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Influence of large wood on channel morphology and sediment storage in headwater mountain streams, Fraser Experimental Forest, Colorado

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ABSTRACT

Large fallen wood can have a significant impact on channel form and process in forested mountain streams. In this study, four small channels on the Fraser Experimental Forest near Fraser, Colorado, USA, were surveyed for channel geometries and large wood loading, including the size, source, and characteristics of individual pieces. The study is part of a larger effort to understand the impact of mountain pine beetle infestation on a suite of watershed properties. Here, we present baseline data collected at the onset of widespread tree mortality. Channels range from 1.5 to 2 m in width, with slopes ranging from 3 to >10%. Median (D_{50}) streambed particle sizes range from gravel to very coarse gravel. Channels are characterized as cascade, step-pool, and plane bed over varying scales. Large wood loads ranged from about 0.4 to 1.0 piece per meter length of channel, which is comparable to values reported for other Colorado sites. Much of the wood showed indications of being in place for long periods of time (decayed/rotten, broken into ramps, and partially buried in beds and banks). Nearly all surveyed reaches contained steps formed from small boulders and/or logs. Significant portions of the elevation drop in some of the reaches were made up by log steps, though the percentages varied (0 to 60%). Individual log steps trap a portion of the coarse sediment moved as bedload, forming wedge-shaped accumulations upstream of the logs. The particle size distributions for measured bedload and step accumulations largely overlapped, but more so for the coarse ends of the distributions, suggesting a trapping inefficiency for the finer component of bedload. Estimates of the total volume of sediment stored behind log steps were approximately an order of magnitude greater than the mean sediment volume exported on an annual basis, as determined from measured accumulations in weir ponds. The particle size distribution of sediment in the ponds – ranging from sand to medium gravel – is considerably finer than sediment stored in steps. The series of comparisons between storage volumes, particle size distributions, and sediment export suggests that log steps effectively trap coarse sediment moved in these small streams and act as a series of check dams that inhibit channel erosion, but may be less effective at trapping finer sediment (sand and small gravel).

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1. Introduction

Large wood (LW) in steams draining forested watersheds is recognized as having significant geomorphic and ecological roles (Gurnell et al., 2002; Montgomery et al., 2003; Hassan et al., 2005). Wood loads are often highly variable between stream reaches, being influenced by position with watershed, adjacent forest type, disturbance history, and relative mobility (Benda and Sias, 2003; Wohl, 2011; Wohl and Cadol, 2011). Wood loads are often greater in small, low-order, forested channels — both in terms of number of pieces and size of individual logs (Keller and Swanson, 1979; Wohl et al., 2006; Wohl and Jaeger, 2009; Wohl, 2011). Individual trunks and limbs, some similar in size to the dimensions of the channel, can exert considerable influence over flow hydraulics, sediment transport and storage in these narrow systems (Bilby and Ward, 1989; Bilby and Bisson, 1998).

Because LW tends to be less mobile in smaller systems, wood jams created by fluvial transport (as opposed to disturbances such as landslides or avalanches) are relatively infrequent (Beechie and Sibley, 1997; Braudrick and Grant, 2001; Jackson and Sturm, 2002). Jams tend to occur where treefall stacks several pieces of LW, rather than by floating individual pieces into place. The longitudinal profile of small streams instead contains individual steps formed by one or more LW pieces, alone or in combination with boulders (Fig. 1A). A step typically consists of a riser (log piece), tread (sediment accumulation), and a scour pool downstream of the riser (Fig. 1B). Log steps trap and store a large

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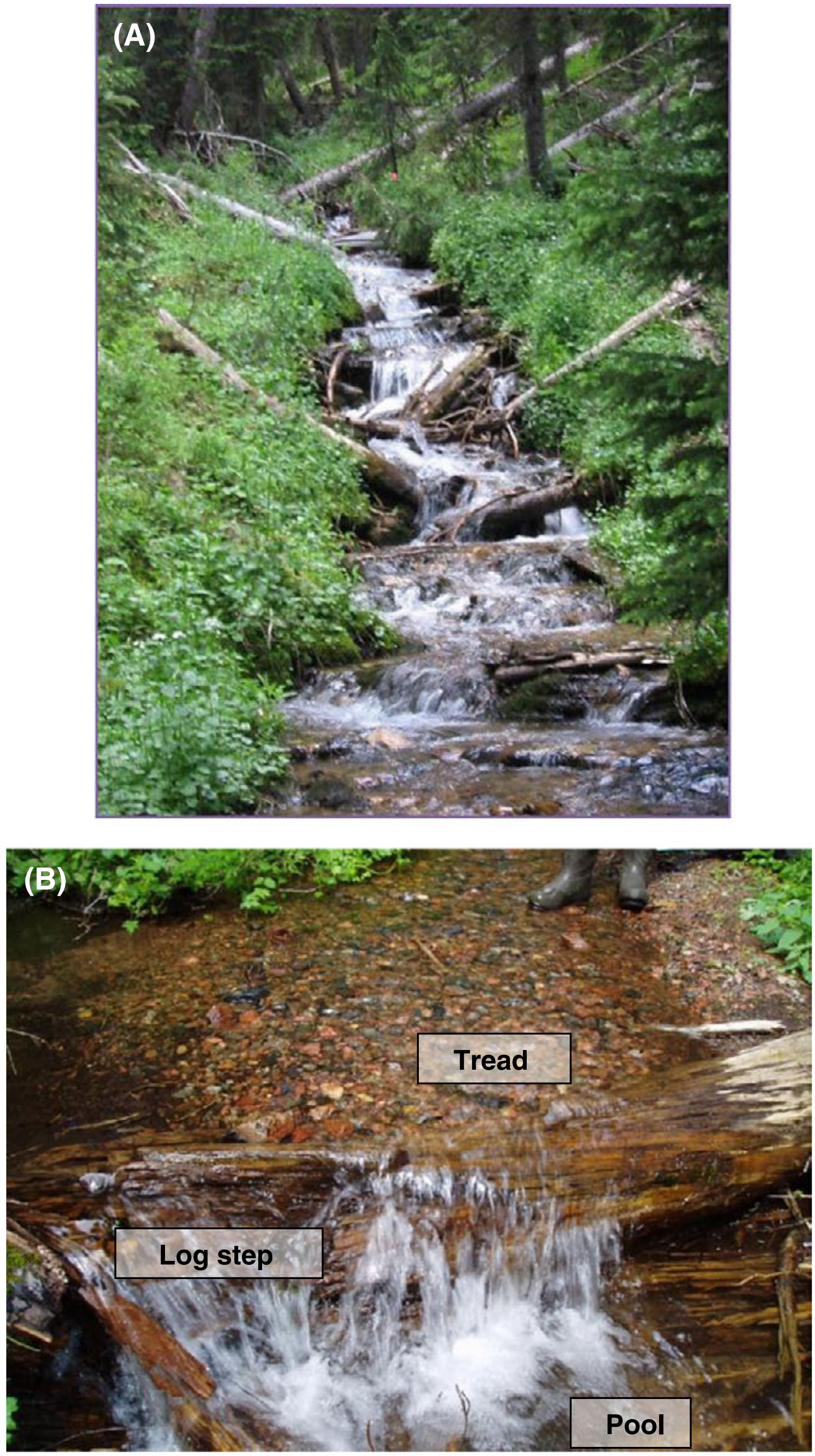

Fig. 1. Photograph of (A) channel marked by a series of log steps on Lexen Creek, Fraser Experimental Forest in summer 2006. Photograph (B) shows the components of a log step.

portion of the coarse sediment load in small systems and so exert an important control over sediment yields (e.g., Gurnell and Sweet, 1998; Faustini and Jones, 2003). Estimates suggest that between 123 and 1500% of the annual sediment yield may be stored in channels behind log steps (Megahan and Nowlin, 1976; Swanson and Lienkaemper, 1978; Marston, 1982; Megahan, 1982; Swanson and Fredriksen, 1982). Hence, sediment accumulations behind LW are a dominant geomorphic characteristic of steep, forested channels.

Sediment stored behind steps is typically finer than the overall bed of the channel and represents material moved as bedload (Faustini and Jones, 2003). However, little is known about the sorting processes that may occur as coarse sediment is trapped behind steps. Gravel- and cobble-bed streams often have an armor layer where the bed surface is coarser than the underlying subsurface sediment (Bunte and Abt, 2001). This armor layer consists of a surface that is usually no more than one 'common particle size' thick. The ratio of the median particle size of the surface and subsurface layers is typically between 1.5 and 3, with higher values indicating a more well-armored bed. The mechanism of armor formation is not completely understood and has not been examined in the context of sediment accumulations behind log steps. More than one process may be involved in its development. Armored channels typically exhibit a near-bankfull threshold for bed sediment mobility (Jackson and Beschta, 1982; Ryan et al., 2005). During armor-breaching flows, bedload transport rates are generally correlated with discharge, and sediment transport is less restricted by supply once the bed is mobilized (e.g., Buffington, 1995). The armor layer is thought to reform during waning flows (e.g., Parker and Klingeman, 1982). A phenomenon known as traction clogging, where coarse grains are deposited and enhance the deposition of other rolling or sliding grains, has also been suggested as a means for bed armoring (Dunkerley, 1990). While the surface and subsurface layers are usually well defined, the boundary between the two may not be distinct (Heede, 1980).

Like a series of instream check dams, LW causes a reduction in bedload availability and travel distance of entrained particles (Bugosh and Custer, 1989; Assani and Petit, 1995; Faustini and Jones, 2003) and ultimately affects sediment yield emanating from a watershed. Sediment not only is stored behind LW accumulations, but it is also re-entrained when structures break and release the trapped material. Individual coarse grains may not travel far distances, depending on flow conditions causing the breakup of the structures. They are often trapped by the next barrier downstream. Nonetheless, fines released likely travel farther and may eventually be exported from the watershed. Irregularity in annual sediment yield may be caused in part by the breakup and formation of log steps and jams (Adenlof and Wohl, 1994).

This study provides baseline information on wood loading, channel morphology, and sediment movement and storage in conjunction with an anticipated increase in LW loading in watersheds impacted by mountain pine beetle (MPB, *Dendroctonus ponderosae*). Many lodgepole pine (*Pinus contorta*) forests in the western USA and Canada have undergone recent widespread infestation by MPB, causing tree mortality over substantial areas. Factors that are thought to have contributed to increased beetle activity include recent extended drought that has stressed trees, leaving them vulnerable to attack (Berg et al., 2006) and absence of sufficiently cold temperatures that keep insect populations in check (Powell and Logan, 2005). The outbreak is widespread owing to large expanses of similar aged, large-diameter trees and dense stands with a high proportion of host trees (Fettig et al., 2007; Raffa et al., 2008). Potentially, widespread forest loss from beetle kill can cause increases in water yield (e.g., Potts, 1984) and secondarily increases in sediment delivery from hillslopes via surface ravel, uprooting of windthrown trees, and possible activation of landslides (e.g., Ammann et al., 2009).

Substantially increased beetle activity was observed beginning in 2003 at the Fraser Experimental Forest (FEF), Sulphur Ranger District, Arapaho–Roosevelt National Forest near Fraser, CO. Since that time, nearly 100% of the old growth lodgepole has been killed and desiccated trees now topple to the forest floor, increasing coarse wood loads on hillslopes and in adjacent channels. Several subwatersheds within FEF have extensive records of water and sediment yield, providing an opportunity to evaluate flow and stream sedimentation following widespread beetle outbreak. However, additional information on wood loads, channel dimensions, and instream sediment storage was needed to assess impacts of MPB infestation on channel morphology. This paper reports on the baseline channel conditions near the onset of widespread beetle mortality.

2. Objectives

The primary objective of this project, undertaken in 2006 and 2007, was to provide baseline information on wood loads, channel morphology, and sediment storage in small channels on the FEF in anticipation of an increase in LW inputs in watersheds impacted by MPB. The specific objectives of this paper include:

- Characterize morphology and wood loads in four first- and second-order subalpine headwater streams.
- Evaluate the number of log jams and steps in these systems, comparing the characteristics of these features to values reported for other streams in the region.
- Quantify and relate the volume and particle size distribution of sediment stored behind log steps to bedload measurements and the annual volume of exported sediment determined from accumulations in weir ponds.

3. Geographic setting

3.1. Fraser Experimental Forest

The four study streams are first- and second-order channels within the Lexen and Deadhorse Creek watersheds. These drainages are located on the northwest portion of the FEF (Fig. 2). Established in 1937, FEF is located ~80 km northwest of Denver, CO in the southern Rocky Mountain province. The experimental area has been managed by the U.S. Forest Service, Rocky Mountain Research Station, for the past 75 years and is the location of experiments that examine forest management issues, such as forest/hydrologic system interactions, water yield/quality, nutrient cycling, snow hydrology, forest disease, and instream channel processes (http://www.fs.usda.gov/fraser). Elevation ranges from 2600 m at the forest entrance to 3900 m at the summit of Byers Peak. Thirty percent of the forest area is above timberline and 75% lies above 3000 m. Average annual temperature at FEF is 1 °C (33 °F). Sixty-five percent of total annual precipitation (71 to 76 cm) falls as snow between October and May (Alexander et al., 1985). All streams originating on FEF are characterized by a snowmelt runoff regime. Discharge begins to rise from melting snow in April, peaks during May or June, and returns to base flow by late summer.

3.2. Geology, soils, and vegetative cover

The FEF watersheds are underlain primarily by granite, gneiss, and schist bedrock with an outcrop of sandstone bedrock in the headwall areas (Green, 1992). The area was glaciated during the Pleistocene, and evidence of glacial deposition and outwash exists throughout the basin (Retzer, 1962; Wohl and Jaeger, 2009). The study watersheds are characterized by alpine peaks and narrow, steep-sided valleys filled with glacial outwash, alluvium, and colluvium (Alexander et al., 1985). Soils are dominated by gravelly sandy loams and are classified primarily as Inceptisols with relatively low inherent soil fertility (Stottlemyer and Troendle, 2001). While the frequency of mass wasting in the region is thought to be lower than in the (post-glacial) past (Caine, 1986), there is evidence of recent landsliding from the headwall of one of the subwatersheds (Deadhorse South, visible in Fig. 2B). Deposits from this landslide overlie a former logging landing site, indicating that the failures are <30 years old. Snow avalanches have occurred in several of the FEF watersheds, including Lexen Creek.

Forest cover at FEF consists primarily of Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) at higher elevations, north-facing slopes, and riparian areas. Lodgepole pine (*P. contorta*) occurs predominantly on drier, upper slopes (Popovich et al., 1993). Tree age ranges typically from 200 to 500 years old in old growth stands (Alexander et al., 1985; Huckaby and Moir, 1995). Alpine meadow occurs above treeline at ~3350 m. Substantial fires burned on the north side of FEF in 1684 and 1907 (Huckaby and Moir, 1995), and these may have affected the areas containing the study streams. Charcoal was observed in eroded banks at some of the reaches, suggesting that the riparian area burned in the past or sediment and organic matter

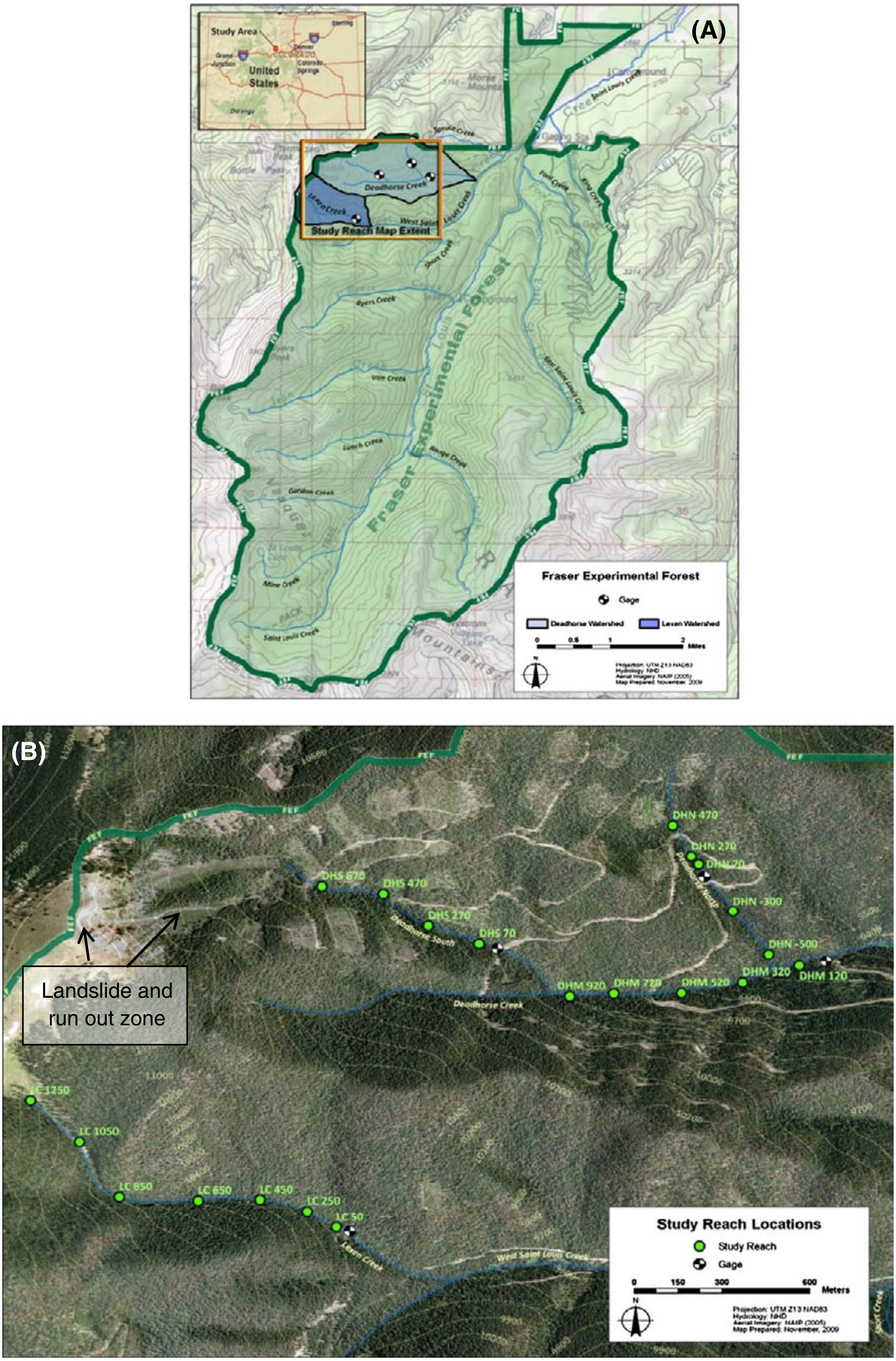

Fig. 2. (A) Map of the Fraser Experimental Forest, located within the state of Colorado (inset). (B) Image of Lexen and Deadhorse Creek watersheds, with approximate locations of 21 reaches and gages in the four studied watersheds. Landslide and run out zone in upper Deadhorse South watershed are also shown.

were moved by mass wasting following burning. Past outbreaks of spruce and fir beetles have occurred in the region (Baker and Veblen, 1990), which may also have influenced wood loads in the study streams and valley bottoms.

3.3. Study streams: Lexen and Deadhorse Creeks

Lexen and Deadhorse Creeks are small, headwater streams that drain narrow, steep-sided valleys with east-facing aspects (Fig. 2A). The Deadhorse Creek drainage area is 270 ha, and the main stem is a second-order channel. Two first-order tributaries, Deadhorse North (DHNorth, 40 ha) and South (DHSouth, 81 ha), join with Deadhorse Main (DHMain). Lexen Creek is 124 ha in area and is a first-order channel. Subwatershed elevations range from 2880 to 3536 m, and channel gradient ranges from 3 to over 10%. Slopes of adjacent hillslopes in both watersheds average 40%. Alluvium along main stem streams is a mixture of glacial till and more recent valley fill (Alexander et al., 1985). Channels are typically single thread; banks are stable with dense to moderately dense vegetative cover (Fig. 1A). The riparian overstory is composed of Engelmann spruce, subalpine fir, and, to a lesser extent, lodgepole pine. The youngest forest stand ages in these two main watersheds are over 200 years, with some stands in Lexen estimated to be over 600 years old (Huckaby and Moir, 1995). Willows (*Salix* species) occupy wider, flatter valley bottoms, and numerous herbaceous species (e.g., *Carex* species and grasses) occur in the understory (Fig. 1A).

Several road crossings and clearcut areas exist in the Deadhorse watershed (Fig. 2B), which was cut beginning in the mid-1970s as part of a study on changes in water yield following timber harvest (Troendle and King, 1987). No timber harvest or road construction (except for a short road to the gage) occurs within the Lexen watershed, which acts as an untreated reference watershed. Roads in the Deadhorse watershed were constructed over a 26-year period between 1955 and 1981 and cross the streams at several points. None of the roads directly cross any study reach, and an unharvested leave area is adjacent to all portions of the channel. Based on field observations at the study reaches and surrounding areas, wood recruitment comes from natural hillslope, riparian, and avalanche processes (the latter at the most upstream sites in Lexen Creek) and not from past harvest activities. The primary impact that timber harvest may have had on the morphology of these streams would be from increases in flow associated with timber harvest (Troendle and King, 1987). Measured increases in annual sediment yield in weir pond surveys were associated with increased flow following harvest (Troendle and Olsen, 1994); it was surmised that the primary source of sediment was internal, from channel bed and banks, rather than the external (to the channel) from harvesting. If the change in transport regime following harvesting was substantial, we might expect to see differences in channel form between the harvested and reference watersheds in response. This was not readily apparent in the data collected herein.

The two main watersheds (Lexen and DHMain) were gaged beginning in 1955, and flow between the two gages is well correlated (Alexander et al., 1985). Flow gaging began in the early 1970s at the two tributary sites (DHNorth and DHSouth). In addition to flow, data on annual sediment yields, bedload transport, suspended sediment loads, and other various water quality data measures (e.g., Stottlemyer and Troendle, 2001) have been collected.

4. Methods

4.1. Field data collection

4.1.1. Channel surveys

Study reaches were selected at 200-m intervals above their respective gages (and in the case of DHNorth, two reaches below the gage). This frequency was selected based on the relative size of the streams (1.5 to 2 m) and length of channel to be monitored. A total of 21 monitoring reaches were established: 14 sites on the Deadhorse system and 7 sites on Lexen Creek (Fig. 2B). All reaches were 20 m in length, which is about 10 times the mean channel width. The reaches cover 8% of the total channel length of Lexen Creek, 5.9% of DHSouth, 11.2% of DHNorth and 10.7% of the portion of DHMain that extends from the gage to the confluence with DHSouth. No study reaches were established on DHMain above the confluence with DHSouth. Reach numbers on Fig. 2B signify the approximate distance of individual reaches from the gaging stations.

Reaches were surveyed using a Topcon™ total station to map channel extent and cross sections (including distance across valley bottoms to valley walls), bank location, and longitudinal profile. A total of 11 cross sections were collected at 2-m intervals along the 20-m reaches. Bank location and longitudinal profile were measured wherever a change in bank contour or break in bed slope was apparent. These data were used to define mean bankfull width and depth, channel gradient, and valley bottom width. All measurements and surveys were made during base flow, and bankfull widths were estimated from plots of cross-sectional data. The longitudinal profile included bed and water surface elevations.

A standard pebble count (Wolman, 1954) was used to characterize the particle size distribution of the channel beds. A total of 100 particles were selected and each was measured and classified using a gravelometer (Stream Systems Technology Center, 2012). The gravelometer is a thin aluminum or plastic plate with varying square-shaped holes drilled through it. The holes correspond to the sizes of standard 0.5 phi-increment (*f*) sieve sets, starting at 2 mm. The largest holes are typically 128 or 180 mm, depending on the size of the template (Bunte and Abt, 2001). Particles are passed through the opening, and the size class through which the particle does not pass is recorded. Any particles larger than the largest opening are measured using a handheld tape and later binned by 0.5 *f* classes. Particles larger than about 300 mm were lumped into one 'boulder' category.

4.1.2. Large wood (LW) classification

Systematic surveys of LW occurrence and characteristics were conducted in all 21 study reaches during the 2006/07 field seasons following guidelines outlined in Wohl et al. (2010). For each LW piece >1 m in length and 10 cm in diameter, the following data were collected: (i) relative age class, (ii) presence or absence of a rootwad, (iii) perceived stability of the LW piece, (iv) stream channel type, (v) source of LW, (vi) angle of LW relative to flow direction (measured to nearest 10°), (vii) structural association (what holds or retains the piece), (viii) length (total and in-channel portion), (ix) diameter of both ends, and (x) function of LW piece within or adjacent to the channel. These categories are detailed further in the Results section. All pieces were tagged using numbered metal tree tags – nailed in at visible locations on the trunk – to aid in identifying new pieces and to determine the fate of previously located pieces in future surveys.

4.1.3. Log step survey

Data on the frequency and characteristics of log steps were collected during base flow in 2007. Beginning at the downstream end of each reach and moving upstream, the dimensions of each log step encountered were measured using retractable and cloth measuring tapes. The dimensions included step height, length, and width and an approximation of orientation within the channel. A qualitative estimate of dominant particle sizes (e.g., sand, gravel, pebble, cobble) was determined for sediment that accumulated near the step front. Step heights (top of log to depth of downstream pool) were the average of two or more measurements taken across the breadth of the step. Step length was the distance from the top of step-forming log to the farthest extent upstream where sediment accumulation appeared to be influenced by the presence of LW. Accumulation width was measured at the step and at the upstream end of the deposit. Where the accumulation was an irregular shape, multiple length and width measurements were taken to more accurately define step dimensions. Where there was a difference between the height of the step and height of the accumulation, the height of the accumulation was used in the calculation. Volume of sediment associated with the step was determined from width, height, and length measurements. We assumed that the accumulation had an approximate wedge shape and a constant slope beneath the deposit (May and Gresswell, 2003). The formula for estimating the volume of the sediment wedge (V) is as follows:

$$V = \frac{h_s\, l_w}{6}(2w_s + w_w) \quad (1)$$

where h_s is the height of the step, l_w is the mean length of the wedge, w_s is the width at the step, and w_w is the width at the upstream end of the wedge. Porosity within the deposit was not taken into account. The survey of log steps continued until either 20 steps were measured (as recommended by Wohl et al., 1997) or the next study reach was encountered. Hence, the step survey extended upstream of the study reach in order to collect data on a sufficient number of steps for characterization of their features. The total number of steps surveyed was 315 between the four subwatersheds.

In addition to the information on step dimensions, data on particle sizes on the surface and from the subsurface within the accumulation were obtained for the first step encountered at each study reach. Individual particles ($n = 100$) were chosen randomly from the surface for measurement, taking care not to disturb the underlying sediment. Where the surface of a step was too small in area to sample 100 particles, a sample of 50 was collected. Particle size was classified using the gravelometer, described previously. The subsurface was sampled by removing the surface layer to a depth of one 'common grain size' and collecting a bulk sample. A flexible plastic sheet was used to slow and divert the flow to stop fines from being carried away during sampling. Material was collected using a small, handheld plastic container to excavate the topmost 10 to 15 cm of sediment. The sediment was then placed into canvas soil sample bags and allowed to drain. These were later oven-dried, sieved, and weighed using standard methods (Bunte and Abt, 2001). Half f-interval sieves, ranging from 8 to 64 mm (-3.0 to -6.0 f), were used to separate samples into particle size classes.

4.1.4. Coarse sediment transport (bedload)

Coarse sediment moved as bedload had been measured previously near the DHMain and Lexen gaging stations in 1993 and 1995 (Troendle et al., 1996) using Helley–Smith samplers (Helley and Smith, 1971) during snowmelt runoff. A bedload sample consists of all material typically >1 mm collected at equally spaced positions within a sampling cross section. Between five and eight positions were sampled during each visit within these narrow channels, with additional positions added or deleted as the wetted width changed. The bedload sampler was held in place for 2 min/position while sediment collected in an attached mesh bag. The sample represents a spatially and temporally averaged transport rate measured over a period ranging from about 15 to 20 min. This procedure is referred to as the single equal width increment (SEWI) method (Edwards and Glysson, 1999). Bedload samples were oven-dried and sieved using standard methods for grain size analysis (Bunte and Abt, 2001). Full f-interval sieves, ranging from 1 to 64 mm, were used to separate bedload samples into grain size classes.

4.1.5. Weir ponds

Annual sediment yield has been estimated from measurements of material that accumulated in the weir or settling ponds that are associated with each of the stream gages. Each fall, gage instrumentation is shut down for the winter and the ponds are drained and the elevation of accumulation within the pond area is surveyed. The material is removed and the survey is repeated. Differences in surface elevation are multiplied by the cross-sectional area of the pond to determine the volume of material removed. Virtually all of the bedload and some portion of the suspended load accumulate in the ponds (Leaf, 1970). Data on the annual sediment yield have been collected since 1955 at DHMain, 1957 at Lexen Creek, 1971 at DHNorth, and 1976 at DHSouth. Only the mean of measurements between 1976 and 2007 were used in our comparisons to determine sediment yields over a common period, thereby reducing the influence of particularly wet or dry periods. The gaging stations and weir ponds do not directly affect the survey study reaches, although sediment trapped in the ponds over the long term may influence the grain size distribution of the sites located downstream of the DHNorth gage.

4.2. Analytical methods

Descriptive statistics were developed to characterize the reaches in the four watersheds. A multi-response permutation procedure (MRPP) was used to determine differences in channel geometry and wood loading between sites. The MRPP is a nonparametric approach for testing for similarity between two or more groups (Mielke and Berry, 2001). The test statistics are computed from Euclidean distances among observations within each group and compared against cross-group distances (or permutations). The null hypothesis is that observations among the designated groups are similar, and this is assessed based on the proportion of permutations that produce a test statistic more extreme than the observed test statistic. Several statistical parameters are developed for each comparison, including a p-value that we report here. A sufficiently small p-value indicates when the null hypothesis of group similarity should be rejected (when $p < 0.05$).

Finally, linear and nonlinear regressions were developed to define trends in channel geometry and wood loads against various metrics of watershed position, including drainage area, valley constraint ratio, and slope. The regression function was assumed to be significant when $p < 0.05$.

5. Results

5.1. Channel characteristics

Channels in Deadhorse and Lexen Creeks are characterized as narrow, stable, headwater channels with cascade, step-pool, or plane bed morphology (in the terminology of Montgomery and Buffington, 1997). Mean channel width for all reaches was 1.64 m, ranging from 0.65 to 2.35 m. Widths in Lexen, DHMain, and DHSouth were comparable (mean between 1.8 and 2.0 m), while channels in DHNorth were substantially narrower (mean = 1.0 m) (Fig. 3A). The MRPP indicated that channel width in DHNorth was dissimilar from the other streams in all pairwise comparisons. Mean cross section depth ranged from 0.07 m (standard deviation = 0.01) in Lexen Creek to 0.16 m (standard deviation = 0.12) in DHMain (Fig. 3B); the greater depths in DHMain are skewed by one particularly scoured reach (mean depth = 0.32 m). The MRPP analysis indicated that cross-sectional depths at the four streams were similar ($p = 0.19$). Average width/depth ratios were highest for Lexen Creek and DHSouth (23–25) (Fig. 3C). A larger width/depth ratio indicates that the channel is more 'bowl' shaped compared to narrower, deeper channels indicated by a smaller width/depth ratio (e.g., DHNorth mean ratio was 12). The MRPP indicated that the width/depth ratios for four streams were similar, though the p-value was borderline (0.08). Divergence between sites was rejected primarily because the range of variability on DHMain and DHSouth encompassed the other sites. The channels on DHSouth exhibited the widest range of width/depth ratios, indicating that channel shape varied from narrow/deep to wide/shallow.

Valley constraint, calculated as the width of the valley bottom divided by the width of the bankfull channel, was lowest in Lexen

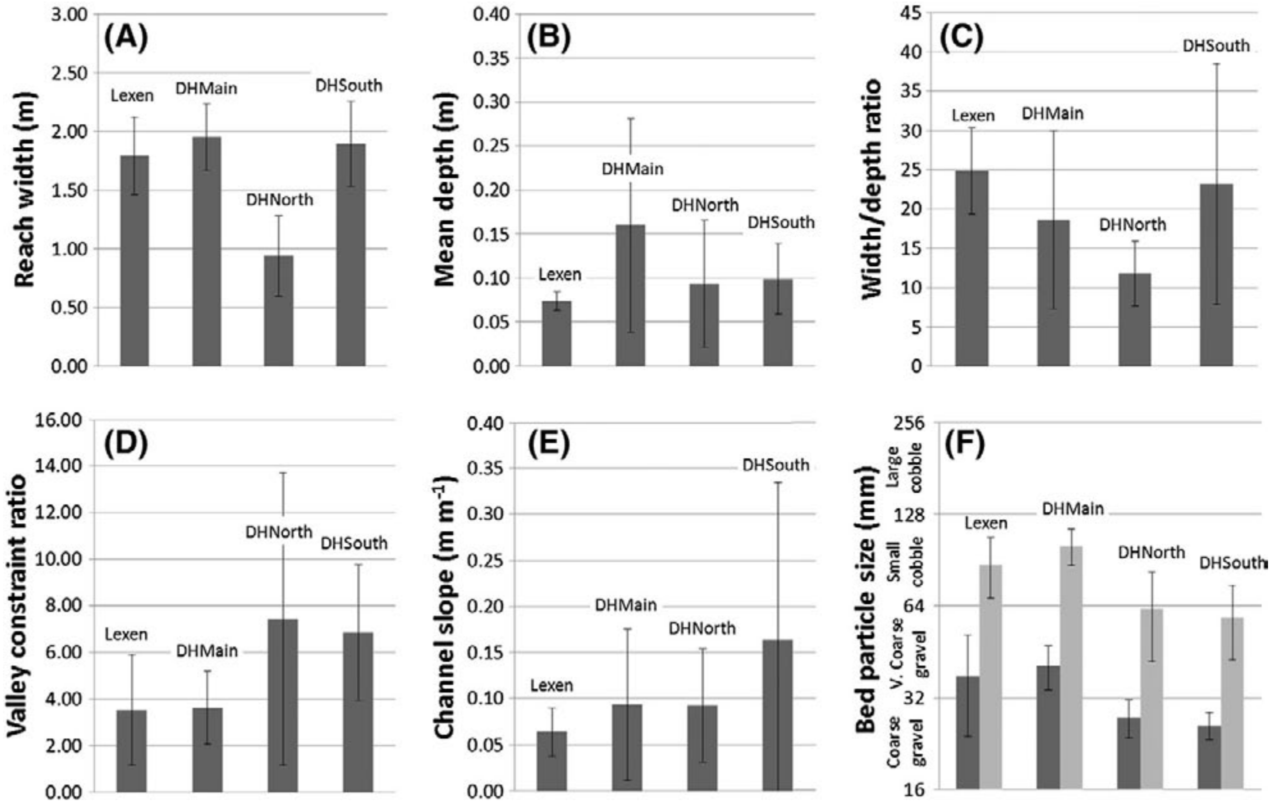

Fig. 3. Series of plots of summarizing channel characteristics for the four watersheds. (A) Reach-averaged width, (B) reach-averaged channel depth, (C) width/depth ratio, (D) valley constraint ratio, (E) mean channel slope, and (F) bed particle sizes. Dark gray bars in (F) represent the D_{50} values and light gray circles represent D_{84}. Error bars are the standard deviation in all plots.

Creek (3.5) and DHMain (3.6), where channels are more confined by steep valley walls (Fig. 3D). Values were highest in DHNorth and DHSouth (about 7), but the degree of valley constraint was more variable. The MRPP indicated that valley constraint was similar for the four watersheds, though the p-value was small ($p = 0.14$). Channel slopes averaged about 0.10 m m^{-1}, with the mean ranging from 0.06 at Lexen to 0.16 at DHSouth (Fig. 3E). The MRPP indicated that channel slopes were similar for the four streams ($p = 0.51$). As a general observation, the steepest slopes (>10%) occurred closest to the headwall (data not shown).

The median particle size (D_{50} on a cumulative-percent-finer-than plot) was about 32 mm, ranging from coarse to very coarse gravel for the four watersheds (Fig. 3F, dark gray bars). Overall, D_{50} was larger at Lexen and DHMain (38–40 mm) relative to DHSouth and DHNorth (26–28 mm). The MRPP indicated that DHMain was dissimilar from both DHNorth and DHSouth ($p = 0.016$). Lexen, because of the greater range of values (standard deviation = 14 mm), was similar to the other sites in pairwise comparisons. The D_{84} values (84th percentile on a cumulative-percent-finer-than plot) were in the small cobble range (Fig. 3F, light gray bars). Mean D_{84} at Lexen and DHMain was larger (90 to 100 mm) relative to DHSouth and DHNorth (about 60 mm). The MRPP indicated that Lexen was similar to the other three streams and that DHMain was dissimilar to the tributaries ($p = 0.02$ for DHMain and $p < 0.01$ for DHSouth). To generalize the information on grain size distributions, DHMain appears to have a more coarse bed than the tributaries, while Lexen has a range of variability that overlaps that of the other three streams.

A series of linear and/or nonlinear regressions were used to detect trends in channel metrics (width, depth, width/depth ratio, slope, and particle size percentiles — D_{50} and D_{84}) with position in the watershed. No clear or significant trends in channel metrics with downstream position or slope were indicated for any of the four watersheds (Bishop, 2011). Rather, the sites apparently represent a sampling of reaches that characterize the range of morphologic variability in steep, headwater channels in this subalpine forest environment. It was hypothesized that the degree of channel constraint would influence channel metrics, with reaches in wider valley bottoms exhibiting tendencies associated with more alluvial (less hillslope-influenced) channels, such as greater width/depth ratios, smaller grain sizes, and lower slopes. However, no statistically significant relationship between the channel metrics and valley width or constraint ratio was apparent (data not shown). Among the comparisons, only a weak, but significant, nonlinear trend ($y = 5.1435x^{-0.461}$, $R^2 = 0.42$) between channel slope (x) and the width/depth ratio (y) was shown, indicating that among reaches with lower slope, there is a tendency for a wider, more shallow channel shape.

5.2. Large wood loading

The number of pieces of LW was comparable between the four streams, likely reflecting their position in the landscape as well as similarity in the processes that contribute wood to the channels (primarily treefall from narrow riparian areas and adjacent hillslopes). The MRPP p-value from a comparison of piece numbers was 0.59, which indicates a high degree of similarity. Mean number of wood pieces was 0.69 pieces/m, median was 0.75 pieces/m (Fig. 4A), and standard deviation was 0.28. The reaches with the largest (1.20 pieces/m) and smallest (0.10 pieces/m) numbers were both in the upper portion of Lexen Creek that is influenced by avalanche processes. The lowest value is from wood being exported during these events, and the highest value occurs in a depositional zone. For comparison, LW numbers from other streams in the region, with different degrees of flow and forest disturbances, averaged 0.37 pieces/m, ranging from 0.02 to 2.06 pieces/m (standard deviation 0.35) (Ryan, 1994). In another work, Richmond and Fausch (1995) found an average of 0.43 pieces/m in 11 undisturbed, north-central Colorado streams, ranging from 0.18 to

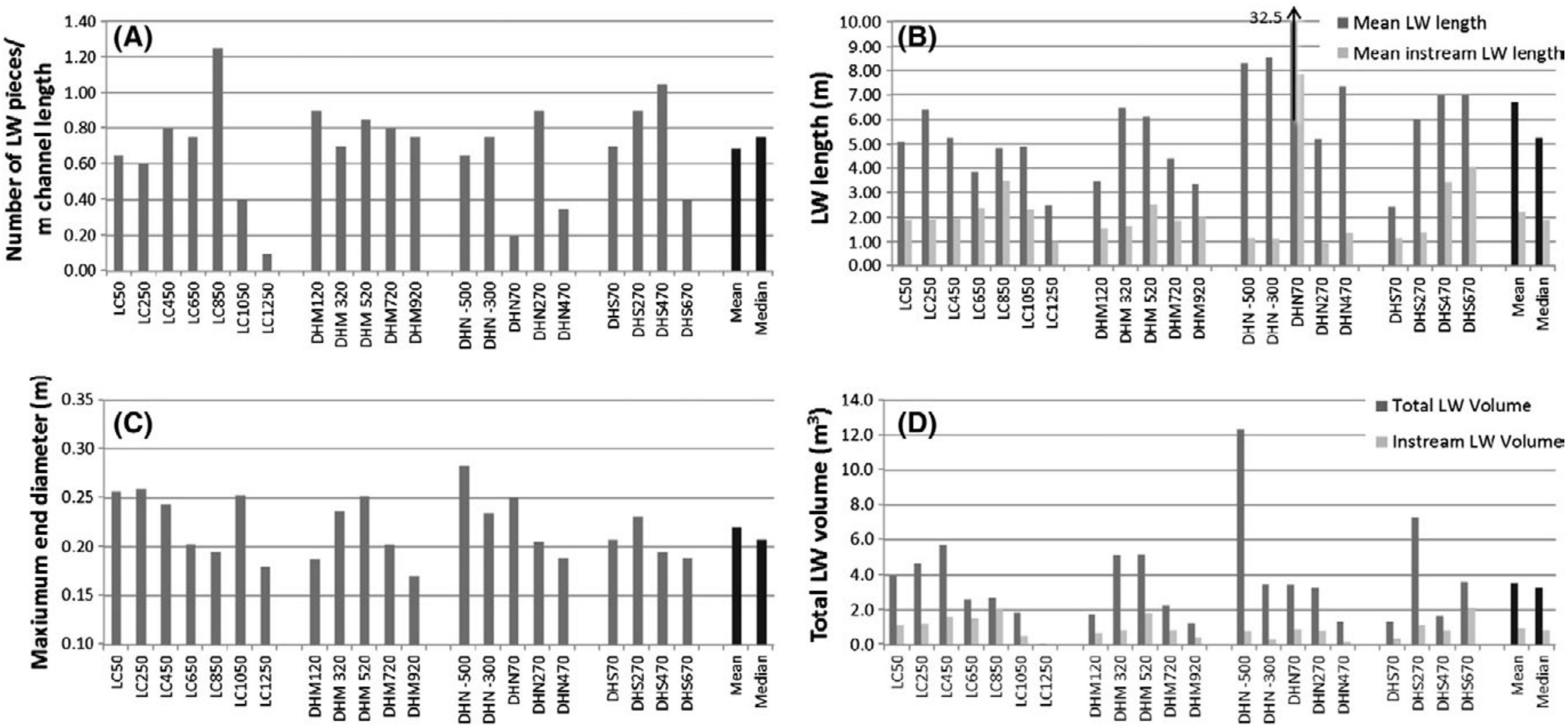

Fig. 4. Series of plots of the numbers and dimensions of LW in 21 reaches. (A) Total number of pieces of large wood per meter channel length, (B) mean length of LW in total (dark bars) and instream portion only (light bars), (C) mean of the diameters of the larger end of LW pieces, and (D) volume of LW in total (dark bars) and instream only (light bars).

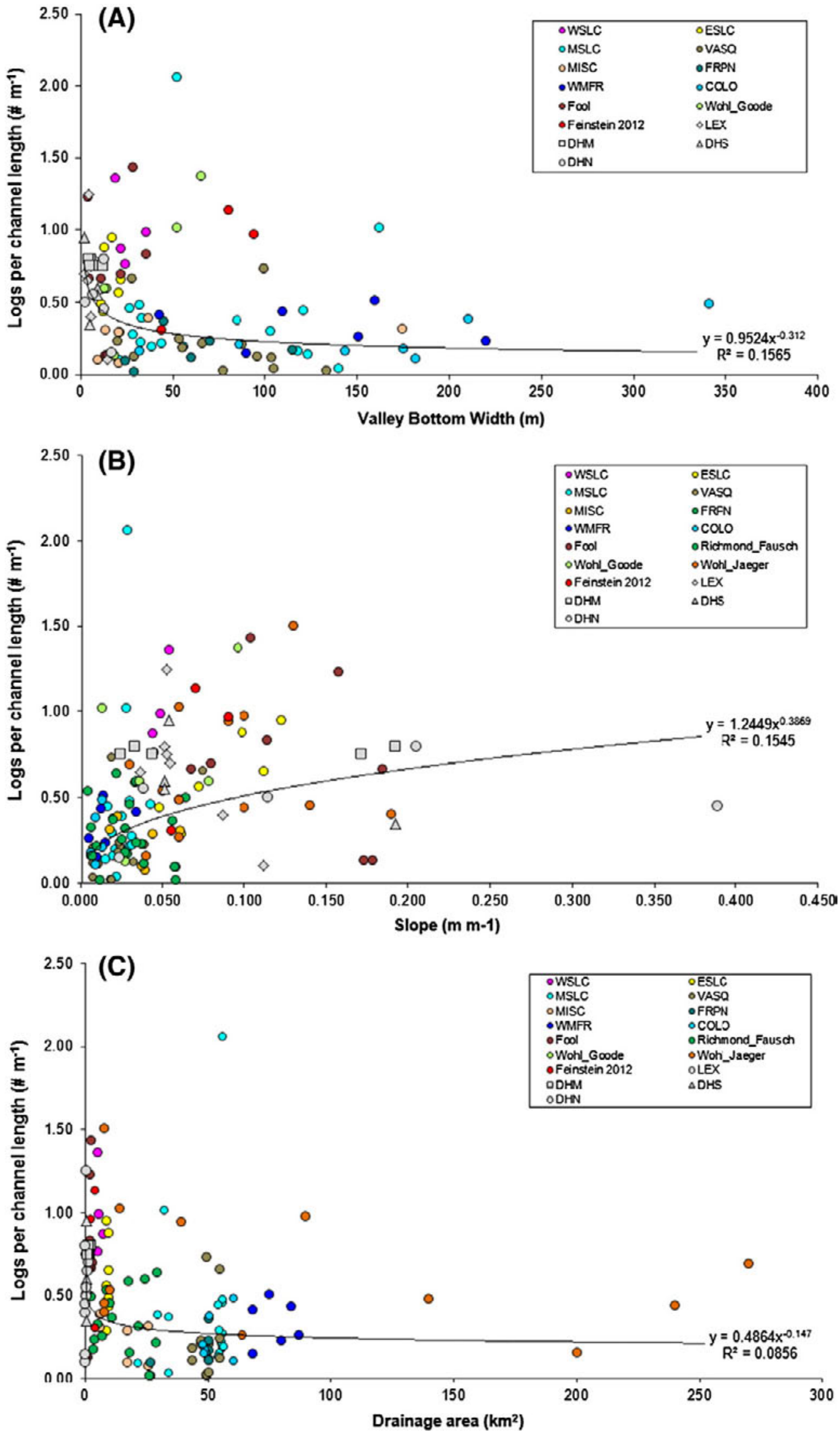

Fig. 5. Composite of LW data from Colorado streams (this study and others). Abbreviations are as follows: WSLC (West St Louis Creek at FEF), ESLC (East St Louis Creek at FEF), MSLC (Main St Louis Creek at FEF), VASQ (Vasquez Creek), MISC (Missouri Creek), FRPN (Fryingpan River), WMFR (Williams Fork River), COLO (Colorado River in Rocky Mountain National Park), Fool (Fool Creek at FEF), Richmond_Fausch (from Richmond and Fausch, 1995), Wohl_Good (from Wohl and Goode, 2008), Wohl_Jaeger (from Wohl and Jaeger, 2009), Feinstein blowdown study (Feinstein, 2012), LEX, DHM, DHN, DHS (this study). Plots show trends in number of pieces of LW per meter of channel with (A) valley bottom width, (B) channel slope, and (C) drainage area.

0.64. They also documented lower numbers between 0.02 and 0.22 pieces/m in channels influenced by past forestry and other management activities. In an annual census of five Colorado streams, Wohl and Goode (2008) found an average of 0.86 pieces/m, though the numbers varied between sites (0.13 to 1.40 pieces/m) and between years. In an acute example of increased wood loading, instream piece counts increased 154 and 380% following a wind storm that caused trees to be uprooted and toppled on the Routt National Forest, Colorado in 1998 (Massey, 2000). Loads increased another 50 to 100% following intense wildfire that burned much of the remaining standing riparian forest 6 years later (Feinstein, 2012). Total wood numbers in 2010 were 1.19 pieces/m and 1.01 pieces/m along 300-m channel segments with blowdown/burn. Wood numbers at a nearby control site were 0.31 pieces/m. To generalize, the number of pieces of wood reported for Colorado channels with different management and disturbance histories varies by about 2 orders of magnitude (0.02 to 2.00 pieces/m of channel length), and our four streams at FEF fall within this reported range.

The wood loads for the FEF streams and the additional sites in the region were pooled and compared against several watershed level predictors, including drainage area, valley bottom width, and slope, where comparable data were available from the various studies (Fig. 5). Because not all of the sites contained the full suite of data, only single-variate analyses were used to detect overall trends. Power curves provided the best fits between wood load and valley bottom width (Fig. 5A), channel slope (Fig. 5B), and drainage area (Fig. 5C). The coefficients of determination for valley bottom width and slope were low (0.16, 0.15), but significant ($p < 0.01$), indicating that an overall trend exists, but the predictive capability of the relationship is very low. Because the data come from different studies and the streams have differing levels of forest disturbance that affect wood loads, the poor predictive capability is not unexpected. The general trends indicate higher wood loads in channels in narrower valley bottoms and with steeper slopes. Lower wood loading tended to occur in valley bottoms wider than about 50 m, with slopes <0.04. These are more likely to be in the downstream portions of the watersheds where there is a change in the type of riparian vegetation (less forested) that influences the sources of LW to the channel. Wohl and Cadol (2011) also observed variation in wood load with longitudinal setting, but found that segments with lower slopes (0.04 to 0.06) and wider valley bottoms contained higher concentrations of wood. The wider, alluvial sites in their work were located downstream of bedrock gorges and may represent an interplay between localized zones of transport and deposition of wood and sediment. Finally, the pooled data from the Colorado sites showed a general decline in wood load with increasing drainage area, but the coefficient of determination was low (0.09) and only borderline significant (Fig. 5C). In other works, a decline in wood loads with increasing drainage area has been attributed largely to increasing transport capacity in larger drainage basins and to reductions in the supply of streamside sources (e.g., Keller and Swanson, 1979; Marcus et al., 2002; Wohl and Jaeger, 2009). However, the considerable scatter in the pooled data supports the idea that local factors – such as valley characteristics, riparian forest composition and structure, or disturbances – exert a strong control on wood loading at the reach or segment scale (Wohl and Cadol, 2011).

While the numbers of pieces of LW were comparable for the FEF reaches, the size of the wood showed greater variation, perhaps reflecting differences in the composition of the old growth forest adjacent to the channels. Unfortunately, data on stand characteristics are not available for all riparian areas in this study, and so we are unable to directly examine this further. Measured upland tree heights at FEF range from 15 to 40 m, depending on species (e.g., Kaufmann and Ryan, 1986) so substantially smaller lengths would suggest a high degree of breakage. Mean LW length in individual reaches ranged from 2.4 m at DHS70 to 32 m at DHN70 (Fig. 4B, dark gray bars). An MRPP indicated that the length of LW pieces measured for reaches

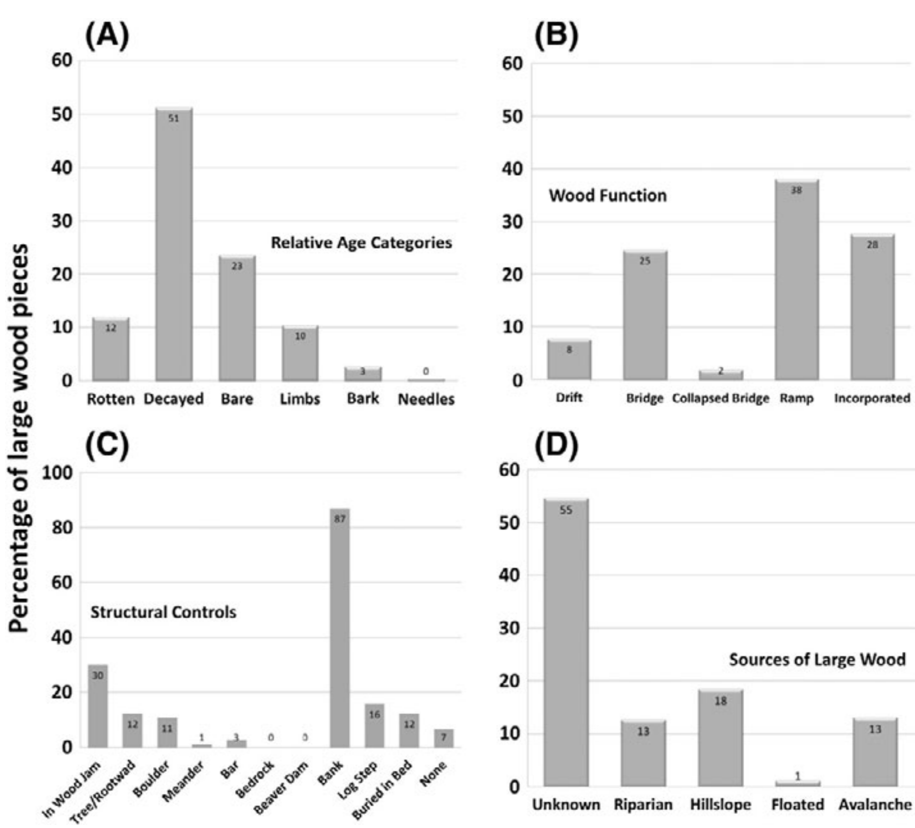

Fig. 6. Series of plots of the characteristics of LW (in composite) for the four watershed sites. (A) Decay class, used to infer approximate age of LW, (B) function of wood in channel, (C) structural controls on LW pieces, and (D) sources of LW.

within a watershed were similar, except for DHSouth where the pieces measured at DHS70 were, overall, substantially shorter. In comparing between watersheds, the length of LW was, on average, longer in the two tributary channels. Mean length for all Lexen reaches was 4.9 m (±standard deviation 4.2 m), 4.6 m for DHMain (±4.9 m), 8.4 m for DHNorth (±8.9 m), and 6.2 m for DHSouth (±6.4 m). An MRPP indicated that LW pieces in DHNorth were longer than the other sites in a combined analysis (three sites vs. DHNorth, $p = 0.23$) and longer than Lexen and DHMain in pairwise comparisons. This may reflect a tendency toward older forest stands (and presumably larger trees) identified in the upland portion of Deadhorse watershed (Huckaby and Moir, 1995). Because the resolution between our small stream reaches and the associated forest type from that study is quite coarse, further analysis was not attempted.

The portion of LW length contained within the channel was, on average, 40–45% of the total wood length for DHMain, DHSouth, and Lexen Creeks (Fig. 4B, light gray bars). The inchannel portion at DHNorth was only about 20% of the total piece length, reflecting the fact that both the LW pieces were longer and the channels were narrower. The maximum end diameter for individual pieces was on average 0.2 m for all streams (Fig. 4C); the maximum diameter for the largest pieces at individual reaches ranged from 0.5 to 0.8 m (not shown).

Mean total volume of LW in the 20-m reaches was 3.6 m^3, with a standard deviation of 2.7 m^3 (Fig. 4D). The DHN-500 reach, where three long, large diameter trees crossed the channel, had the highest total volume of LW (12.3 m^3). Despite the higher wood volume in DHN-500, the MRPP indicated that the four watersheds are similar in terms of total wood volume per reach of channel ($p = 0.95$). Expressed for 100-m lengths of channels, there was an average total volume of 18 m^3/100 m, but only 4.7 m^3/100 m was contained within the channel banks. For comparison, Richmond and Fausch (1995) reported a mean total volume of 13 m^3/per 100 m of stream (ranging from 6.6 to 27). In other works, instream wood volumes ranged over 3 orders of magnitude from 0.01 to 10 m^3/100 m (recalculated from Wohl and Jaeger, 2009) and 1.2 to 15.2 m^3/100 m (Wohl and Goode, 2008).

5.3. Characteristics of wood loads

Instream LW exhibited evidence of having been in place for substantial periods, being decayed to some degree and incorporated into the channel beds and banks (Fig. 6A). Much of the LW (63% total) was classified as decayed (51%) or rotten (12%). Almost 90% of the LW in DHMain was in the decayed or rotten categories while the percentages were closer to 50% for the other streams. Categories 'bare' and 'retained limbs' describe LW pieces where the fibrous structure of the tree trunk remains largely intact, indicating that they are probably newer recruits; 23% of the wood was bare (but not decayed) and 10% retained their limbs. Less than 3% of the pieces had needles and bark that would suggest that they were fresh recruits. Many LW pieces were broken at least once, forming ramps in the channel (38%) or were partially buried and incorporated into the beds and banks of the channel (28%) (Fig. 6B). Twenty-five percent of the pieces bridged the channel (25%) or were collapsed bridges that were not broken through the entire width of the trunk (2%). Only 8% were classified as 'drift,' representing pieces that were not stabilized and therefore more likely to have been moved. These lines of evidence suggest that LW is retained for long periods at these sites, to the extent that it decays and becomes incorporated into the channel structure. This differs from other studies that indicate that wood is relatively mobile in steep mountain streams (Wohl and Cadol, 2011). Differences may be attributed to the size of the streams in our small watersheds relative to the size of the fallen wood (Marcus et al., 2002). Subsequent surveys of tagged pieces will help provide general estimates on the relative mobility of wood in these smaller systems.

Structural controls represent categories of channel and riparian features that interact with individual pieces of wood and therefore influence their capacity to be mobilized. Often two or more structures trap individual pieces, so LW can have more than one structural control in the classification scheme (Fig. 6C). Most of the logs (87%) were stabilized by channel banks, which is expected, given the narrow channels and large trees. Other controls on LW movement included live trees or rootwads on the banks (12%), in-channel boulders (11%), incorporation into the channel as a log step (16%), and burial in the channel bed but not acting as a step (12%). Very few pieces were associated with bars, meanders, exposed bedrock, or beaver dams because these controls are rare in these systems. Notably, 30% of the surveyed wood was in jams, defined as 3 or more pieces that are in contact. Jams were contained within 14 of the 21 reaches. Typically, these were small accumulations that contained between 3 and 6 pieces of wood; the largest jam contained 25 pieces that were contributed by avalanche processes. Nearly all of the wood in jams was associated with other stabilizing controls, such as banks (85%), steps and burial in channel (20%), live trees and rootwads (14%), and boulders (5%) (data not shown).

Source of LW was sometimes difficult to discern and over half of the pieces were classified as 'unknown origin' (Fig. 6D). The high percentage of unknowns is likely because of our stipulation for a clearly identifiable association between a piece and its source for this classification. Of the remaining pieces of LW with known origin, 18% could be linked to a hillslope source and 13% originated from the narrow riparian zone adjacent to the channel. Thirteen percent were from avalanche processes in the upper portions of Lexen Creek. Only about 1% of the wood was attributed to floating into its current position.

5.4. Log steps in Lexen and Deadhorse Creeks

5.4.1. Step frequency

Unlike channels with predominately boulder step-pools that are considerably coarser (large cobble and boulder) than the study reaches, steps in the Lexen and Deadhorse streams were frequently formed from LW that had fallen and become incorporated into the channel beds and banks (Fig. 1A). As noted in the previous discussion of LW characteristics, ~16% of the wood pieces formed an instream step while another 11% had become part of the bed but were not acting as a step owing to the absence of a riser. Individual study reaches contained between 0 and 5 log-steps over 20-m lengths. Estimated mean frequency of log steps (based on the average step frequency in the study reaches extrapolated over 100 m) was 12.5 steps/100 m at Lexen (only in the stream segment downstream of avalanche zone), 14.0 steps/100 m in DHMain, 8.0 steps/100 m at DHNorth, and 11.3 steps/100 m at DHSouth. The frequency of steps at the FEF is comparable to or less than that reported for 'young conifer' stands (15.8 steps/100 m) and 'old growth' stands (23.0 steps/100 m) in similar sized headwater streams in southeast Alaska (Gomi et al., 2003). Conversely, step frequency at FEF is up to an order of magnitude greater than that reported in other studies from higher order systems (e.g., Marston, 1982; Faustini and Jones, 2003; Montgomery et al., 2003; Comiti et al., 2006; Andreoli et al., 2007).

5.4.2. Step height

Log steps ranged in height from about 0.15 to 0.45 m (~10th to 90th percentiles for the four streams, composite) (Fig. 7A). Median step height was marginally higher at DHSouth (0.31 m) than the other streams (0.23 to 0.25 m). An MRPP indicated that the three streams, as a composite, were dissimilar from DHSouth ($p = 0.22$), but only DHMain was dissimilar to DHSouth in pairwise comparisons. Overall, the height of the steps is comparable to the reported diameters from the LW survey (about 0.20 m). It would follow that step height within the reaches is a reflection of the size of the wood available for recruitment in the watersheds (Wohl et al., 1997).

A substantial portion of the total elevation drop (and, hence, energy dissipation) within steep, forested channel is often contained within the

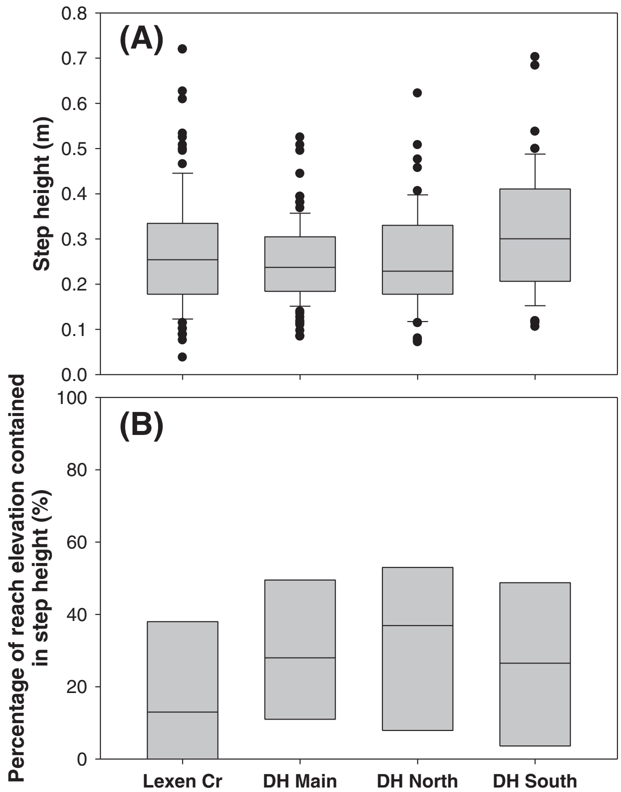

Fig. 7. Box plots of the distribution of (A) height of log steps in the four watersheds and (B) the height of the steps expressed as a percentage of reach elevation drop. The bars represent 25th and 75th percentiles and the median value (mean not shown). Lines represent the 10th and 90th percentiles. Circles represent outliers.

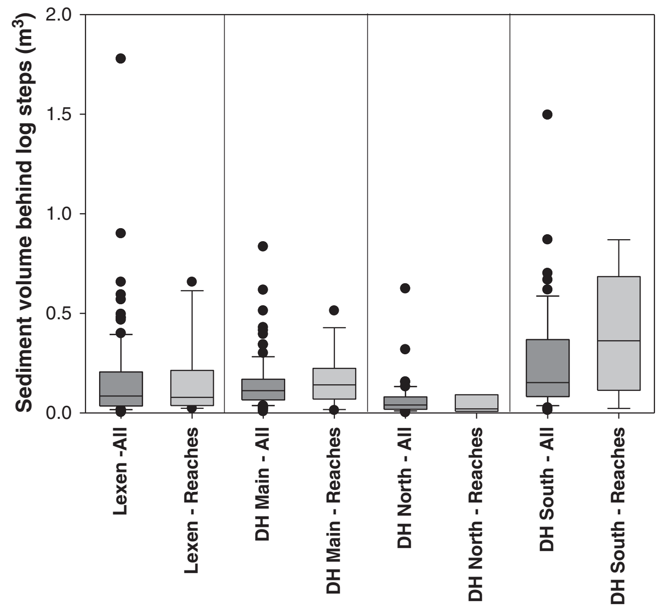

Fig. 8. Box plot of the distribution of the sediment volume stored behind log steps, estimated for all steps in the watershed (darker bars) and for only those contained within the 20-m reaches. The bars represent 25th and 75th percentiles and the median value (mean not shown). Lines represent the 10th and 90th percentiles. Circles represent outliers.

height of the boulder and/or log steps. At the FEF reaches, the percentage of elevation contained within log steps ranged from 0 (no log steps) to typically <60% in most reaches (Fig. 7B). This estimate was based on the total height of the steps divided by the overall elevation change from the total station survey. Other studies have also observed a high degree of variability in the percentages of elevation drop accounted for by log steps. Keller and Swanson (1979) noted that step heights in small, western Oregon streams accounted for between 30 and 80% of the instream elevation drop. Comparatively, log steps accounted for <15% of the total drop in elevation for a stream in Vermont (Thompson, 1995), 19 to 22% for steep channels in the southern Andes (Comiti et al., 2008), and 27% for a mountain stream in the Chilean Andes (Andreoli et al., 2007). Still lower percentages have been reported for coastal streams in Oregon (Marston, 1982).

5.4.3. Sediment storage

The dimensions of at least 80 steps were measured in each of the four streams and the volume of sediment stored behind each step was estimated. The smallest volumes were in DHNorth (mean = 0.055 m^3; median = 0.030 m^3) and the largest volumes were in DHSouth (mean = 0.41 m^3; median = 0.36 m^3) (Fig. 8, light gray bars). The MRPP analysis indicated that mean sediment volume was dissimilar between streams, although the differences between Lexen and DHMain were marginal ($p = 0.03$). Volume of sediment storage reflects the size of the channels to some extent, with the smallest volumes occurring in the smallest channel (DHNorth). However, 7 of the 14 largest sediment wedges (storing more than 0.50 m^3, Fig. 8, dark gray bar) were in DHSouth, also a tributary channel. Sections of DHSouth have relatively wide channels (Fig. 3A) and the step heights are slightly higher (Fig. 7A), both of which would contribute to larger sediment wedges forming behind some of the steps.

Estimates of total sediment stored behind steps in the four watersheds were determined from mean step volume extrapolated over the length of the study channels. Mean step volumes within the reaches were usually comparable to the mean of the full sample obtained for the study channel (recall that the sampling design included steps outside of the 20-m reaches) (Fig. 8, dark gray bars). The exception was in DHSouth where the estimate for the 20-m reaches (0.41 m^3) was 1.6 times that of the full sample (0.26 m^3). An adjustment was made to the volume estimates for DHSouth to correct for potential bias from the limited number of within-reach steps. Mean storage volume per unit length of channel varied from 0.004 $m^3\ m^{-1}$ in DHNorth to 0.04 $m^3\ m^{-1}$ in DHSouth. These values were multiplied by the respective length of contributing channel upstream of the gages and weir ponds, as estimated by map distance. The highest volume of sediment stored behind steps was in DHMain (35.5 m^3) and DHSouth (26.3 m^3). In calculating the total volume for DHMain, the unsampled 500-m length of contributing channel was included in the total, assuming that this segment contains similar numbers of steps and storage volumes comparable to that found along the lower portion of DHMain. This additional length of channel was added because the estimates of total inchannel storage are compared against exported volume estimates later in this paper.

5.4.4. Particle size distributions of stored sediment

The particle size distribution of the sediment stored by log steps was always finer than the overall bed of the reach (examples shown in Fig. 9A and B). The differences in the distributions were typically more pronounced for coarser percentiles and indicate an absence of large cobbles on the surfaces of the steps. As a further support of the differences, a qualitative survey of the dominant particle size on step surfaces showed that <10% of the 315 steps were characterized as 'cobble' (>64 mm). Comparing the coarser components of the distributions, the D_{84} of the bed surfaces ranged from very coarse gravel to small/medium cobble (45 to 124 mm, Fig. 3F), while the D_{84} of the step surfaces ranged from coarse to very coarse gravel (16 to 45 mm). The bed/step surface ratio ($D_{84bed\_surf}/D_{84step\_surf}$) for individual sites ranged from 1.3 to 5 (Fig. 10A, mean = 2.7), signifying that the coarse particle sizes composing the two bed areas were usually distinct. Notably, the ratio was

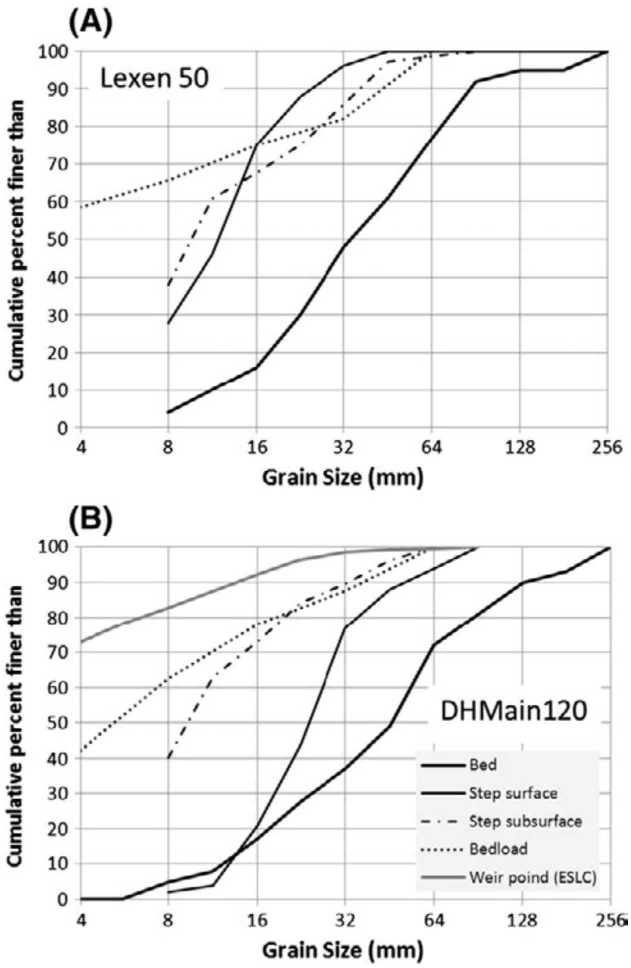

Fig. 9. Comparison of the particle size distributions of channel bed surface, step surfaces, step subsurfaces, bedload at high flow (composite of five samples taken at highest measured discharges), and weir pond accumulations (estimated using data from East St Louis Creek on the FEF) at (A) Lexen 50 and (B) Deadhorse Main 120 (reaches closest to the gages).

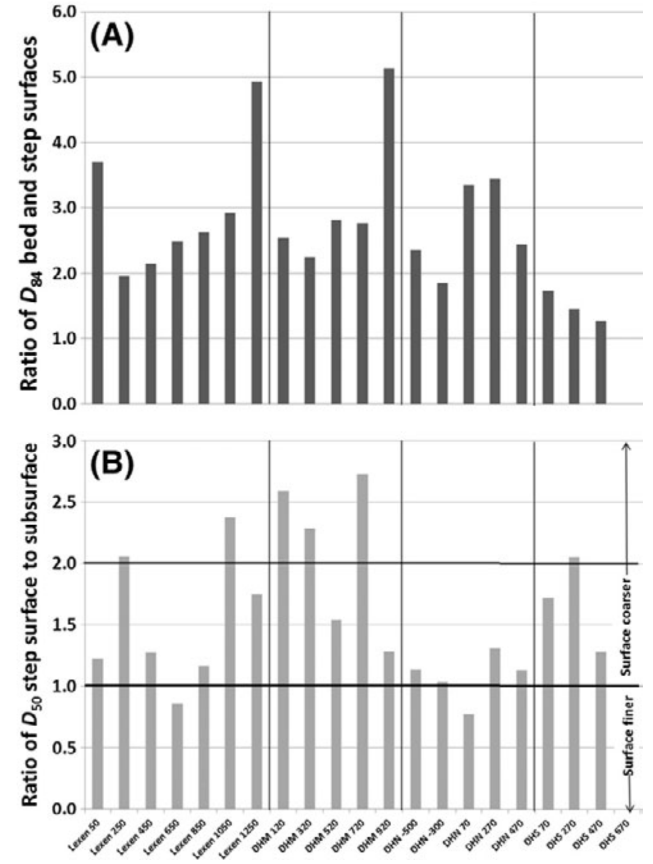

Fig. 10. (A) Ratio of the D_{84} of the bed surface to the step surface in individual reaches. Larger ratios indicate that coarser particles that are present in the overall bed of the channel are largely absent from step surfaces. (B) Armor development – defined as the ratio of the D_{50} of the step surface to the step subsurface – for individual steps. A ratio of ~1 indicates that the distributions are similar. Ratios <1 indicate that the surface is finer than the subsurface. Ratios substantially >2 indicate more well-defined armor layers.

smaller for three reaches in DHSouth where the bed and step surfaces were more comparable. This appears to be because of the slightly finer bed distributions measured in this watershed and shown in Fig. 3F.

A comparison of the particle size distribution of the step surfaces and subsurfaces showed that they often overlapped (e.g., Fig. 9A). This indicates poor development of an armor layer within the step deposit. The armor ratio, defined as $D_{50\text{step\_surf}}/D_{50\text{step\_sub}}$, assumes that the distribution shapes are largely similar and compares the median of the surface to the subsurface. Distinct armor layers in gravel-bed rivers are loosely defined as having a ratio >2 (Hassan et al., 2006). The mean armor ratio for the sampled steps was 1.6, ranging from 0.8 (subsurface was coarser than the surface) to 2.7 (well-defined armoring) (Fig. 10B). Slightly larger ratios were calculated for DHMain (mean = 2.08), while the mean ratios for DHSouth, Lexen, and DHNorth were lower (1.68, 1.53, and 1.08, respectively). The results of the MRPP indicated that the armoring ratios for the four streams were largely similar, although the *p*-value was borderline (0.06). Of the 21 steps with particle size data, only 4 had ratios substantially >2 that would indicate more well-defined armor layers (Fig. 10B).

5.5. Comparisons of sediment stored behind log steps, moved as bedload, and stored in ponds

Data collected on bedload transport in 1993 and 1995 provide insight into transport processes and particle sizes that are moved over a range of flows. Generally, rates of transport are relatively low in these streams, consisting primarily of sand and small gravel (2–8 mm) at low to moderate discharge, with larger gravel (16–64 mm) beginning to be transported at flows approaching bankfull (Ryan et al., 2002; 2005). Although grains larger than small cobbles are not well sampled by the methods used in those studies (sampler orifice limit is about 70 mm), they typically are moved only infrequently and then only for short distances. Cobbles seldom comprise a significant component of the bedload, which may explain their low prevalence in the makeup of step accumulations described previously.

Similarity between the particle size distributions of bedload and sediment stored in steps would support the notion that material trapped behind steps represents the more mobile component of the bed. To evaluate this, a compilation of five particle size distributions from bedload measurements collected at the highest sampled discharges was compared to the steps of the reach closest to the sampling location (LC50 and DHMain 120, Fig. 9A and B). These comparisons show that the particle size distributions of the steps and bedload largely overlap in the coarser gravel fraction, although bedload typically contains a higher percentage of sand and fine gravel. In DHMain 120, 2% of the step surface and 40% of the step subsurface contained particle <8 mm (fine gravel) compared to 62% of the bedload. In LC50, 30% of the step surface and 40% of the subsurface contained fine gravel relative to 65% of the bedload. These differences suggest that trapping efficiency by steps may be better for the coarser fraction and less efficient for fine gravel and sand. This was also noted in the surface layers of the full suite of sampled steps, where only 11% (on average) of the particle sizes were <8 mm (+10.7% standard deviation). About 33% (+14%

standard deviation) of the step subsurface consisted of particles <8 mm. Although a higher percentage of fine gravel occurs in the subsurface, it is still less than that found in the composition of bedload, which supports the idea of reduced efficiencies in trapping — though less convincingly.

In a comparison of stored vs. exported sediment, the total volume of material stored behind log steps (described previously) is approximately an order of magnitude greater than the volume of sediment exported on an annual basis from the four watersheds (Fig. 11). The differences were lower for DHNorth (3×), which is probably from less storage behind log steps rather than higher export: weir pond accumulation (per unit drainage area) at DHNorth was about the same as the other two Deadhorse sites (about 0.015 m^3/ha). Although we lack specific data on the particle size distribution of sediment exported annually at the sites, bulk samples of ponded sediment were collected for analysis at another FEF subwatershed (East St Louis Creek — ESLC). Assuming similarity in the sediment supply and trapping capabilities of steps at ESLC, we compare the particle size distribution of ponded sediment against Lexen and DHMain channel and step distributions (Fig. 9B). Visual assessment of material pulled from all of the ponds suggests that the comparison is valid. Data from ESLC show that D_{50} is typically medium sand to very fine gravel (depending on the year) and nearly 100% of the sediment is <32 mm (coarse gravel). This curve plots to the left of the bedload curve on Fig. 9B (shown only for DHMain), signifying that the exported sediment is the finer component of the bedload transport processes.

6. Summary, conclusions, and future work

Large wood, channel, and step surveys were conducted in 2006/07 to provide baseline information on wood loads, channel morphology, and sediment storage in small channels on the FEF in anticipation of an increase in instream LW in watersheds impacted by MPB. Deadhorse and Lexen Creeks are characterized as steep, narrow, stable, headwater channels with cascade, step-pool, or plane bed morphology. While variations in measured channel metrics (width, depth, and slope) were apparent and some statistically significant differences existed between watersheds (e.g., smaller channel in DHNorth, greater variability in channel form in DHSouth), there were no clear trends in these metrics with downstream position or valley constraint for any of the four watersheds. This indicates that the reaches represent an expected range of morphologic variability for steep, headwater channels in this subalpine forest environment.

The results from the wood survey showed that the LW numbers in the four watersheds were fairly comparable and within the range reported for other Colorado mountain streams — particularly those in steep systems with narrow valley bottoms. Transport of LW pieces in our channels is thought to be low, owing to the obstructions encountered by large trunks in small channels in narrow valleys carrying small discharges. On average, more than half of the length of individual pieces extended beyond the channels and onto the narrow floodplain or adjacent hillslopes. Individual pieces showed indications of having been in place for long periods as most of the wood was decayed/rotten, broken into ramps, and partially buried in beds and banks. With low potential for movement in these streams, accumulation of wood into large, discrete jams was relatively uncommon. Although wood jams were encountered in 66% of the reaches, they were small, being composed of between 3 and 6 pieces of wood that had typically fallen in place rather than transported (with the exception of the avalanche zone in Lexen). This finding differs from other studies that suggest a higher degree of mobility, including the development of significant wood jams in steep mountain channels (e.g., Wohl and Jaeger, 2009; Wohl and Cadol, 2011). Differences are likely from the low potential for transport of LW at the small Deadhorse and Lexen channels until individual pieces break down and can be mobilized. Subsequent surveys will help establish estimates on the fate and relative mobility of wood in these smaller systems.

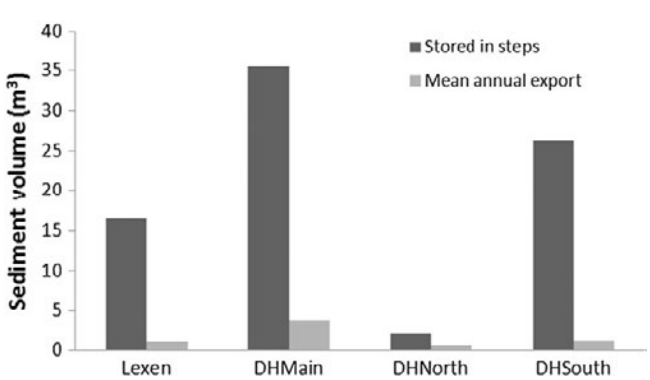

Fig. 11. Comparison of total sediment volume stored in steps upstream of the gages against the mean annual sediment exported from the watershed, as determined from weir pond accumulations.

Rather than forming jams, LW pieces at the Deadhorse and Lexen sites were more likely to be incorporated into the bed and banks of the channel and many formed steps, with the log acting as a riser and accumulated sediment forming the tread. Step frequency among the four watersheds ranged from 8 to 14 steps/100 m. Step heights were on the same order as the diameter of LW pieces measured in the survey. Significant portions of the elevation drop in some of the stream reaches were made up by log steps, though the percentage varied between reaches (0 to 60%).

The volume of sediment stored behind the steps at FEF varied between the four watersheds, though not in a predictable manner. The smallest volumes were measured in the smallest channel (DHNorth, mean = 0.068 m^3), while larger volumes were measured in the second small tributary (DHSouth, mean = 0.26 m^3). Seven of the 14 largest sediment wedges were in DHSouth, which has segments of relatively wide channels and slightly higher step heights that apparently permit larger wedges to form. Estimates of the total volume of material stored behind all log steps were approximately 10 times greater than the mean volume of sediment exported on an annual basis for the respective sites. Similar observations have been made for disturbed and more geomorphically active streams, such as those in the Pacific Northwest region of the US. There, accumulations of LW (steps and jams) were estimated to store between 10 and 15 times the annual sediment yield (Swanson and Lienkaemper, 1978; Swanson and Fredriksen, 1982). In a general sense, LW in forested watersheds acts as a barrier to the export of sediment, the scale of which can range from sediment wedges behind individual steps to large accumulations that force the creation of alluvial stretches in coarse or bedrock channels (e.g., Smith et al., 1993; Montgomery and Buffington, 1997; Massong and Montgomery, 2000; Gomi et al., 2003; May and Gresswell, 2003). The propensity for LW to form steps and jams and store and release sediment is a key structural and functional component of many steep, forested stream systems.

Previous work in the headwater streams at FEF has shown that the coarsest sediment on the channel bed is largely stable over a range of flows, but the mobile component of bedload moves irregularly, primarily during peak runoff (Troendle et al., 1996; Ryan et al., 2002; 2005). The particle size distributions of sediment moved as bedload and accumulated in steps largely overlap in the coarse fractions, indicating that log steps effectively trap coarser bedload but may be less effective at trapping small gravel and sand. As supporting evidence of this inefficiency, the particle size distribution of exported sediment was considerably finer than the sediment transported as bedload or accumulated in steps, thereby representing material that more readily passes through the system. The lack of a well-developed armor at many of the steps suggests that sediment is deposited fairly rapidly, with minimal sorting or separation between layers. The log structure causes a rapid reduction in shear stress available to transport coarse bedload and physically blocks the movement of individual clasts (Smith et al., 1993; Thompson, 1995; Faustini and Jones, 2003).

Subsequent work at the FEF sites evaluates the impacts of additional large wood – primarily lodgepole pine –contributed to the system following the outbreak of mountain pine beetle. The outbreak represents the most significant natural disturbance to these watersheds in over 200 years. Though lodgepole pine is less common in the adjacent subalpine forest, desiccated trunks of beetle-killed trees have begun to fall into the channel from hillslope and narrow riparian areas. Future work includes assessing the number of new recruits to these streams, the rate of breakdown of new wood, and its rate of incorporation into the stream channel.

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