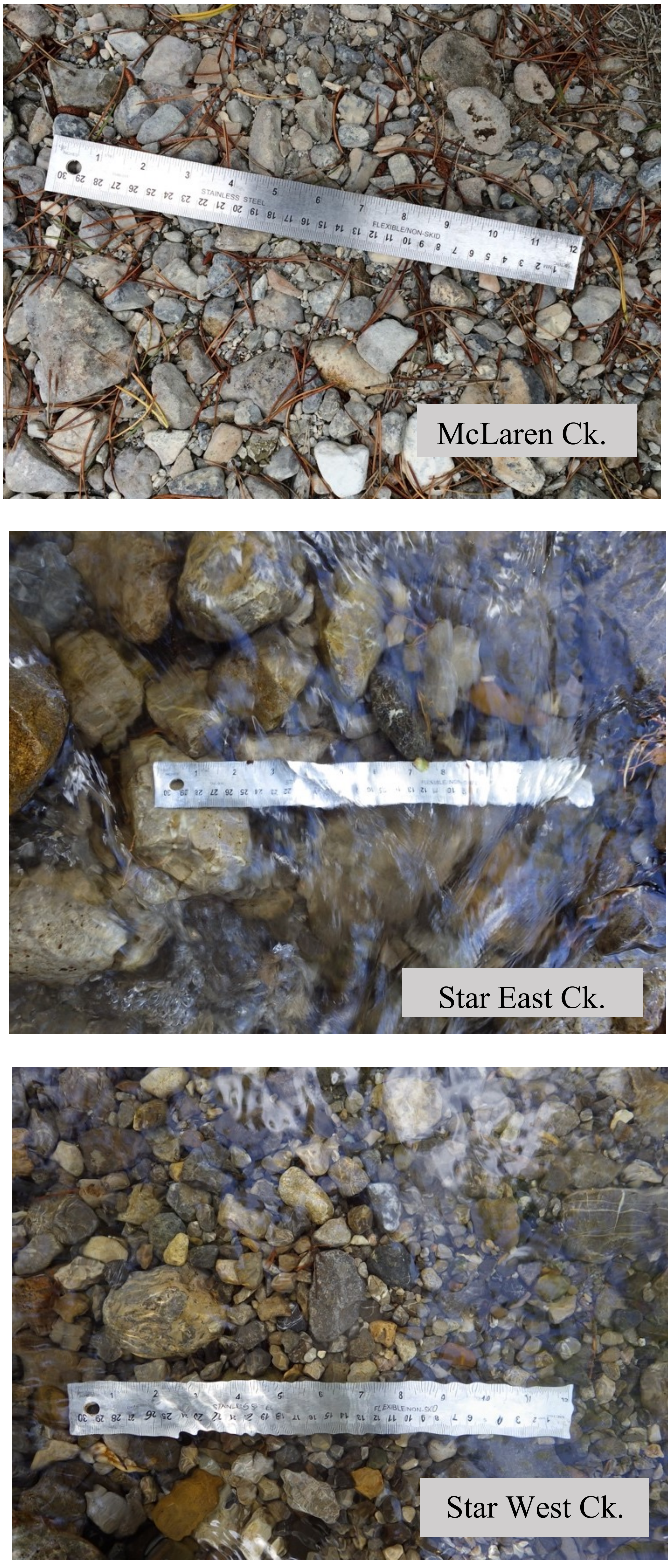

Figure 3-1. Photographs of typical streambed substrate in McLaren (top), Star East (middle) and Star West Ck. (bottom), with a 30-cm ruler for scale.

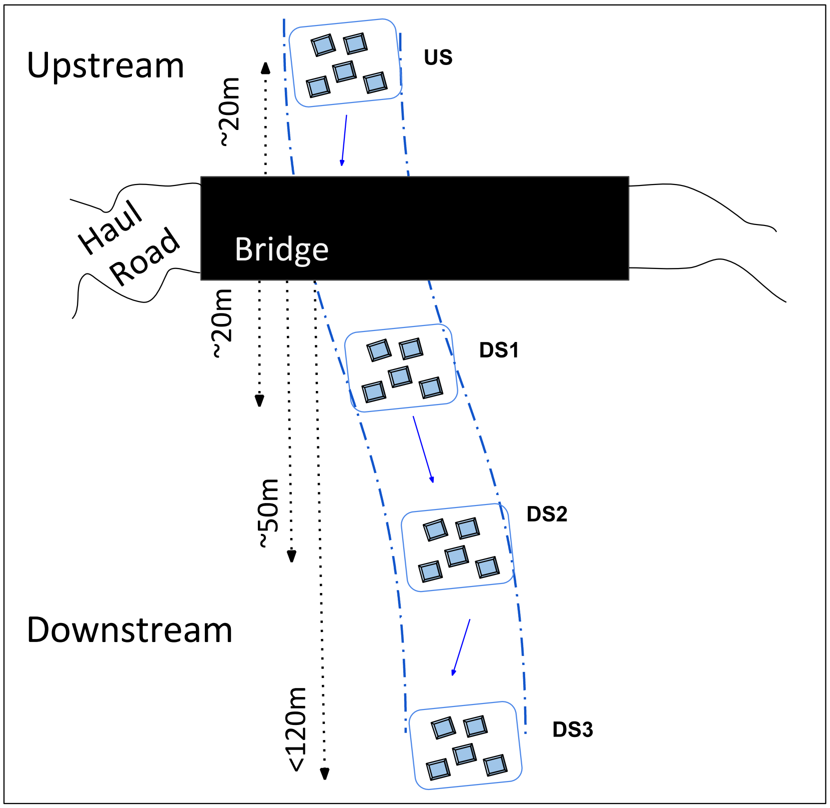

Figure 3-2. Idealized experimental design to capture sediment ingress at road-stream crossing sites (not to scale). Control (upstream; US) pump samplers were located 20 m above bridge crossings, while three downstream transect (DS1, DS2, DS3) were spaced between 20 - 40 m apart depending on suitability of run habitat. All downstream transects were less than 120 m below bridge crossings. Star East and Star West had all three downstream transects, while McLaren only had one due to its ephemeral nature.

Figure 3-3. Photographs of ingress sediment traps components including: i) typical layout of transects (each consisting of five-sediment ingress traps), ii) out-of-stream plywood-based anchors used to prevent trap loss during high-flow events, iii) nested traps covered with plastic garden mesh and placed flush to streambed, and iv) example of ingress sediment collected within the interstitial void space following 2-3 week deployment.

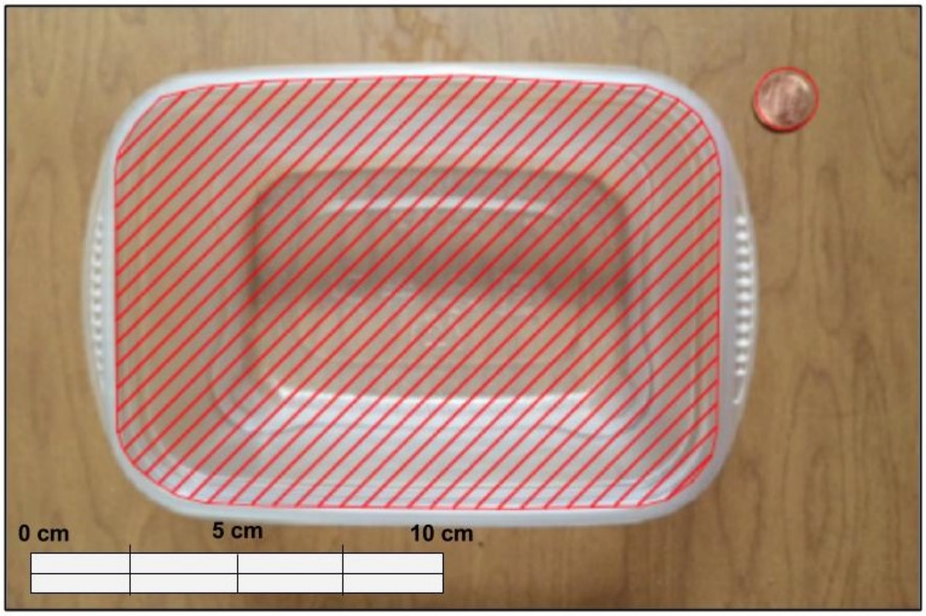

Figure 3-4. Two-sizes of sediment ingress traps were used. Larger sediment traps were utilized in Star West and Star East (156.3 cm^2), while smaller ingress traps (145.0 cm^2) were utilized in McLaren. Area (cm^2, red) of trap orifice was determined using AutoCAD software (AutoDesk, 2017), using a penny for scale.

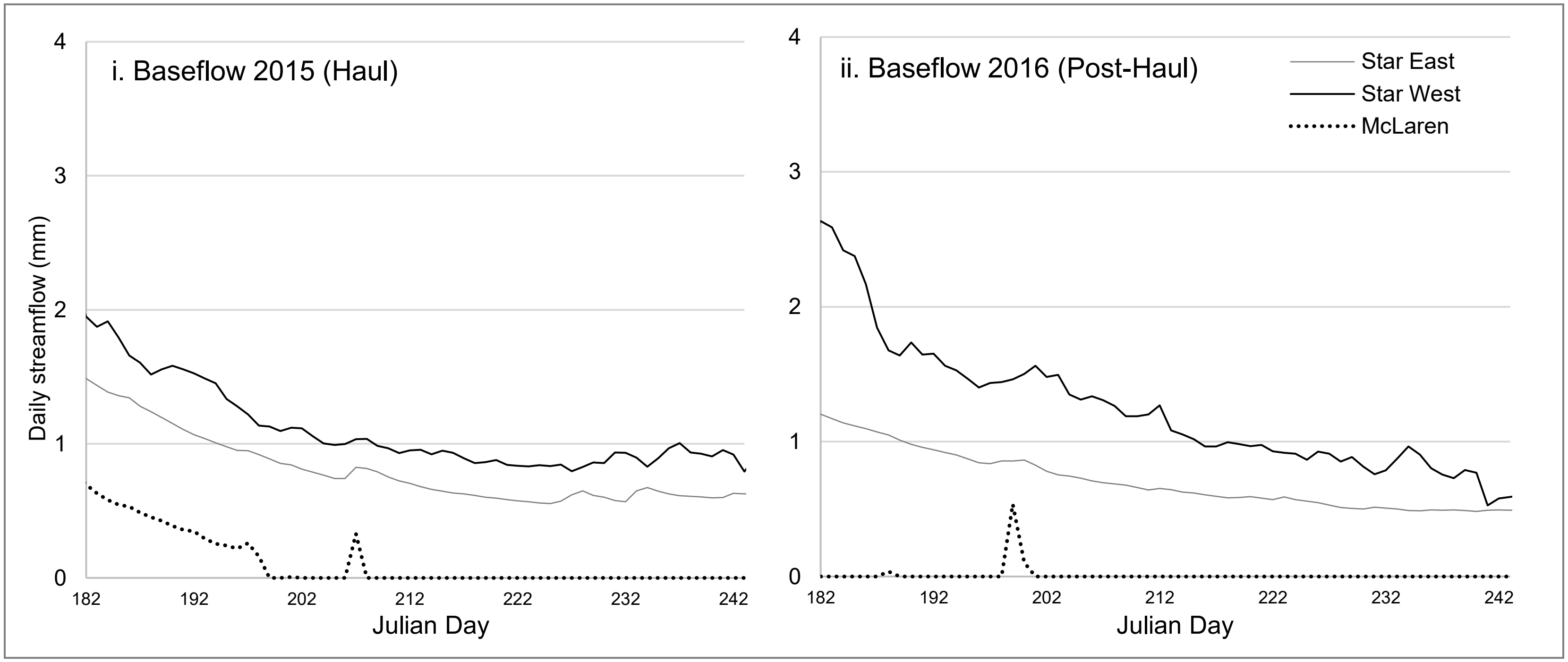

Figure 3-5. Hydrographs displaying baseflow conditions (July 1st- August 30th; Julian Day 182-243) for the deployment of Total Ingress Solid (TIS) traps during the Haul (2015) and Post-Haul (2016) life-phase in McLaren (dashed), Star East (grey) and Star West Ck. (black).

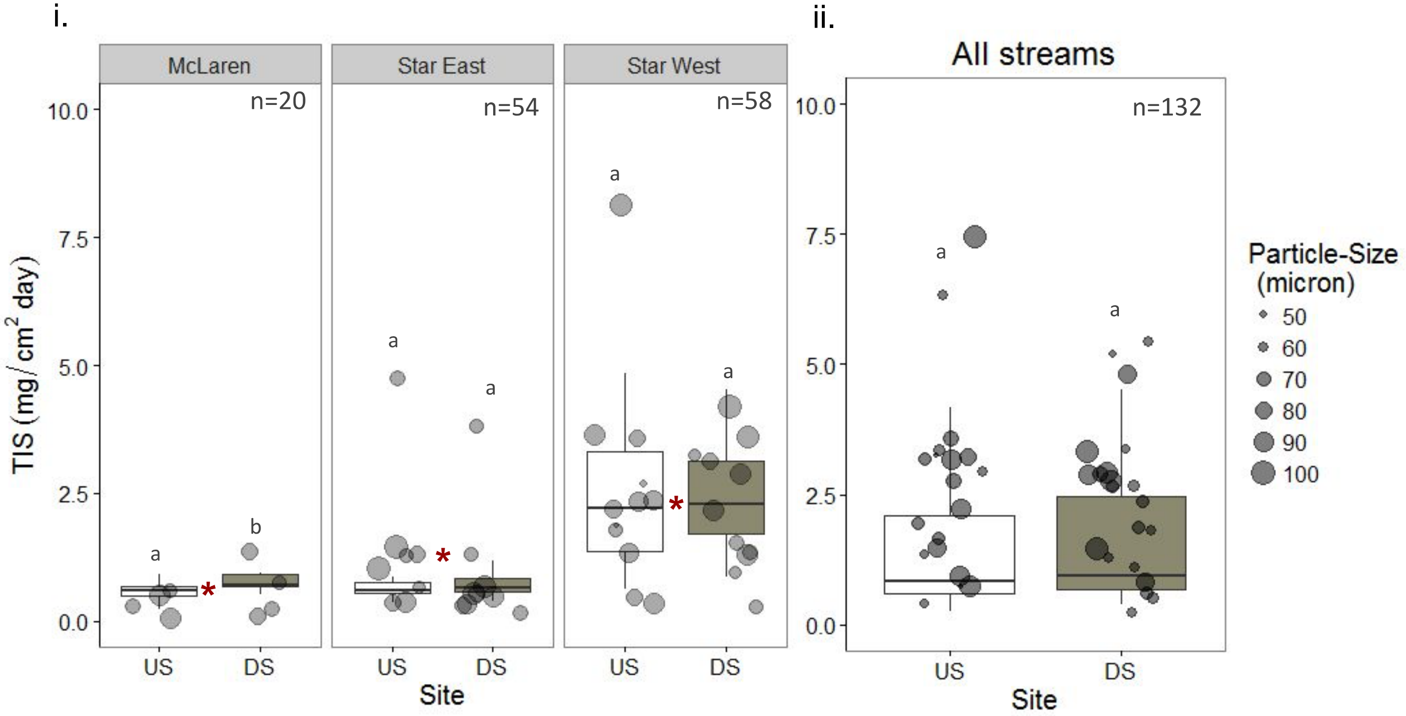

Figure 3-6. Boxplots displaying the distribution of Total Ingress Solids (TIS; g/cm^{2}day, < 2 mm) upstream (US; white) and downstream (DS; beige) for i) individual streams crossings and ii) pooled across stream crossings during baseflow conditions (July-August). Dotplots represent median particle-size (μm) for a subset (n=54) of TIS samples. Horizontal lines represent medians, red stars represent average ingress rates by stream, upper and lower limits of boxplots indicate 75th and 25th percentile, whiskers indicate the 95th and 5th percentile. Different letters indicate significance (Wilcoxon-sign ranked).

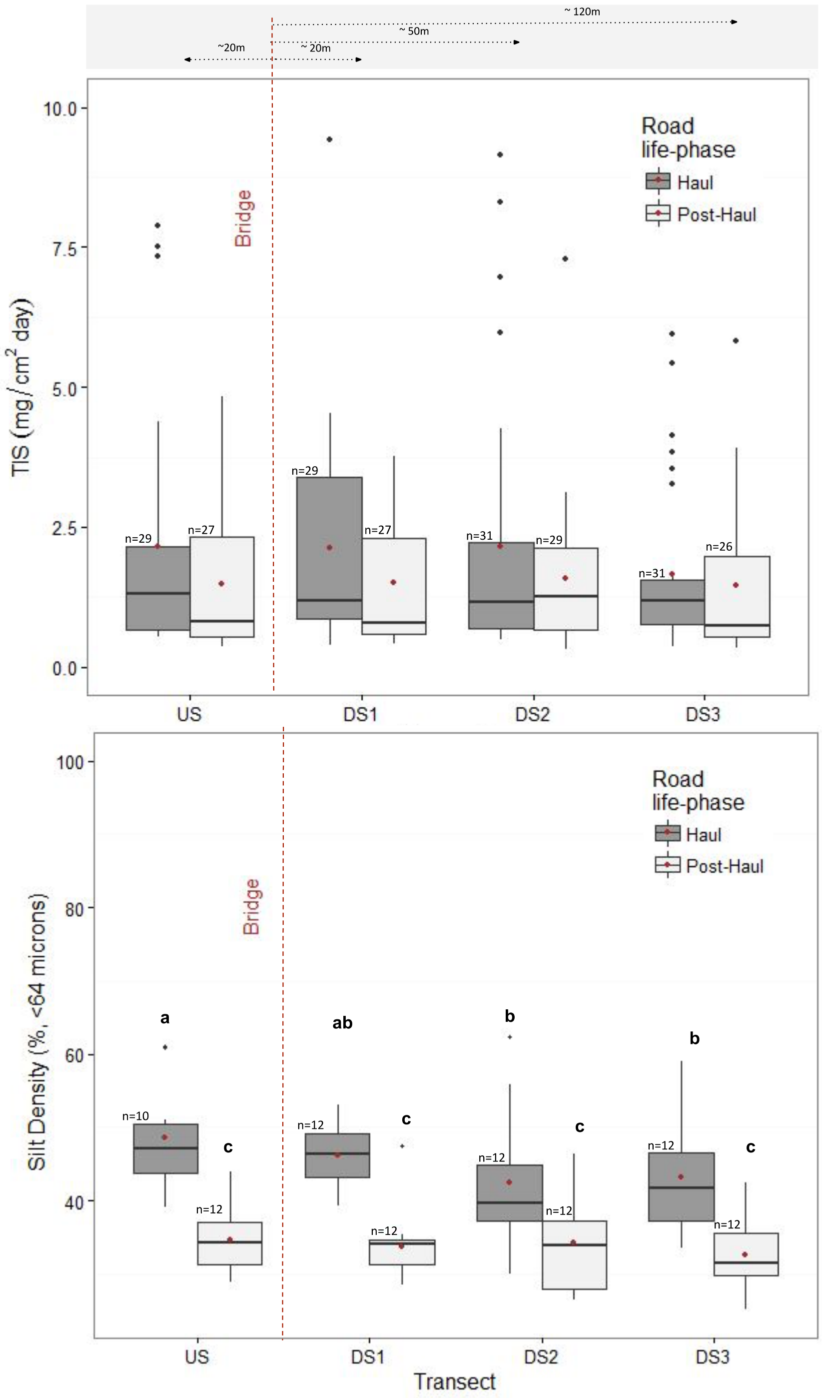

Figure 3-7. Distribution of i) total ingress solids (TIS; $mg/cm^2 day$,< 2mm) and ii) silt density (%, < 64 microns) during baseflow conditions (July-August) across transect sites (US, DS1, DS2, DS3) and road life-phases (Haul (dark grey), Post-Haul (light grey)). Mean (red points) and median (horizontal line) values are presented, while upper and lower limits of boxplots indicate 75th and 25th percentile, whiskers indicate the 95th and 5th percentile, black solid dots indicate outliers. Different letter indicate significance.

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Chapter 4: Synthesis

The primary goal of this study was to quantify the overall effect of the 'get-in and get-out' forest harvesting practice on stream sediment inputs at road-stream crossings. With the knowledge that headwater systems are critical to both drinking water supplies and habitat for sensitive fisheries, rapid harvest and subsequent road decommissioning was designed and implemented over a 10-month timeline to limit sediment exposure and delivery to receiving streams. This study concurrently investigated suspended sediment inputs (Chapter 2) and the fate of sediment (Chapter 3) downstream of three road-stream crossings during the rapid harvest (2015) and season following road decommissioning (2016).

The 'get-in and get-out' approach effectively limited suspended sediment inputs to streams at road-stream crossing sites (Chapter 2). Total suspended solids (including storm samples), turbidity and wash load concentrations upstream of road crossings did not vary significantly from downstream study reaches. Similarly, stream crossings did not meaningfully affect sediment ingress rates in the stream reaches downstream of crossings (Chapter 3). No measurable differences in the ingress of coarse (<2mm) or fine sediment (<64 μm) were observed at either the site (20 m) and reach-scale (120 m). Although impacts on both suspended and ingress sediment did vary across streams, this was primarily attributed to natural variation of sediment dynamics in stream reaches. For instance, McLaren Creek was the only stream that had significant increases in suspended sediment (turbidity), as well as ingress sediment input downstream of the road-stream crossing. Although minor, increased turbidity and rates of ingress were attributed to the mobilization of fine sediment behind these woody debris storage elements during high flows. Increased sediment may also reflect input from heavy equipment tracks present on the stream valley banks, however, field reconnaissance during large storm events showed no evidence of this. Again although increases were minor, this may highlight the importance of preventing the entrance of heavy equipment into waterbodies or immediately above streambanks in order to mitigate sediment impacts (US Forest Service, 2004).

Across the investigated road life-phases: Non-haul (seasonal deactivation), Haul (active haul) and Post-Haul (fully decommissioned), no increases in suspended sediment (Chapter 2) were observed downstream of crossings. For ingress sediment (Chapter 3), this was only investigated for the Haul and Post-Haul life-phases for which findings also suggest negligible effects on sediment downstream. Although it would be expected that sediment generation would occur across road life-phases, no single life-phase contributed disproportionately to sediment input. My findings contrast what others have reported, as sediment inputs have been associated with construction (Anderson and Potts 1987; Aust et al., 2011; Wang et al., 2013; Luce and Black 1999; Ziegler et al., 2001), harvesting and hauling (Reid and Dunne 1984; Al-Chokhachy et al., 2016), routine road-maintenance (Luce and Black 1999; Ziegler et al., 2001) and road amendment life-phases (Aust et al., 2011).

Negligible impacts on both suspended sediment and ingress sediment rates is surprising given the prevalence of fine sediment on the haul roads. This study incorporated a unique set of methods to measure the physical characteristics (particle-size distribution) of road generated fine sediment, its transport dynamics and the fate in three gravel bed tributaries of Star Creek. During the active haul period, road associated material consisted of fine-silt material (median: 18 μm) and large rates of airborne dust deposition were observed (~0.2-2.1 mg/m^2 day), while during the Post Haul period predominantly fine-sand material (median: 75μm) comprised the decommissioned road surface. Despite the prevalence of fine sediments, negligible differences in the proportion of silt or clay size fractions (i.e., silt density) in wash load occurred downstream of crossings. This finding is unique in the fact that particle-size of continuous suspended sediment samples is often not used to assess impacts of fine sediment contribution from road stream crossings, as studies generally focus on the streambed component of fine sediment impacts. Additionally, this study found no evidence of fine sediment ingress. Negligible impacts on ingress sediment downstream of crossings aligns with what others have reported when BMPs are employed at road-stream crossing sites (Rex and Petticrew 2011).

Fine material was exposed during hauling operations and was potentially available for transport to these streams. While it might be argued that energy limited conditions (summer rainfall) during the study period were not sufficient to deliver sediment to streams (Figure 4.1), a total of 12 rainfall events > 10mm did occur during the 2 year study period. This included 9 rainfall events >10mm during the Haul and Post-Haul road-life phases (Figure 2-5). For the Non-Haul period, even though two large rainfall events resulted in the mobilization of fine sediments from the road surface during the Non-Haul phase, no increases in either suspended sediments or ingress rates were observed downstream. It is hypothesized that the employment of secondary BMPs during the Non-Haul phase mitigated impacts on stream sediment downstream. Specifically, the installation of a water bar diversion network and the cessation of hauling/harvesting activities during the wet season likely mitigated the generation and delivery of overland flow from the road surface. Although secondary BMPs were in place throughout all life-phases (Appendix B), it is believed that they were especially useful in limiting sediment delivery during the Non-Haul phase, when conditions were the wettest. Additionally, the use of large-spanning bridges was another BMP assumed to contribute to negligible sediment impacts due to the preservation of streambanks. Indeed, this research aligns with the general acceptance that bridge crossings often have the least impact on water quality (Aust et al., 2011; Witt et al., 2013).

In contrast to sediment transport and ingress measured in Star Creek, other studies report at least 5-fold increases in suspended (Anderson and Potts 1987; Aust et al., 2011; Wang et al., 2013; Luce and Black 1999; Ziegler et al., 2001) and deposited sediment inputs following road construction and upgrading activities (Kreutzweiser et al., 2005). However, in comparison to the construction life-phase, the decommissioning or road restoration life-phase has not been as well-studied (Roni et al., 2002). In particular, this study highlighted that negligible impacts on sediment can be achieved during the time period surrounding road and road-stream crossing decommissioning. This is somewhat surprising given that decommissioning activities are essentially the reverse of construction, therefore it might be expected to have similar sediment impacts as that of the construction phase (Aust et al., 2011).

Haul road decommissioning immediately after harvesting operations is recognized as an effective strategy to mitigate chronic sediment pollution. In Star Creek, the rapid harvest and rapid decommissioning of roads and stream crossings after harvesting activities effectively reduced short-term sediment transfer to three tributaries. Although there are considerable financial costs associated with temporary steel bridges ($9000-11,000 USD, Mckee et al., 2012) and with decommissioning road networks ($100,000 USD/km, Robinson et al., 2010), here the ‘get-in and get-out approach’ proved effective at mitigating immediate impacts on stream sediment. In large part, this was reflective of the timing of rapid harvest and road-stream crossing decommissioning during low rainfall El Nino years (Figure 4.1), which resulted in the minimal increase in sediment production downstream. Nonetheless, this research highlights that this *a priori* harvesting strategy serves as an effective overarching Best Management Practice to guide land managers and road management policy. It is suggested that ‘get-in and get-out approach’ is ideal for smaller harvesting compartments where rapid harvest and decommissioning timelines can be achieved. It is also suggested that this strategy works for harvesting compartments that are in close proximity to permanent mainline haul roads, allowing access for silviculture operations. However, this approach may prove especially effective in headwater catchments where limited exposure of linear feature disturbance is required to mitigate effects on downstream water quality and aquatic habitat.

4.1. Future Research

While this study answered broad research objectives regarding the efficacy of the rapid harvest and subsequent road decommissioning strategy on immediate stream sediment inputs at road-stream crossings, knowledge gaps still remain with regards to:

1. **Evaluating the long-term and catchment-scale impacts on sediment downstream of a decommissioned haul road network.**

As the decommissioning of roads and road-stream crossings in itself is seen as a BMP to reduce chronic sediment pollution, the next step of this research would be to monitor these sites over the long-term. Long-term monitoring efforts will prove useful in capturing data from high-intensity storms when impacts on sediment production are generally the greatest. Additionally, the effects of decommissioning on sediment across multiple spatial scales is another recognized research gap (Switalski et al., 2004). Although in this study this was addressed at the site and reach scale (Chapter 2), research focusing on the catchment scale would provide insights into the broader regional impacts of linear feature disturbance, as well as sediment impacts associated with the decommissioning on downstream water resources.

2. **Evaluating the impacts on sediment associated with large storm events, and the effectiveness of various secondary BMPs.**

The greatest impacts on instream sediment production occur following high-intensity storm events. However, due to timing of rapid harvest and decommissioning across two relatively low rainfall years in this study, few number high intensity storms likely limited sediment delivery at these sites. Here, rainfall experiments simulating high return period storms could provide insights regarding the general erosivity of these crossings across various road life-phases, including decommissioning, as well as the effectiveness of specific secondary BMPs employed here (Anderson and Lockaby 2011).

3. **Evaluating the effectiveness of time-integrated siphonator device in capturing wash load.**

In general, insights regarding particle-size characterization of suspended sediment is a research area not often explored at sediment point sources. In this study this was done using a siphonator to capture continuous wash load (Figure 2-4). Although the siphonator may provide an opportunity to capture ‘first flush effects’, as well as provide a method for characterizing both concentration and particle-size characteristics of fine sediment, this technique was not tested against other standard sapling methods. Testing the effectiveness of the siphonator could include analyzing particle-size of sediment loss in outflow, as well as pairing continuous in situ particle-size analysis (i.e., via LISST) with the siphonator technique. The siphonator offers a unique opportunity to answer future research questions surrounding effective (natural flocs) vs. ultimate (dispersed primary particles) particle-size relationships (similar to investigations by Grangeon et al., 2012), as well as provides an inexpensive means of capturing large quantities of sediment for geochemical analyses. This includes analyses related to the sorption of heavy metals and nutrients to fine sediment material.

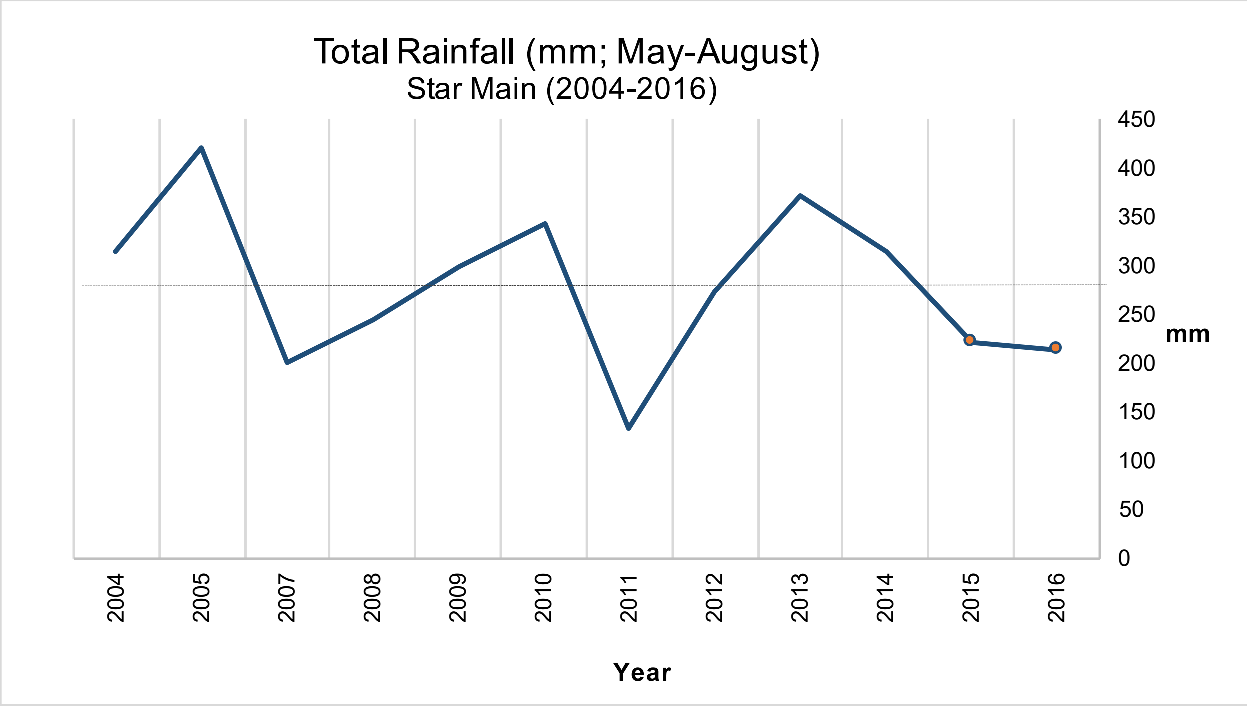

Figure 4-1. Historic summer rainfall (May-August) from 2004-2016 at Star Main gauging station (49°36' 36.560" N; 114° 33' 21.747" W). Mean summer rainfall (dotted horizontal line) and 2015/2016 study seasons (orange dots) also shown.

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Appendix A: Approximate timeline for Star Creek rapid harvest and road decommissioning operations in 2015 and 2016, with corresponding road life-phases also presented.

Date	Approximate Duration	Activity	Road life-phase
January 2015	30 days	Road construction	n/a [a]
January - March 2015	60 days	Winter harvest	n/a [a]
March - June 30th 2015	120 days	Water-bar diversion network in place	Non-Haul[b]
July 1st - July 16th 2015	14 days	Water-bar decommissioning	Non-Haul
July 16th - Sept 30th 2015	75 days	Summer/fall harvest	Haul
Sept 15th - October 13th 2015	20 days	Road roll-back to bridge sites	Haul
October 8th - 15th 2015	1-2 days each	Bridge decommissioning	Haul
October 15th- present	n/a	Put-to bed; amended site	Post-Haul[c]

[a] Not monitored during this study, [b] Non-Haul period referring to May-June 30th 2015, [c] Post-Haul period referring to 2016 ice-free season only

Appendix B: Description of primary and secondary Best Managements Practices (BMPs) implemented during the Star Creek harvest across Non-Haul, Haul and Post-Haul road life-phases.

BMP Classification	Best Management Practice (BMP)	Timeline	Source of sediment mitigation	Road life-phase	Description
Primary	Rapid harvest and subsequent road removal	January-October 2015	Point source sediment delivery	Non-Haul; Haul; Post-Haul	Road construction, harvesting, hauling and decommissioning took place over the course of 10 months; here, we refer to this as the 'get-in and get-out' strategy
Secondary	Water-bar diversion network	March-June 30th 2015	Overland flow, incision of gullies	Non-Haul	Installation of 29 temporary water-bars (cross drain channels) during spring melt; structures were 79% effective at diverting some form of overland flow.
Secondary	Cessation of hauling during wet periods	March-June 30th; Aug 15-16th 2015	Rill and gully incision, splash erosion	Non-Haul; Haul	During spring melt and large rainstorms (Aug 15-16th).
Secondary	Large spanning bridges	January-October 2015	Streamside bank collapse (in channel sources)	Non-Haul; Haul	Bridges spanned 30-70ft; also wrapped in geotextile fabric.
Secondary	Dug-outs	January-October 2015	Ditchflow	Non-Haul; Haul	Dug-outs, ranging from 0.5-1.0 m deep, were used as a natural settling ponds in road side ditches, or at the end of culverts.
Secondary	Silt fences	January-present	Overland flow, ditchflow	Non-Haul; Haul; Post-Haul	Two sets of silt fences were utilized at each stream crossing. One set used during the presence of road crossing, one set used at decommissioned toe slope.
Secondary	Swamp mats	October 8th, 13th,15th 2015	Streamside bank collapse (in channel sources)	Decommissioning	Large 12ft timber beam bundles initially placed across stream to avoid heavy equipment entrance during installation and decommissioning.
Secondary	Native sod	October 2015-present	Rill and gully incision, rain splash erosion	Decommissioning; Post-Haul	Native sod mats (saved from initial road construction), placed at toe slopes of amended road.
Secondary	Reclaimed road and toe slopes	October 2015-present	Overland flow	Decommissioning; Post-Haul	Mineral matric and organic matter of soil was reworked ('tufted') resulting in coarser material at toe slopes; also incorporated the use of large woody debris and large boulder barriers to dissuade future recreational traffic.

Appendix **C**: Comparisons of means using least mean square comparisons (lsmeans) for linear mixed effects model. Comparisons with the same group numbers are not different from one another.

Comparison	Response	Factor	lsmean	SE	LCL	UCL	Group
(~ site|Life-phase)	TIS (<2mm, mg/cm^2 day)	Haul					
		US	2.15	0.32	1.53	2.77	1
		DS1	2.11	0.32	1.49	2.73	1
		DS2	2.14	0.30	1.54	2.74	1
		DS3	1.66	0.30	1.06	2.27	1
		Post-Haul					
		US	1.48	0.33	0.84	2.13	1
		DS1	1.51	0.33	0.86	2.15	1
		DS2	1.59	0.32	0.97	2.21	1
		DS3	1.46	0.33	0.80	2.12	1
(~ site|Life-phase)	Silt Density (<64 µm, %)	Haul					
		US	**49.01**	4.05	-2.47	100.49	**2**
		DS1	**46.08**	4.01	-4.92	97.08	**12**
		DS2	**42.48**	4.01	-8.52	93.48	**1**
		DS3	**43.17**	4.01	-7.83	94.16	**1**
		Post-Haul					
		US	34.69	4.01	-16.30	85.69	1
		DS1	33.75	4.01	-17.24	84.75	1
		DS2	34.23	4.01	-16.77	85.23	1
		DS3	32.54	4.01	-18.45	83.54	1
~ Life-phase	Silt Density (<64 µm, %)	Post-Haul	**33.80**	3.90	-15.78	83.39	**1**
		Haul	**45.18**	3.90	-4.43	94.80	**2**
~ site	Silt Density (<64 µm, %)	US	**41.85**	3.76	-5.91	89.62	**2**
		DS1	**39.92**	3.75	-7.72	87.55	**12**
		DS2	**38.35**	3.75	-9.28	85.99	**1**
		DS3	**37.85**	3.75	-9.78	85.49	**1**

UCL= Upper confidence level   LCL= Lower confidence level