THESIS

CONTROLS ON AND TRENDS IN SEDIMENT AND PARTICULATE ORGANIC MATTER STORAGE BY INSTREAM WOOD IN NORTH SAINT VRAIN CREEK, COLORADO

Submitted by

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ABSTRACT

CONTROLS ON AND TRENDS IN SEDIMENT AND PARTICULATE ORGANIC MATTER STORAGE BY INSTREAM WOOD IN NORTH SAINT VRAIN CREEK, COLORADO

Sediment and particulate organic matter (POM) retained by wood within the bankfull channel were evaluated for 58 stream reaches at the headwaters of North Saint Vrain Creek, Colorado. Wood-induced storage in headwater regions is hypothesized to be important in buffering downstream transport of material. However, the magnitude of storage has not been thoroughly investigated in relation to different potential control variables (e.g., wood volume, channel gradient, channel confinement, and riparian basal area) and spatial scales (jam, reach, and drainage basin) of control.

Multiple and single variable linear regressions informed results. On the jam scale, no relationship was observed between storage and visually estimated jam porosity and permeability. In contrast, the reach-scale volume of stored coarse sediment (gravel, cobble) responds strongly to reach-scale wood volume. Reach-scale fine sediment (sand and finer) volume responds most strongly to wood piece characteristics (average piece length/average channel width and longitudinal spacing) and reach-scale coarse sediment storage. POM storage was most strongly related to riparian controls (channel confinement and riparian forest basal area). These results were translated into a drainage basin-scale analysis in ArcGIS. Despite comprising 14% of the stream network, third-order reaches were found to store 41% of total estimated coarse sediment, 34% of total wood, and 23% of total fine sediment. Large logjams likely exert a high cumulative storage effect in a relatively small portion of the watershed. In contrast, 60% of estimated total POM storage occurs in first-order streams (47% of network stream length). Low transport

capacity in these small streams retains highly mobile POM and lateral roots from the nearby riparian forest may serve as retention structures. These results indicate that wood exerts different geomorphic effects depending on its location within the stream network. From a management perspective, road building and campsite development should avoid impacts to first-order streams, as they are important to overall drainage basin POM retention. Third-order streams are hotspots of wood, coarse sediment, and fine sediment; promoting or allowing wood recruitment processes in these areas can facilitate high sediment retention and buffering of downstream transport.

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1. INTRODUCTION

1.1 Overview of research objectives

The geomorphic effects of instream wood, specifically in relation to channel size, gradient and confinement, are an area of active investigation. One of the primary effects of wood is to facilitate storage of particulate material (both sediment and organic matter) within rivers. Studies such as Nakamura and Swanson (1993) and Wohl and Scott (2016) have examined correlations among wood, stored sediment, and other variables to evaluate the relative importance of potential control variables acting at the local scale (e.g., stream gradient or lateral confinement) versus larger scale patterns that appear in relation to drainage area. However, the contributions of wood in small channels to cumulative storage at the watershed scale are not well constrained. First-order (Strahler, 1952) channels clearly matter, as they constitute the bulk of total stream length in a network and are strong connection points of water and sediment between hillslopes and streams (Wohl, 2010; Downing et al., 2012). By creating longitudinal segmentation, wood in small streams controls localized processes as well as the transport and storage of sediment downstream. However, the bulk of research on sediment storage associated with instream wood thus far has focused on reach-scale characterization of second- and third-order channels (Wohl and Scott, 2016) and it remains unclear where the majority of wood-induced sediment storage occurs within a watershed. The goal of this project is to sample a diverse array of streams at different drainage areas and with varying channel confinement and gradient in the 80 km^2 of North St. Vrain Creek watershed within Rocky Mountain National Park in Colorado to assess trends in sediment storage at spatial scales of individual logjams, channel reaches of consistent geometry (typically 10^1-10^2 m in length), and the entire drainage basin.

A secondary goal is to perform a similar analysis on particulate organic matter. Pools behind wood, especially logjams, cause flow to decelerate such that POM accumulates. POM retention is especially important in small streams, as without roughness elements and retention structures such as wood, these streams are generally conduits of nutrients to larger channels, leaving the smaller streams poor in nutrients (Bilby and Likens, 1980; Bilby, 1981). High concentrations and residence times of POM behind wood create biogeochemical hotspots that are important for ecological productivity (Allan and Castillo, 2007; Battin, 2008). These zones of productivity are extremely important in headwater streams, which generally have low baseline productivity and high transport capacity for POM (Bilby, 1981). POM storage has been well investigated in relation to jam and wood piece characteristics and riparian controls (Beckman, 2013; Livers, 2016). There appears to be a relationship between POM carbon content and surrounding riparian forest age (Beckman and Wohl, 2014a). Whether this is a result of old-growth forests contributing more litterfall to the channel or more wood (and therefore more trapping potential) is not clear. Forest age's effect on POM retention is likely a combination of these factors. POM has not been thoroughly investigated in relation to physical channel controls on the reach or drainage basin scales.

Basin-wide spatial patterns of POM storage have not been examined for North Saint Vrain Creek or other watersheds. I characterize the relationship between POM storage and riparian forest stand age on a range of spatial scales and compare this relationship to the longitudinal distribution of sediment storage. These two components of the project illuminate the role of wood in geomorphic form and ecological productivity throughout a mountain river network and quantify cumulative effects on a range of stream spatial scales.

1.2 Background

1.2.1 Wood effects on hydraulics and local channel morphology

Instream wood is commonly defined as a piece that is at least 10 cm in diameter and 1 m in length, some part of which lies within the bankfull channel (Wohl et al., 2010). A single piece of wood creates an impediment to flow in a stream; flow decelerates in some places and accelerates in others. Flow goes above, around, or under the obstacle. These effects multiply as wood pieces accumulate into a jam and become a complex, dynamic structure. Over time and over distance (i.e., a reach of stream), sediment transport and bed and bank morphology strongly respond to these changes in flow. This insight is not new; researchers have previously quantified localized hydraulic forces and geomorphic forms to find structure and predictability in logjams. Before moving to the focus of my research, which is based more on trends and controls on the features created by wood, it is valuable to review these forces.

First and foremost, wood creates boundary resistance in a channel. Hydraulically, wood presents the most effective obstruction when it spans the channel (enhancing bank resistance) and spans the bed to the water surface (bed resistance) (Abbe and Montgomery, 1996; Faustini and Jones, 2003). This frictional resistance can cause flow to locally decelerate and induces sediment deposition in backwater pools (Keller and Swanson, 1979; Moseley, 1981). Scour pools also develop from localized plunging flow or flow acceleration (Bilby and Ward, 1991; Buffington et al., 2002). Logjam structure has been a recent target for explaining these patterns. Porosity and permeability of a jam, although difficult to quantify, appear to control the amount of stored sediment (Manners et al., 2007). Porosity can be quantified through tracer tests, but this technique is not practical for research on a high number of reaches and jams. Another method to assess logjam structure is classification of pieces by their position and anticipated structural and geomorphic effects (Abbe and Montgomery, 2003; Wohl and Goode, 2008). For example, ramps are pieces that extend from a bank into the flow and impart bank resistance, whereas bridges are pieces that span the channel and allow for vertical resistance to build from the bed to the water surface. Comparison of key structural elements with hydraulic, depositional, and erosional properties allows for a first-order approximation of the relationship between logjam and channel characteristics.

1.2.2 Controls on wood in a stream network

Instream wood is sourced from the upland and riparian forests. The key processes that create downed wood include bank erosion, fire, hillslope mass movements, individual treefall, and wind blowdowns (Swanson and Lienkamper, 1978; Benda and Sias, 2003). The ways in which downed wood enters the channel are more difficult to quantify and depend upon forest age and proximity to the stream, precipitation, and stream-floodplain and stream-hillslope connectivity (Benda and Sias, 2003). However, slope instability appears to be a more important contributor in colluvial reaches whereas bank erosion and wind blowdowns are more prevalent sources of wood in alluvial sections (May and Gresswell, 2002). Much of the wood recruitment literature comes from the Pacific Northwest, a region where hillslope mass movements can dominate wood introduction to the stream (Swanson and Lienkamper, 1978; May and Gresswell, 2002). Research from the Colorado Front Range identifies patch blowdowns as an important process in recruiting wood to the channel and redistributing carbon stores (Wohl, 2013). Contributions from hillslope instability are less well known in this region.

Once in the stream, the depth of flow and orientation of log pieces relative to flow determines their mobility (Braudrick and Grant, 2000). Mobility of individual pieces, in turn, affects jam formation. Wood in a jam aggregates and affects channel morphology in a non-linear manner in which the effects are not proportional to the size of the jam (Braudrick et al., 1997; Wohl, 2011).

There has been extensive research on North Saint Vrain (NSV) Creek in Rocky Mountain National Park (RMNP), Colorado to assess trends and controls on instream wood volume, or wood load (Wohl and Goode, 2008; Wohl and Jaeger, 2009; Wohl and Cadol, 2011; Wohl and Beckman, 2014a; Beckman and Wohl, 2014b; Livers and Wohl, 2016), in part because this watershed includes extensive stands of old-growth forest of 200 plus years in age (Sibold et al. 2006). Streams surrounded by old-growth forest have high wood loads, especially compared to areas that have experienced timber harvest (Richmond and Fausch, 1995; Wohl and Cadol, 2011; Beckman; 2013, Beckman and Wohl, 2014a). Once in the stream, transport capacity and unit stream power in the channel determine wood's stability. Small channels (first order) are transport-limited with respect to wood, as flows are too low to move and aggregate wood in a geomorphically meaningful way (Marcus et al., 2002; Wohl and Jaeger, 2009). In contrast, larger (fourth order and above) channels are supply limited with respect to wood because the dimensions of wood pieces relative to channel dimensions allow wood to be much more mobile (Marcus et al., 2002; Wohl and Jaeger, 2009). This relationship may be scale-able, as wood load appears to peak at the middle drainage areas of a watershed. However, this inference is based on very limited data from larger rivers (Wohl and Scott, 2016). The balance between localized and drainage-scale trends on wood load is still not clearly defined. In this project, I seek to quantify the relative importance of local channel geometry (gradient, confinement) within this larger transport capacity framework and to assess whether local-scale controls dominate basin-scale patterns of wood load and associated sediment and organic matter storage, or whether progressive downstream trends as a result of increasing drainage area and transport capacity best characterize basin-scale patterns of wood load and sediment storage.

1.2.3 Sediment storage trends

Research has also addressed the influence of wood-induced sediment storage on the morphology and sediment budget of a stream network. On a single jam or piece scale, wood creates “openings” in which available stream power is less than critical stream power necessary for sediment transport (Keller and Swanson, 1979). This facilitates sediment retention (Keller et al., 1995). Wood can account for a high proportion of sediment storage in a watershed, ranging from 49% in a series of watersheds in central Idaho (Megahan, 1982) to 81% for a small New Hampshire watershed (Bilby, 1981). Stored sediment can create alluvial sections in otherwise predominantly cascade or bedrock reaches (Massong and Montgomery, 2000). Wood-induced sediment storage, especially at the headwaters of a network, dampens the geomorphic effects of debris flows and acts as a buffering system that facilitates more regular episodes of fine sediment transport to downstream reaches (Swanson and Lienkaemper, 1978; May and Gresswell, 2002). Both field-based and modeling studies identify wood’s role in delaying downstream sediment pulses following concentrated sediment input events, such as debris flows (Keller et al., 1995; Lancaster et al., 2001). Wood and logjams are permeable, transient structures but were found to store individual sediment particles on the order of 100 days in a Maine watershed (Fisher et al., 2010). On a cumulative basis, this can account for storage ranging from equal to or up to ten times greater than annual basin sediment yield (Megahan, 1982; Bilby and Ward, 1989; Comiti et al., 2008).

The distribution and controls of stored sediment on a network scale are still relatively poorly constrained. Researchers rarely distinguish between fine and coarse sediment storage. I assume that most previous research focuses on coarse (gravel and cobble) retention given that the study areas are predominantly in high-gradient streams of the Pacific Northwest in which fine sediment is more transient. Bilby and Ward (1989) found that the volume of stored sediment on a reach scale appears to be related to channel size, as storage is more prevalent on smaller streams (width less than 7 m) versus larger streams (width greater than 10 m). This study only assessed whether there was storage, categorizing pools behind wood as depositional or scour, and did not quantify the amount of storage in different stream sizes. Nakamura and Swanson (1993) quantified the distribution of storage and developed a predictive relationship between sediment volume and channel width and gradient for step-pool, second- to third-order channels in Oregon. Without a wood load term, though, their predictive model identifies depositional features created by instream wood but does not fully disentangle these from pre-existing bed morphology. Wohl and Scott's (2016) synthesis of wood and sediment from a range of watershed scales and climates introduced a wood load term to this model.

These papers strongly guide my thesis. I sought to test connections between wood and sediment trends by extensively surveying wood-induced sediment storage in relation to jam, reach, and drainage scale controls. Moreover, by distinguishing fine (sand and finer) and coarse (gravel and cobble) sediment, this project provides insight into what is more likely to be transient sediment storage (fine sediment) and more persistent storage (coarse sediment).

1.2.4 Particulate organic matter (POM) dynamics

Particulate organic matter (POM) is grouped into two categories: fine POM (0.45 μm to 1mm) and coarse POM (greater than 1mm) (Vannote et al., 1980). Much of the research on POM focuses on highlighting the importance of irregularities and obstructions (such as wood) in storing POM by quantifying POM export from a stream after wood removal (Bilby and Likens, 1980; Bilby, 1981; Raikow et al., 1995). Many different sizes of wood and streams are important for POM retention. Similar to sediment storage, wood at the headwaters of a network can store POM instead of allowing it to move quickly downstream (Ehrman and Lamberti, 1992; Cordova et al., 2008). Temporally, POM retention and transport depend on seasonal changes in discharge. Overall storage is highest during baseflow, as POM settles on the streambed and is not readily transported (Raikow et al., 1995). However, wood-related storage may be more important during slightly higher flow conditions, as wood and debris dams are the only way to trap POM (Smock, 1990; Jones and Smock, 1991). I minimized the confounding influence of temporal POM variations by conducting measurements during baseflow to obtain a snapshot analysis of the spatial distribution of POM and the factors influencing it.

POM reservoirs strongly influence stream ecology and metabolic cycling. Backwater pools facilitate retention of organic matter. Increased residence times of this material create biogeochemical and ecological hotspots of productivity in mountain river networks (McClain et al.; 2003; Allan and Castillo, 2007; Battin et al., 2008). These streams generally lack well-developed floodplains, so there is less riparian ecosystem development and quicker transport of sediments and nutrients due to close coupling with upland areas (Wohl, 2010). By creating flow resistance and storing sediment and nutrients in backwater pools, wood increases opportunities for ecological uptake and stream metabolism (Bilby and Likens, 1980; Battin et al., 2008; Wohl and Beckman, 2014b).

On a larger carbon cycle scale, headwater areas are important organic carbon sinks in a river network, with unconfined reaches flowing through old-growth forest landscapes promoting high storage of organic carbon (an estimated 75% of total watershed carbon retention) in floodplain sediment and in downed wood in the channel and floodplain (Wohl et al., 2012;

Beckman and Wohl, 2014). Multithreaded reaches serve as zones of especially high floodplain and in-channel carbon storage, creating a repository of carbon for the rest of the stream network (Wohl et al., 2012). It is important to note that wood constitutes the vast majority of riverine carbon content and POM represents a very small fraction (Beckman and Wohl, 2014). Instream wood is also a prevalent source of POM as flowing water physically abrades wood into smaller pieces and moisture enhances microbial decomposition (Harmon et al., 1986; Ward and Aumen, 1986). However, POM is more biologically available than wood and therefore may be a better indicator of potential stream productivity (Wohl et al., 2012). There is a paucity of research that quantifies the spatial distribution of wood-induced POM storage, especially in relation to jam, reach, and drainage basin controls. I aim to quantify basin-wide POM storage in pools created by wood and mesh my findings with previous research on the ecological and biogeochemical implications of POM.

1.3 Objectives and Hypotheses

The primary objectives of this project are to quantify sediment (fine and coarse) and POM storage in relation to potential controls at the spatial scales of an individual jam, a stream reach, and the drainage basin. Although the effects of wood on channel morphology and sediment storage are fairly well studied on reach scales, very few studies address spatial distribution of wood-stored sediment across an entire watershed. Moreover, the literature delineating fine versus coarse sediment storage is sparse. Understanding the balance and controls on storing different sizes of sediment is important for understanding downstream morphology and sediment budgets. Similarly, there is an extensive literature on reach-scale POM transport following wood removal and the carbon cycle implications of stored POM, but few studies on the spatial distribution of stored POM (Bilby and Likens, 1980; Bilby, 1981; Beckman and Wohl, 2014A).

In this study, sediment (fine and coarse) and POM storage are related to jam characteristics (porosity, permeability, jam volume/average channel width), reach-scale controls (lateral channel confinement, channel gradient, Montgomery-Buffington bedform category, forest basal area, wood load, and wood piece characteristics), and potential drainage basin-scale controls (drainage area) on a large number of study reaches within a single drainage basin. By observationally and quantitatively understanding sediment storage patterns on these diverse reaches, I estimate cumulative stored material within the watershed. This project builds upon previous research by addressing headwater (first- and second-order) stream contributions to cumulative storage in a network. Estimating storage on these reaches better informs understanding of their buffering capacity relative to the rest of the watershed with respect to sediment and POM transport dynamics.

1.3.1 Wood load controls

Objective 1: Assess potential controls on instream wood load in NSV at the reach and drainage basin scales.

Hypothesis 1: Wood load, expressed as m^3 of wood per meter of channel length, peaks at intermediate portions of the NSV network (i.e., drainage areas of ~40 km^2).

Rationale 1: The volume of instream wood in a given reach reflects the unit stream power and transport capacity at that reach (Marcus et al., 2002; Wohl and Jaeger, 2009). These factors are related to drainage area. Small drainage areas are transport limited for wood and wood load reflects primarily wood recruitment to the channel. Large drainage areas are supply limited for wood and wood load reflects primarily transport of wood downstream. Intermediate drainage areas have a balance between wood supply and transport that maximizes wood load. Transport in stream reaches with intermediate drainage area is sufficiently high to mobilize and aggregate wood into stable positions in the channel, yet not so high that wood is easily flushed through the channel. This relationship has been proposed for larger watersheds (Wohl and Scott, 2016) but has not been extensively analyzed for a single headwater stream network. I expect at least half the variation in wood load versus drainage area is explained by a quadratic fit (R^2=0.5). With regard to expected non-significant predictors, wood is effectively retained and stabilized within a range of Montgomery-Buffington (MB) (Montgomery and Buffington, 1997) stream types (and gradients) (Curran and Wohl, 2003; Faustini and Jones, 2003). Although old-growth forests along the Front Range tend to produce higher instream wood loads (Richmond and Fausch, 1995), basal area, a continuous variable, poorly predicts wood volume, as there is wood transport between different forest types in NSV (Wohl and Cadol, 2011; Beckman, 2013). Consequently, I expect that there is no linear relationship between wood load and surrounding forest basal area nor are there significant differences in wood volume between lateral channel confinement and Montgomery-Buffington classification categories. In other words, I expect drainage-basin-scale trends to override local controls in governing where the highest wood loads occur in a river network.

1.3.2 Material storage hypotheses

Objective 2: Analyze the strongest predictors of reach-scale coarse, fine, and POM storage using a combination of single and multiple variable regressions.

Hypothesis 2a: Coarse sediment storage correlates most strongly with wood load.

Rationale 2a: Wood (both jams and individual pieces) has been shown to create longitudinal steps that effectively store gravel and cobble-sized sediment (Figure 1; Nakamura and Swanson, 1993; Keller, 1995). Wood is commonly more important than other flow obstructions in inducing sediment deposition in cascade or even bedrock reaches (Massong and Montgomery, 2000). Therefore, wedges of stored coarse sediment should correlate strongly with reach-scale wood load. Gradient and MB category are expected secondary controls, as wood's ability to adjust channel form and retain sediment is strongest in step-pool or plane-bed reaches (gradients of 0.6 to 4.6 degrees) (Montgomery and Buffington, 1997). The most effective gradients for sediment storage have not been fully delineated, but previous research suggests that channels with pre-existing steps in the bed are primed for wood-induced coarse sediment retention (Keller and Swanson, 1979; Moseley, 1981; Nakamura and Swanson, 1993; Lancaster et al., 2001; Montgomery et al., 2003). Drainage area is another expected secondary control as it strongly correlates with wood load (Hypothesis 1). Much of this work comes from steep environments in the Pacific Northwest, but whether hypothesized declines in sediment storage are more influenced by changes in slope or drainage basin changes in wood load on certain reach types is not well constrained.

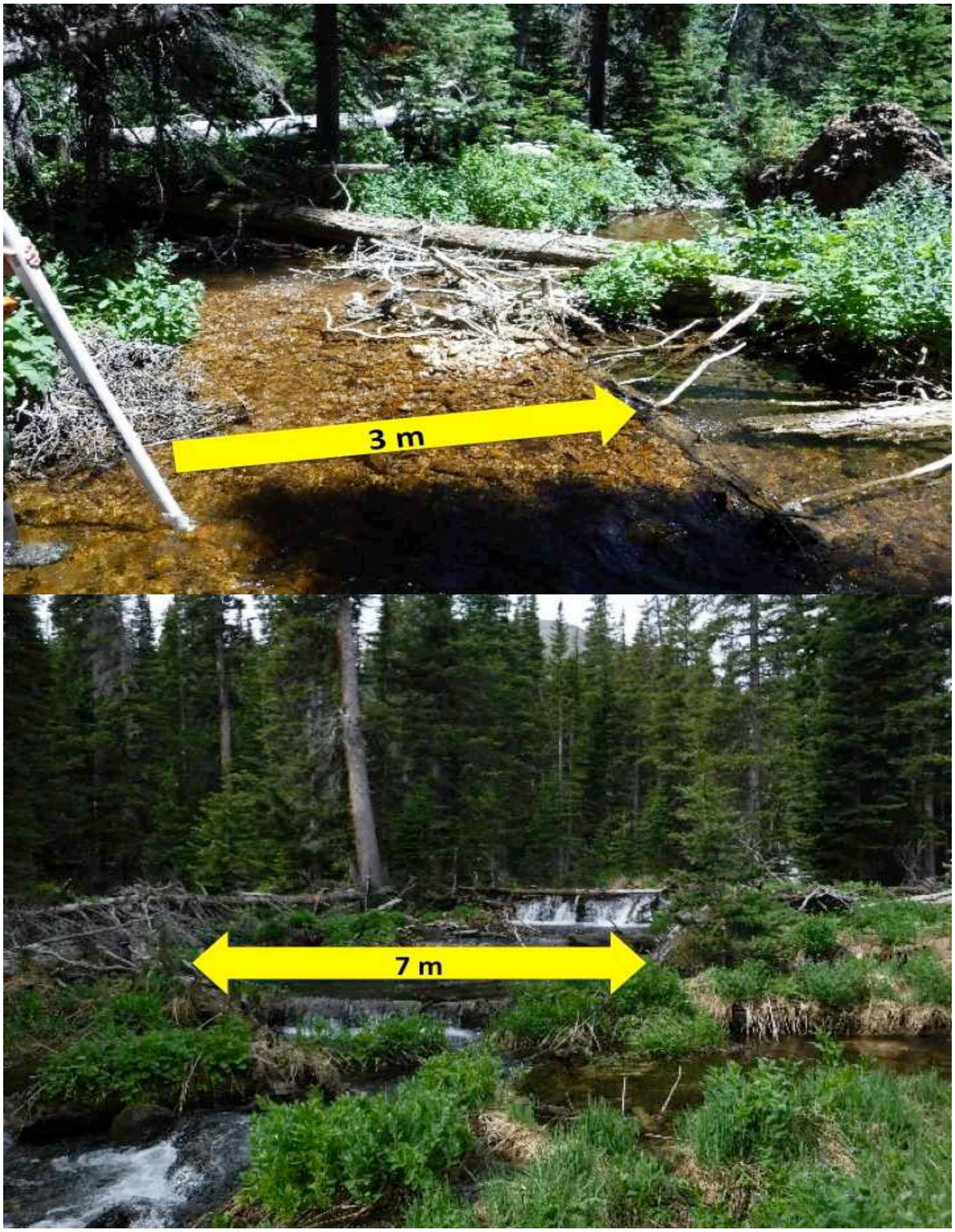


Figure 1. Coarse sediment storage behind a jam (left) and longitudinal steps of stored coarse sediment in a step-pool channel (right). Yellow arrows indicate flow direction and scale.

Hypothesis 2b: Fine sediment most strongly correlates with wood load.

Rationale 2b: Fine sediment deposition is more localized and transient than coarse sediment storage. Figure 2 displays examples of wood-induced fine sediment storage. Very few studies differentiate between fine and coarse sediment storage, so it is difficult to disentangle what grain sizes other investigators are referring to when discussing sediment storage. I expect wood to be a primary factor in any type of sediment storage, as its ability to accumulate and stabilize in the channel has significant geomorphic effects (Keller and Swanson, 1979; Moseley, 1981; Massong and Montgomery, 2000). The reasons why controls of fine sediment storage may differ from those of coarse sediment are more speculative. However, zones of high coarse sediment accumulation behind wood should increase resistance such that fine sediment is more likely to be retained. There is obviously variability in this, as cascade reaches, for example, may have too much energy for extensive fine sediment storage. Longitudinal spacing of wood, especially of ramp and bridge pieces, is indicative of a reach's ability to impede bedload transport and induce transient fine sediment storage (Fisher et al., 2010; Beckman, 2013). Fine sediment storage should be higher in reaches with decreased spacing (increased frequency) of wood. Spacing is likely more important for fine sediment storage than coarse because fine bedload transport is more prevalent than mobilization of coarser material. Factors that are expected to control wood and coarse sediment storage (such as gradient, MB category, and drainage area) are included in the model but are not expected to be significant, as fine sediment is likely more dependent on localized, direct controls, rather than indirect controls.

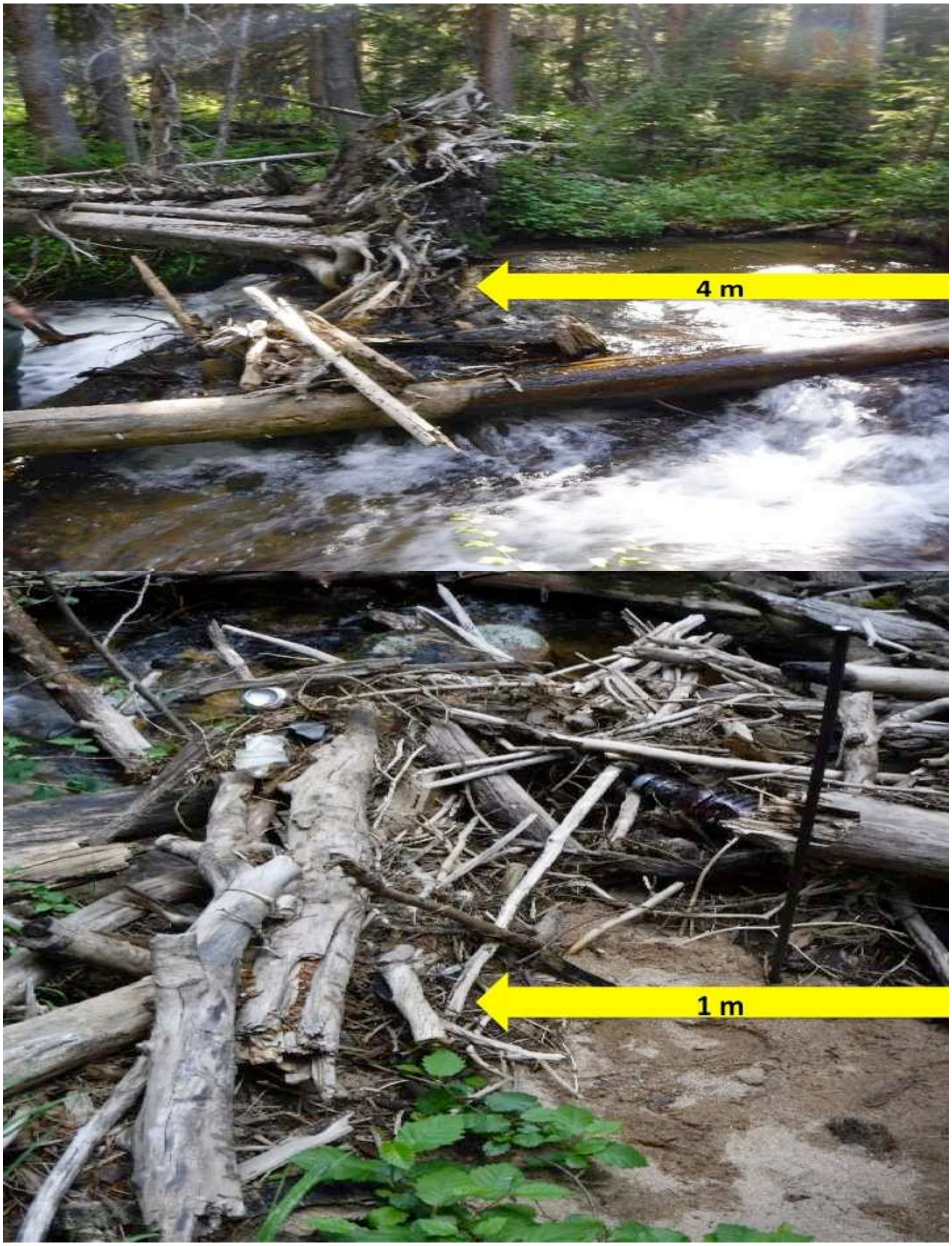


Figure 2. Examples of fine sediment retention; aside from wood, close longitudinal spacing of wood and the presence of stored coarse sediment should induce storage of fines. Arrows display flow direction and scale.

Hypothesis 2c: POM storage correlates most strongly with wood load, followed by fine sediment, basal area, spacing, and lateral channel confinement.

Rationale 2c: All storage trends, including POM, are expected to strongly correlate with wood load, as wood creates the initial obstruction necessary for frictional resistance and pool formation. There is evidence of a strong relationship between the presence of fine sediment and POM behind logjams, as fine sediment wedges in low velocity pools provide a surface on which POM readily settles (Bilby, 1981). Moreover, POM is readily buried and available for episodic processing in fine sediment patches (Smock, 1990; Jones and Smock, 1991). Because longitudinal spacing controls fine sediment storage, POM should also respond strongly to closely spaced pieces and jams. Figure 3 displays pools of fine sediment with a surface of stored POM. Finally, basal area and confinement as potential controls reflect riparian forest POM contributions. Surrounding forest basal area has been documented to correlate with POM and carbon content in the stream, as older forests (compared to burned patches) have higher accumulations of detrital material (Beckman and Wohl, 2014a). Evidence for this relationship will suggest that litterfall contributions to the stream are comparable to instream POM transport driven by wood characteristics (such as spacing). Floodplain-channel connectivity has been identified as an important factor in introducing POM to the stream (Harmon et al., 1986; Jones and Smock, 1991; Raikow et al., 1995). Therefore, laterally unconfined reaches should have more developed POM transport processes and higher instream POM volumes.

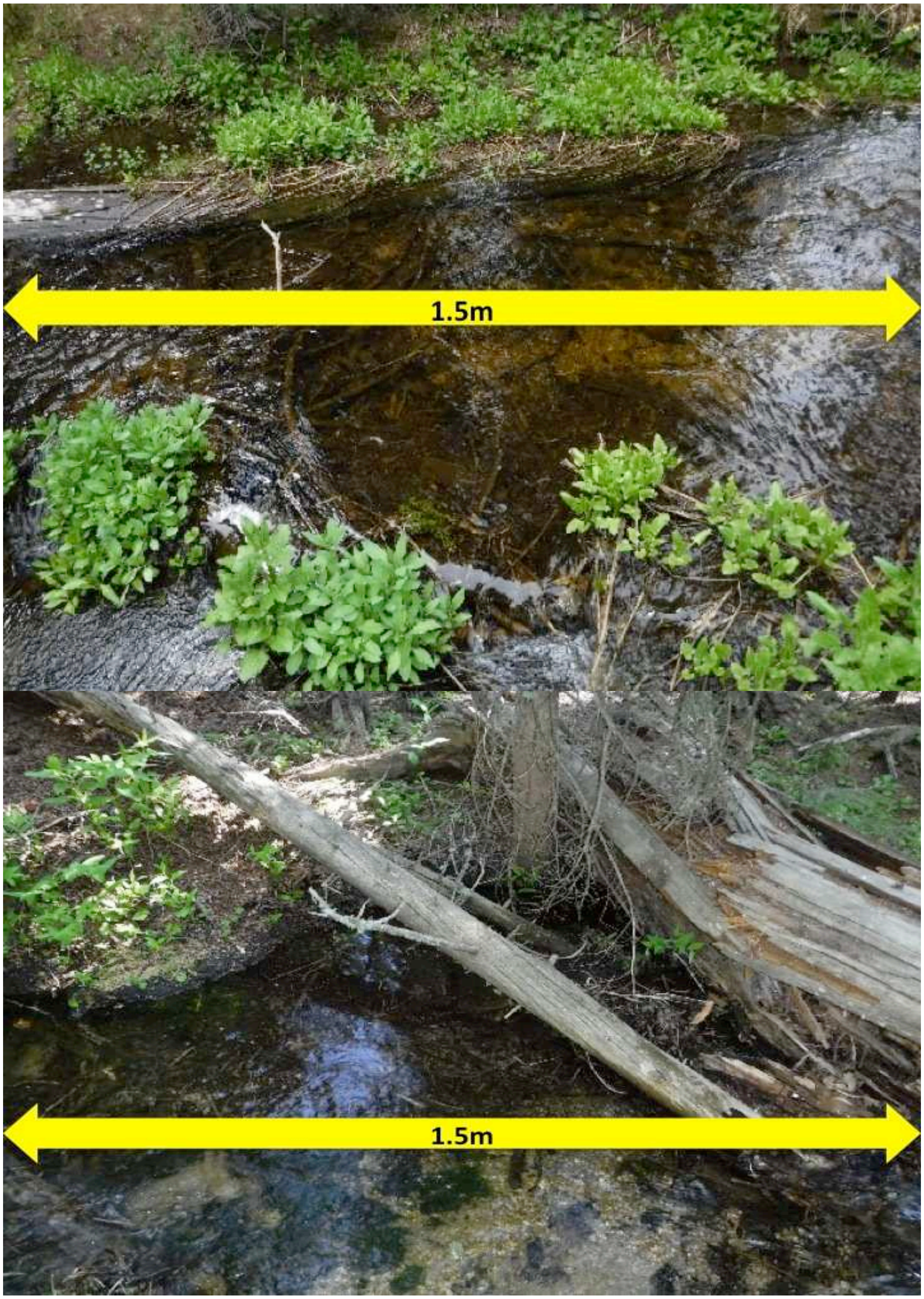


Figure 3. Two examples of stored POM (dark material). The presence of fine sediment and spacing of logjams are expected to exert resistance and induce POM settling. However, litterfall from surrounding riparian forest (expected to be higher in more developed, old growth forest) should also control the amount of instream POM. Arrows display scale.

1.3.3 Jam-scale controls on material storage

Objective 3: Quantify jam-scale effects (porosity, permeability, jam volume) on localized sediment storage.

Hypothesis 3a: On the scale of a single jam, sediment and POM storage are inversely correlated with porosity and permeability. Fine sediment storage correlates more strongly than coarse sediment storage with porosity and permeability. POM storage correlates more strongly than fine sediment with porosity and permeability.

Hypothesis 3b: Sediment and POM storage are positively correlated with jam volume (specifically jam volume/average channel width). Again, POM storage should correlate most strongly with jam volume.

Rationale 3: Logjam porosity is a difficult variable to quantify (elaborated in methods, Figure 7) but is hypothesized to be an important control on sediment retention ability of a jam (Manners et al., 2007; Beckman, 2013). Jams with less pore space and less connected pores (low porosity and permeability, respectively) should better retain material, especially fine sediment and POM. I expect low porosity and permeability to be especially important for POM retention, as this small material requires greater obstruction for storage than coarse or fine sediment. Support for this hypothesis will include negative linear correlations between particulate material storage and porosity and permeability. Regarding jam volume, high localized volumes of wood should be important for deposition and storage of material. Jam volume/average channel width is expected to be a strong predictor and indicator of geomorphic effectiveness relative to channel size.

1.3.4 Drainage basin storage estimates

Objective 4: Estimate drainage basin-scale storage of wood, coarse sediment, fine sediment, and POM

Hypothesis 4: Cumulative storage of wood, coarse, fine, and POM is highest in third order streams.

Rationale 4: The basis for this hypothesis comes from the previous hypotheses; wood should directly or indirectly control storage of all material. Because wood is expected to peak in third-order streams of a drainage area of ~40 km^2 (within NSV), retention of materials should also be highest in these reaches. Figure 4 diagrams this hypothesis as well as reach-scale hypotheses. Wood exerts a primary control on all storage and sediment storage follows drainage-scale wood load trends (Figure 4A). Secondary factors (such as channel gradient and wood piece spacing) modulate storage (Figure 4B).

1.3.5 Conceptual model of hypothesized results

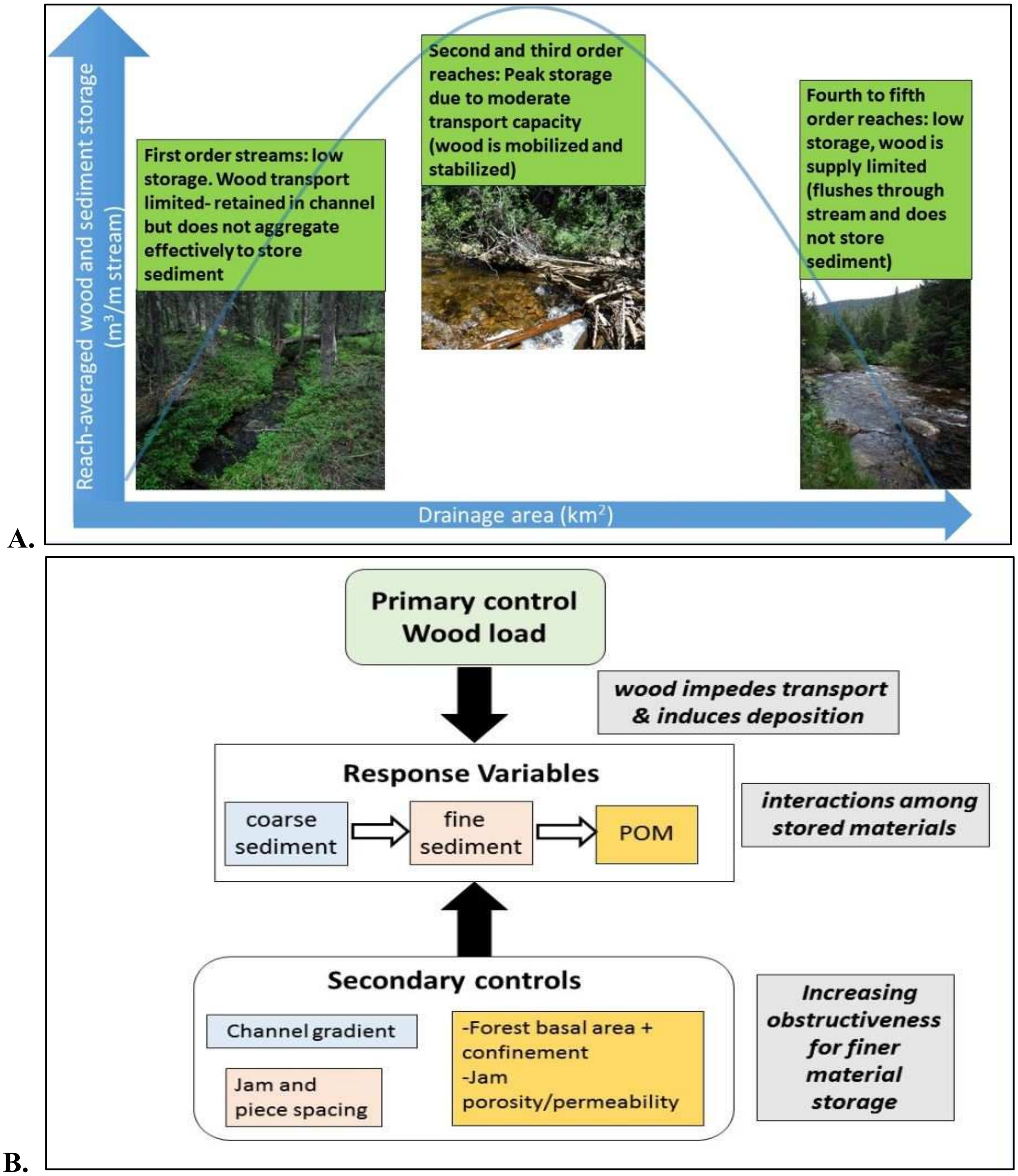


Figure 4 A. Sediment storage is expected to primarily follow trends in wood load versus drainage area (balance of channel transport capacity and wood supply). **B.** Interactions among stored materials behind wood and secondary factors are expected to also exert control on storage. Increasingly greater obstruction is needed for storage of finer material (i.e., jam characteristics more important to POM storage than coarse sediment storage).

2. STUDY AREA

This thesis focuses on the upper 80 km^2 (that lie within Rocky Mountain National Park) of the 250 km^2 North Saint Vrain (NSV) Creek watershed in Colorado (Figure 5). I built on previously collected datasets of wood load and sediment storage from second- and third-order channel segments (Livers, 2016). Specifically, I collected data from first-order channel segments, as well as data from additional channel segments of higher stream order.

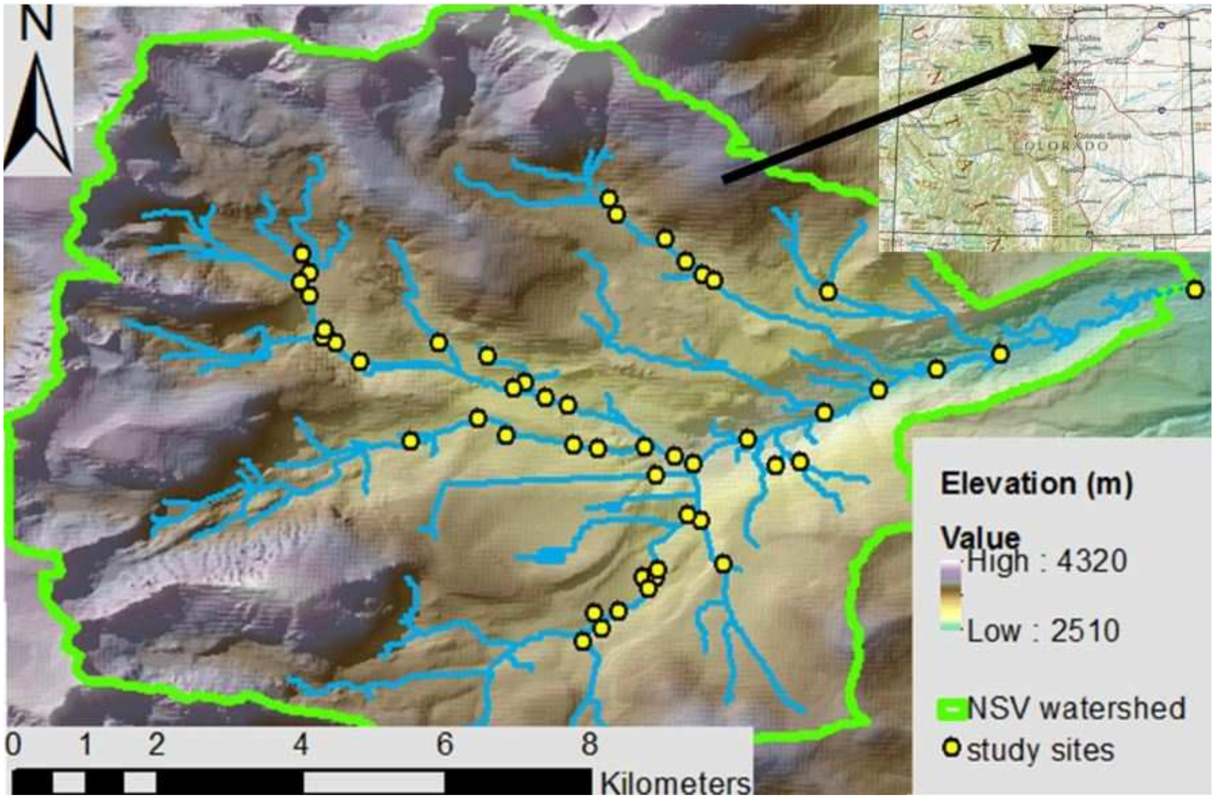


Figure 5. Map of North Saint Vrain (NSV) study area. The basin lies in the southeastern corner of Rocky Mountain National Park, 113 km northwest of Denver. Fifty of the 68 study reaches lie within the upper NSV watershed (green boundary). Eighteen reaches were sampled from outside this area to supplement the dataset. The stream network above was created in ArcGIS using a 0.25 km^2 threshold drainage area for channel initiation. The stream network is clipped to timberline.

The upper NSV watershed is located above the Pleistocene terminal moraine. Underlying lithology is primarily Precambrian Silver Plume Granite, with associated metamorphism (Braddock and Cole, 1990). Although bedrock lithology is relatively uniform, jointing patterns and glacial erosion lead to variability in valley geometry and channel gradient and confinement (Wohl et al., 2004). Channel-bed morphology appears to be controlled by confinement (valley width/channel width (VW/CW) <2 – confined (C), 2<VW/CW<8 – partially confined (PC), VW/CW>8- unconfined (U)) (Wohl et al., 2012) to some extent, with cascade and step-pool bedforms most common in laterally confined valley segments, plane-bed and pool-riffle in partially confined, and pool-riffle in unconfined segments (Montgomery and Buffington, 1997; Wohl and Beckman, 2014a; Livers and Wohl, 2015).

Mean annual precipitation is 71 cm and streamflow is primarily snowmelt-generated, with a May to June peak averaging 20 m^3/s at the national park boundary (Wohl and Beckman, 2014b). Vegetation is classified as subalpine forest composed of Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), lodgepole pine (*Pinus contorta*), aspen (*Populus tremuloides*), and limber pine (*Pinus flexilis*) (Veblen and Donnegan, 2005). Forest disturbances in this region take the form of wildfire, blowdown, insect outbreaks, and hillslope mass movements. Mass movements and debris flows are rare for NSV, although they occurred in other locations of the national park in response to the September 2013 flood (Patton, 2016). Stand-killing disturbances, primarily fires, occurred in 1654, 1695, 1880, and 1978 AD (Sibold et al. 2006). Old-growth forest generally takes at least 200 years to develop; therefore, there are many pockets of younger forest surrounding NSV channels, but also stands of old-growth riparian forest (Veblen and Donnegan, 2005; Sibold et al., 2006) (Figure 6).

Particulate organic matter storage tends to correlate with aforementioned forest characteristics (Beckman and Wohl, 2014a). Although recent pine beetle outbreaks have been documented, riparian trees, thus far, appear to be less susceptible to decay and needle shedding (Beckman and Wohl, 2014). However, these observations were made during the summers of 2010 and 2011, so the long-term effect (or lack thereof) of beetle kill remains to be verified.

Before the creation of Rocky Mountain National Park in 1915, logging and beaver trapping were prevalent in the national park (Wohl, 2001). These land uses affected wood recruitment, channel complexity and morphology, and ecological productivity. A footprint from these activities likely persists today (Wohl, 2006), although NSV was likely less affected by historical land use than most watersheds in the national park. Consequently, the NSV watershed serves as a fairly natural system with respect to wood and sediment dynamics, and one which can potentially inform the use of wood in restoration of more affected watersheds.

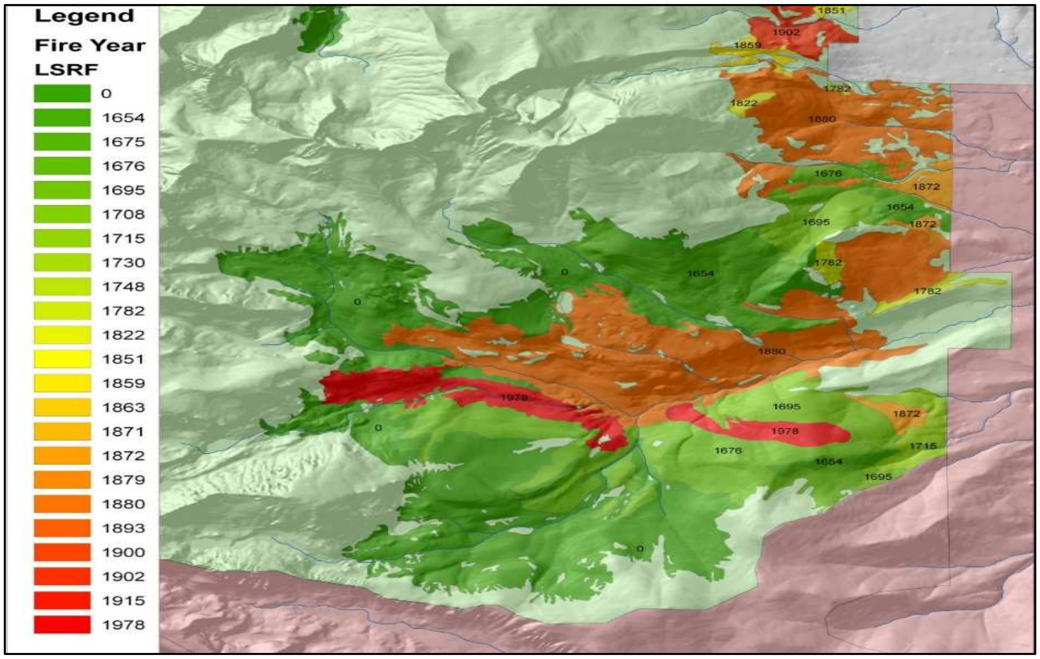


Figure 6. NSV forest age and fire history estimated from tree cores (From Sibold et al., 2006).

3. METHODS

3.1 Site selection

I define a study reach as having consistent channel geometry along a length of at least 10 times bankfull channel width, with a minimum reach length of 10 m. Study reaches were selected on the mainstem NSV Creek and three main tributaries (Ouzel, Cony, Hunters). Fifty of the 68 study reaches are located in upper NSV watershed with an outlet at the park boundary (see Figure 5). Eighteen supplementary reaches from nearby NSV tributaries outside of the park (Rock Creek, Cabin Creek, Horse Creek, Willow Creek) were selected to obtain more first-order streams. These supplementary reaches were assessed for similarity in channel width and contributing area to known first-order streams in RMNP. Twelve of the reaches were from Livers (2016), a study on primarily third-order streams that intensively surveyed wood loads and POM storage. I returned to these sites to measure coarse and fine sediment to develop a fuller picture of material storage. Reach-scale analyses used 58 of these reaches, removing 10 reaches that either were altered by the 2013 flood, in a different forest/elevation zone, or on streams too small to show up on USGS StreamStats (Appendix A). Jam-scale analyses varied due to difficulties matching data between Livers (2016) and my study. Finally, basin-scale analyses used 48 reaches within the portion of the NSV watershed in the national park. Although formal stratified random selection was not used for my sites, I developed a site selection plan before beginning field work and then chose reaches to represent the diversity of drainage area, channel confinement, stream gradient, stream order, Montgomery-Buffington (1997) bedform types, and surrounding forest age and disturbance history within the NSV watershed. Essentially, I did not seek out reaches with high wood loads or high material storage, but rather sought to sample reaches of relatively consistent physical characteristics across the drainage basin. Truly random site selection was limited by accessibility and desire to avoid known disturbances on some tributaries, such as the removal of a dam on Sandbeach Creek in 1999.

3.2 Measurement of channel characteristics

General reach locations were selected before the field season; 12 of these reaches overlapped with those in Livers (2016). Livers conducted detailed wood load and POM storage analysis on second- to third-order, multithreaded sites in NSV. I added to these data by measuring coarse and fine sediment at these reaches. The Livers reaches were much longer than 10x bankfull channel width to inform a nitrogen-cycling component of the project. I only sampled 10x bankfull sections of these reaches. However, assuming that wood and POM are relatively consistent through a reach, I scaled these values to the fraction of the Livers (2016) reaches that I sampled. Specific locations for my reaches were then delineated with a handheld GPS. To the extent possible, reaches were delineated to ensure consistency in bedform and channel confinement throughout the length of the reach. Some reaches, however, included changes in slope or confinement.

Bankfull channel width was assessed at three to four locations in a potential reach; the average width then informed the total reach length. If a channel was multithreaded, the reach length was based on the width of the widest channel. Twelve of the 68 study reaches (17.6%) and under 25% of total stream length in NSV are multithreaded (Wohl et al. 2012). Valley width was also measured and commonly had to be calculated by breaking the valley bottom into lateral segments because of dense forest and limited visibility. Confinement for each reach was calculated by dividing average valley width (VW) by average channel width (CW).

Reach-scale gradient (in degrees) was measured at several locations along the reach and averaged. These metrics were measured with a handheld TruPulse 360B laser rangefinder. The instrument records values to the nearest 0.1 m, with an error of +/- 0.3 m. Predominant bedform and bed material were visually assessed (Montgomery and Buffington, 1997). Surrounding basal area was estimated with a Panama Angle Gauge, which converts a count of trees filling a viewfinder during a 360-degree scan at eye height to a basal area (m^2/ha). Drainage area was calculated using GPS points with USGS StreamStats, a program that uses 10 m DEMs to calculate basin parameters (http://water.usgs.gov/osw/streamstats/colorado.html).

3.3 Wood, sediment, and POM measurement techniques

I measured the diameter and length of all dispersed wood pieces and jams (defined as 3 or more pieces in contact with one another) within the study reach. Volume was calculated by approximating wood pieces as cylindrical. In jams, especially complex ones, two methods were used to estimate volume. First, the largest, key pieces were identified and measured following Abbe and Montgomery (2003). Secondly, the jam was differentiated into manageable parts on which encompassing dimensions (length, width) were measured and summed to a volume by estimating wood and void space. Jam porosity and permeability were also visually estimated. A quick, consistent, and widely used field method for estimating porosity and permeability does not exist. I worked with a systematic methodology for logjam measurements, but continued refinement is recommended. I attempted to categorize porosity in the field and later corroborate my estimates by analyzing photos of jams (see Figure 7 for porosity estimation example). Both variables are highly dependent on flow stage (i.e., which parts of a jam are contributing to flow resistance and sediment storage). I was therefore mindful of flow when assessing jams and did not record porosity or permeability if there was very little or no flow, such as if a jam was in a dry side channel.

Longitudinal spacing of jams or wood pieces was calculated by dividing the number of jams or individual pieces in a reach by the total stream length (units are meters). Spacing approximates the degree of longitudinal segmentation in a reach and was used to assess whether closely spaced wood may be more important than total wood volume in storage trends. Due to the density of wood pieces in many reaches, I decided against taking GPS points at each piece or jam and later calculating spacing in GIS because the error in the handheld GPS (+/- 9 m) exceeds the spacing between wood pieces. Although this method has been used to analyze spacing between jams, it would be less effective when measuring dispersed wood. Therefore, although my method is indirect, it consistently approximates the longitudinal density of wood pieces.

Finally, reach-scale wood piece characteristics may be important to sediment and POM dynamics (Beckman, 2013). The median wood piece diameter (D_{50}) and average wood piece length/average channel width were calculated on a reach scale. The proportion of jammed wood (proportion of wood volume in jams/total wood volume) and proportion of ramp and bridge pieces (# of ramp and bridge pieces/total # of pieces) were also calculated.

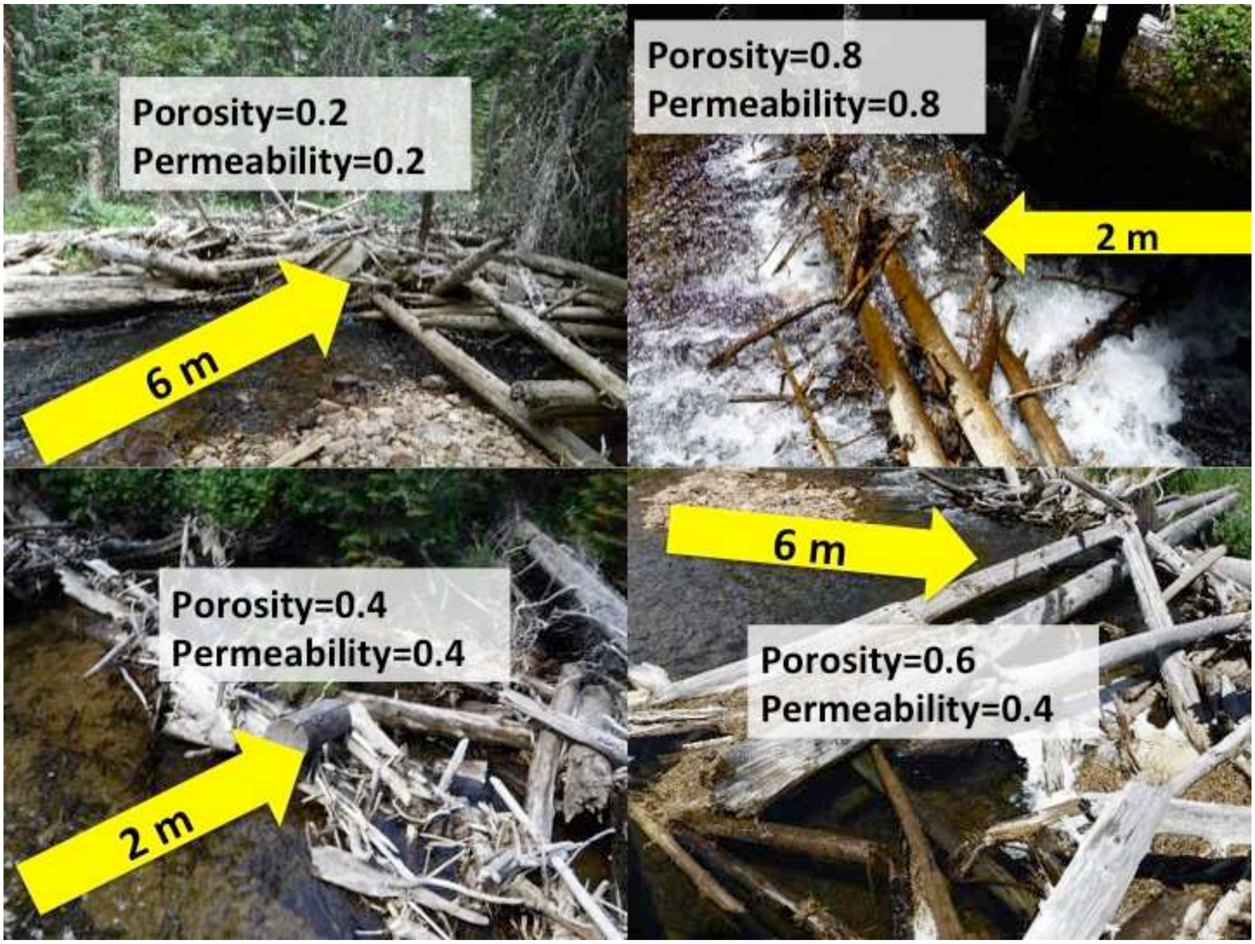


Figure 7. Examples of porosity and permeability in logjams. Porosity was estimated by assessing total void space as a fraction of total logjam volume. Permeability was assessed by looking at flow through the downstream end of the jam, with the assumption that more flow will occur in higher permeability jams. The aim of this method was to gain a quick, visual assessment of a complicated, 3-D metric. Porosity and permeability estimates, as well as scale and flow direction, are displayed.

Coarse and fine sediment were identified by visual assessment. Because of this, there is not a clear 2 mm diameter break between coarse and fine material. Moreover, because granitic basins do not always produce sand (fine gravel instead), some of the fine material may be fine gravel instead of coarse sand. Although this distinction can have important implications in sediment transport analysis, my method should generally distinguish between the size of material stored. Coarse sediment (gravel and larger) was treated as a triangular wedge (volume=0.5(L*W*D), see Figure 8). Length and width were measured with a laser rangefinder or measuring rod, whereas depth was estimated as the difference in bed elevations downstream across a wood piece or jam. The coarse sediment method relies on the assumption that the upstream wedge is stored material (rather than just bed material upstream of wood and a downstream drop caused by scour). Observational assessment of the study area indicated that scour holes are not very prevalent.

Fine sediment (sand and finer) was measured in a slightly different manner; a gridded rebar system was used to probe for average depth to refusal within a fine sediment accumulation and surface dimensions were measured with a laser rangefinder (Figure 9; Hilton and Lisle, 1992). POM dimensions were assessed in a similar manner, apart from using a hand and a tape measure for the smaller depths. Also, because POM is commonly stored on top of sand, I tried to separate POM depths when assessing total sand depths. I did not take POM samples to measure carbon content or distinguish between coarse and fine POM (CPOM and FPOM, respectively). Because I measured bulk POM *in situ*, I am assuming the POM volume estimate includes both CPOM and FPOM. Finally, because I did not measure POM carbon content, my method is not appropriate for analyzing large-scale carbon cycle trends within NSV.

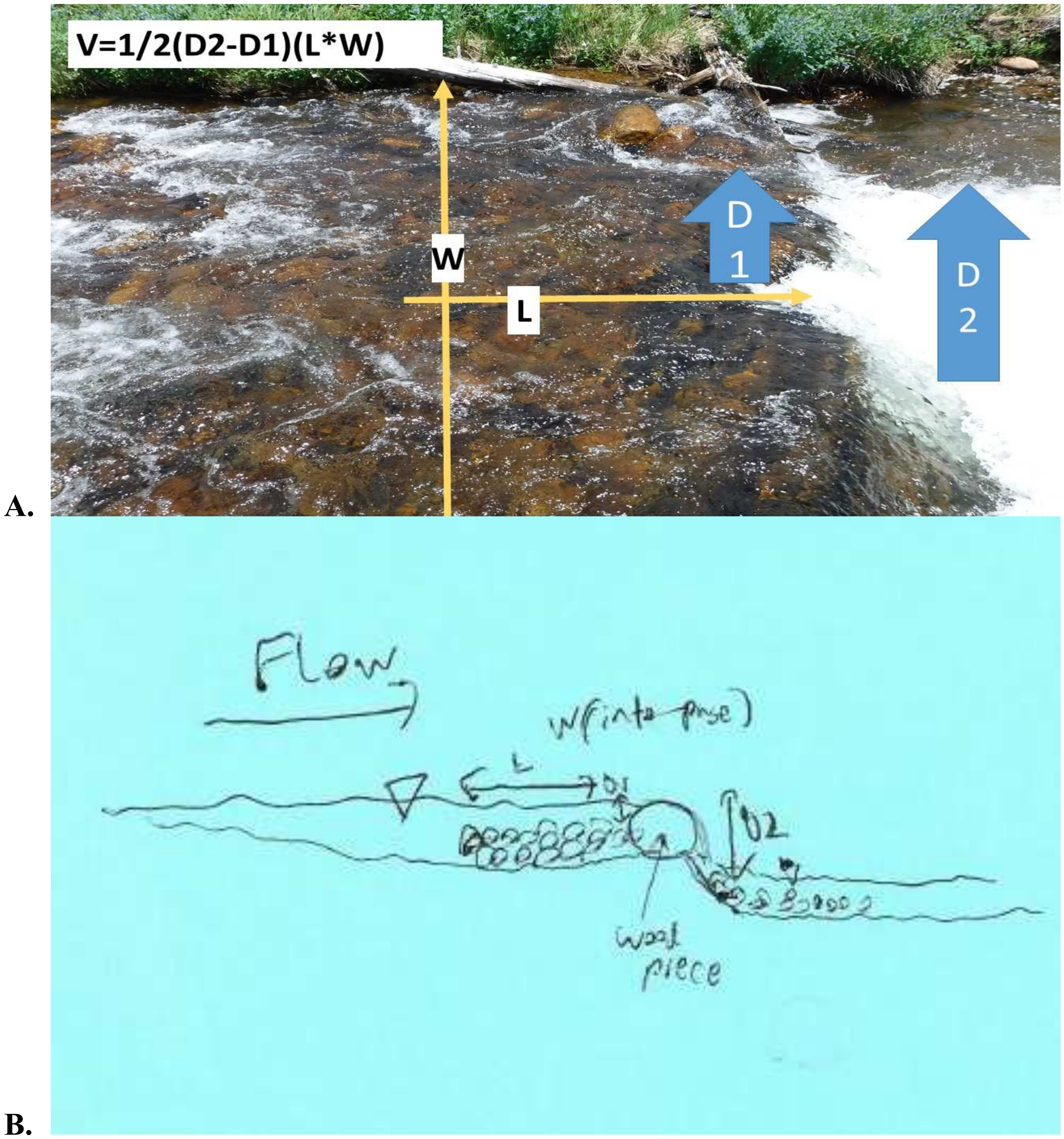


Figure 8. A. Volume calculation for wedge of coarse sediment behind single channel-spanning piece. The wedge is assumed to be triangular, tapering backward along the bed. The longitudinal drop is assumed to be created by wood; therefore, the depth of the wedge is the difference between D1 and D2 (the depths from the bed to the top of the piece on the upstream and downstream sides, respectively). In this case, storage appears to also span the channel. Length was determined by the extent of a relatively lower velocity, pool-like section behind the piece. **B.** Side view of measurement technique. D2 is assumed to be due to the wood creating a step and storing sediment on the upstream side rather than scour.

Table 1. Summary of all variables, showing their scale (jam, reach, drainage basin), whether they are control or response variables, and the method by which the variables were measured or calculated. Unless indicated as categorical, all variables are continuous.

Group of variables	Variable/type	Method
Physical channel characteristics (control, reach)	• Gradient (deg)	• Laser rangefinder, reach averaged
	• Lateral confinement-categorical	• Laser rangefinder, VW/CW
	• MB Category-categorical	• Visual assessment of bed morphology, material, and gradient following Montgomery and Buffington, 1997
	• Drainage area (km^2)	• Calculated in USGS StreamStats using GPS points from field
Wood characteristics (control, reach)	• Wood load (m^3/m)	• Diameter/length measured in field, pieces treated as cylinders and summed
	• D_{50} (m)	• Median diameter of pieces in a reach
	• Average length/channel width	• Average piece length over reach-averaged channel width
	• Proportion jammed	• Proportion of reach wood volume in jams
	• Proportion ramps and bridges	• Proportion of pieces in a reach that are ramps and bridges
	• Spacing (m)	• Longitudinal spacing between jams or individual pieces (reach length/number of measurement points) (i.e. 50 pieces or jams/30 m reach=1.67 m average spacing)

Jam characteristics (control, jam)	• Jam volume/average channel width (m^3/m) • Porosity/permeability	• Excluding dispersed wood and using data from Livers, 2016 • Visual assessment of flow and void space in jam; photo analysis after field season (Figure 7).
Material storage (response, reach and jam)	• Coarse sediment (m^3/m) • Fine sediment (m^3/m) • POM (m^3/m)	• Approximated as triangular wedge (V=0.5(lwd), Figure 8) • Surface dimensions with laser rangefinder/measuring rod, rebar for average depth to refusal (treated as triangular wedge) • Surface dimensions with laser rangefinder, depth with hand or rebar (triangular wedge) *all measurements standardized by reach length (m^3/m)

3.4 Statistical Analysis

Wood, sediment, and POM storage were assessed on a range of spatial scales: jam, reach, and drainage basin. For the reach and drainage basin analyses, volumes were divided by the total stream length in a reach (m^3/m stream). Volume is in m^3 for jam-scale analysis. The statistical program R was used to evaluate the relationship between response variables (stored sediment or POM) and potential controls. All analyses used a confidence level of 95%. Based on the Shapiro-Wilks test, histograms, and qqplots, the data were non-normal. All data were square-root transformed to help meet assumptions of normality. However, because data were not normal after transformation, the Kruskal-Wallis test and Dunn's test were used as an ANOVA alternative to assess differences in stored sediment or POM between categorical variables such as Montgomery-Buffington category, stream order, and confinement. Before single variable and multiple variable linear regressions, regression assumptions such as linear response, equal variance, and normality of data and residuals were assessed. Square-root transformation helped meet these assumptions. However, for ease of interpretation, all data are presented untransformed. Multiple regression was conducted on square-root transformed data to assess the balance between continuous predictors of sediment storage (i.e., drainage area, wood load, slope, spacing between jams). The variance inflation factor (VIF, car package) was used as a model diagnostic to confirm that predictor variables did not display multicollinearity (Fox and Weisberg, 2011). AICc model selection in the MuMIn package (Barton, 2016) was used find the best multiple regression model with a representative adjusted R^2 value. The AICc method is an objective way to assess model quality that penalizes each predictor added to the model. Essentially, the AICc function assesses the strength of all possible models (based on R^2) while penalizing for predictors; the model with the lowest AICc value is the best model. Importance, which is based on weighing the number of models in which a predictor appears, was calculated to assess which predictors were strongest.

3.5 Spatial Analysis

After determining controls on sediment storage, results were extrapolated to a drainage basin scale to visualize the distribution of stored sediment. Reaches were plotted in ArcGIS and a stream network was created using the hydrology toolbox. Each reach's Strahler stream order was determined to obtain average wood load and coarse, fine, and POM storage by stream order (values were standardized by stream length to be m^3/m). This average was then multiplied by the total stream length of each stream order to obtain an estimate of cumulative sediment storage for different parts of the network (m^3/ m stream average storage * m stream= m^3 of storage). The stream order was clipped below timberline so as not to extrapolate wood-induced sediment storage to areas that do not have instream wood. Although stream order (or drainage area) is not always the primary control on stored sediment, this strategy facilitates extrapolation to a larger scale. This basin-scale analysis would not be possible with grouping storage by other variables such as channel width, confinement, or MB category as they do not vary systematically downstream. Although I am assuming an average storage value to be representative of storage for a given stream order (something that may not be the case given the influence of other controls), this method facilitates a cumulative storage estimate as well as providing insight into hotspots of different types of storage.

Based on previous research on Front Range streams (Henkle et al., 2011), contributing areas of 0.1 km^2, 0.25 km^2, and 0.5 km^2 were chosen in ArcGIS to create a stream network. This setup was two-pronged: 1) to find a contributing area that best represented the NSV stream network and 2) to assess the sensitivity of drainage basin storage estimates to contributing area choice. Despite being a relatively simple analysis, this component of the project translates reach-scale controls on sediment storage to a basin-scale estimate of cumulative sediment storage by stream order and throughout the basin. This component of analysis also served to illustrate difficulties in mapping small streams and techniques to address these difficulties. All streams for these analyses were clipped using a polyline at treeline (3400 m elevation; Veblen and Donnegan, 2005) so as not to extrapolate wood-induced storage estimates into the alpine zone, where there is no instream wood.

4. RESULTS AND DISCUSSION

4.1 Physical channel characteristics

This section quantifies and graphically depicts the physical characteristics of the studied channel reaches in the North Saint Vrain watershed within Rocky Mountain National Park. Understanding how channel gradient, lateral channel confinement, and channel width vary downstream provides a context for how wood and sediment respond to these factors. As described in the study area section, neither gradient nor channel confinement vary systematically downstream (Figure 9 A and B). Changes in confinement and channel morphology preclude gradient from displaying clear downstream trends. Variable patterns of bedrock jointing and glaciation likely explain the lack of a relationship between confinement and drainage area. Channel width has a strong positive correlation (r=0.85) with drainage area, which is logical given the need to accommodate higher discharges at larger drainage areas (Figure 10). Because of this high correlation, only drainage area was used as a predictor variable in analysis of storage trends.

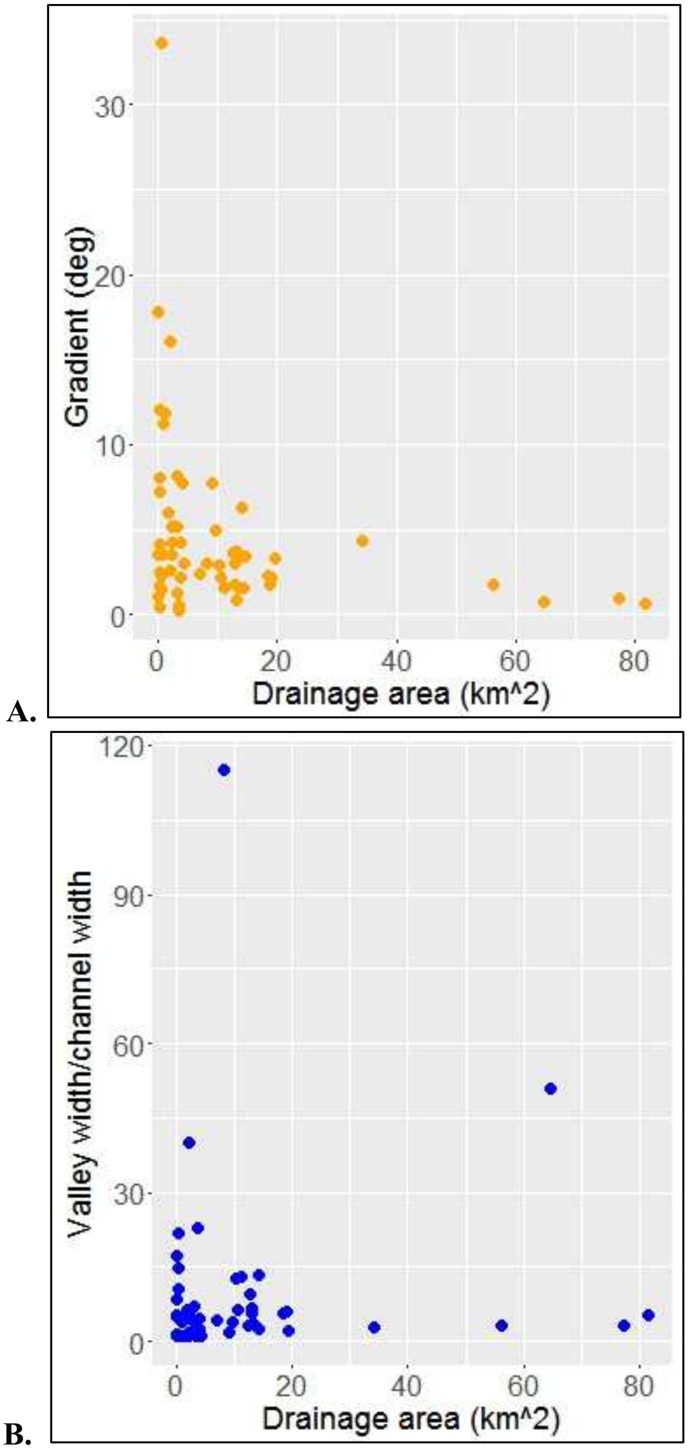


Figure 9. A. Gradient has a very weak negative relationship with drainage area, which makes sense as channel morphologies are less steep (pool-riffle) at the outlet. **B.** Lateral channel confinement (valley width/channel width) displays no discernible trend in the drainage basin. Confinement is displayed as a continuous variable rather than categorically to facilitate easier graphical representation against drainage area. N=58 reaches.

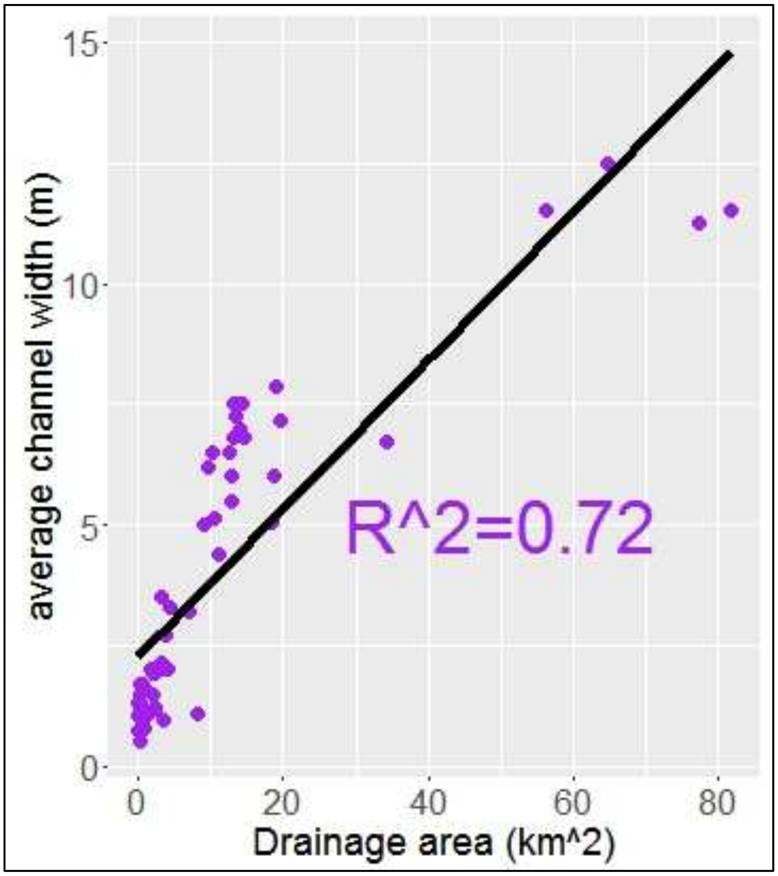


Figure 10. Channel width versus drainage area. Because these two variables are highly correlated(r=0.85), only drainage area was used as a predictor of sediment storage. N=58 reaches.

A reach's position in the watershed is a hypothesized drainage-scale control on wood and sediment dynamics. This can be represented by drainage area or Strahler stream order. The graph below indicates that both are reasonable assessments of watershed-scale controls, because they correlate well and drainage areas group discretely within a given stream order (Figure 11). This relationship is implied in the definition of stream order; higher order streams have more contributing streams and therefore a higher contributing drainage area than lower order streams. However, it is useful to graphically corroborate drainage area-stream order relationships for subsequent analyses so that only one of these variables is used as a predictor.

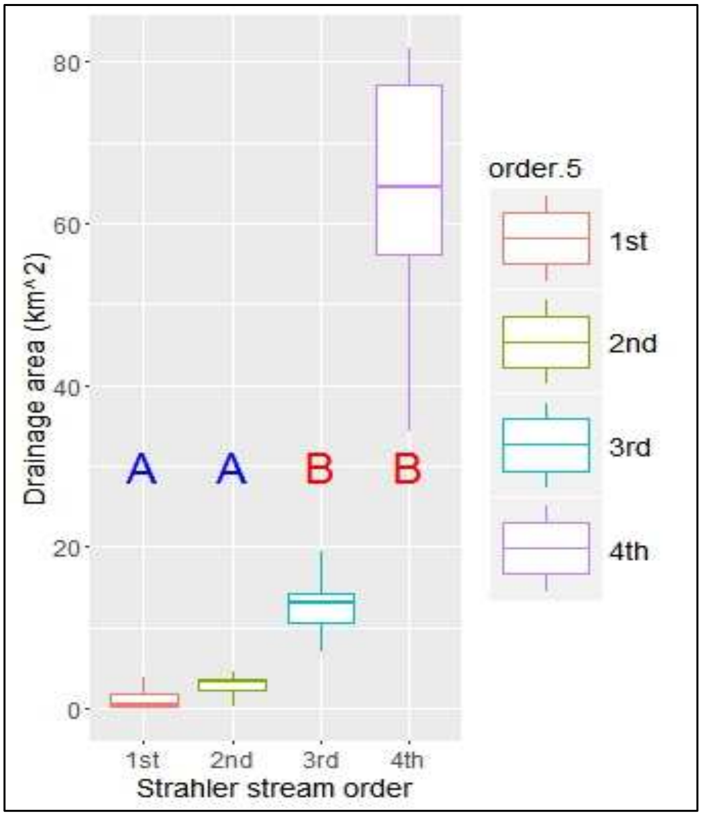


Figure 11. Drainage area versus Strahler stream order. The letters indicate significant differences between groupings at alpha=0.05. Because of this relationship, only drainage area was included as a predictor for multiple regression analyses (to avoid multicollinearity between predictor variables). N=58 reaches.

4.2 Controls on instream wood loads/wood piece characteristics

H1: Wood load peaks at intermediate portions of the NSV network (i.e., drainage areas of 40 km^2).

Wood load peaks at smaller drainage areas than expected (~12-13 km^2 versus 40 km^2, Figure 12 B). Figure 12 illustrates two methods of fitting wood load versus drainage area. Although the quadratic fit maximum occurs at 42 km^2 (consistent with the hypothesis), the lack of sites at larger drainage areas makes it difficult to assess whether this is an actual phenomenon (Figure 12 A). Data were also segmented into separate linear regressions to track the increase and decrease of wood load with drainage area. The break in the data (calculated with Seg Reg http://www.waterlog.info/segreg.htm) occurs at 12.3 km^2, which is close to the value of actual maximum unit wood load (12.7 km^2, Figure 12 B). Regardless of the exact drainage area at which wood load peaks, these results reflect a balance between supply and transport capacities at a given location. Small, first-order streams are transport-limited. Unit discharge and stream power are too small to effectively mobilize and aggregate wood. Larger, fourth-order streams are supply limited. Wood is readily recruited to these channels and moves freely. However, because of high unit stream power and greater channel width and flow depth, wood is unable to stabilize in the channel and moves easily through the channel.

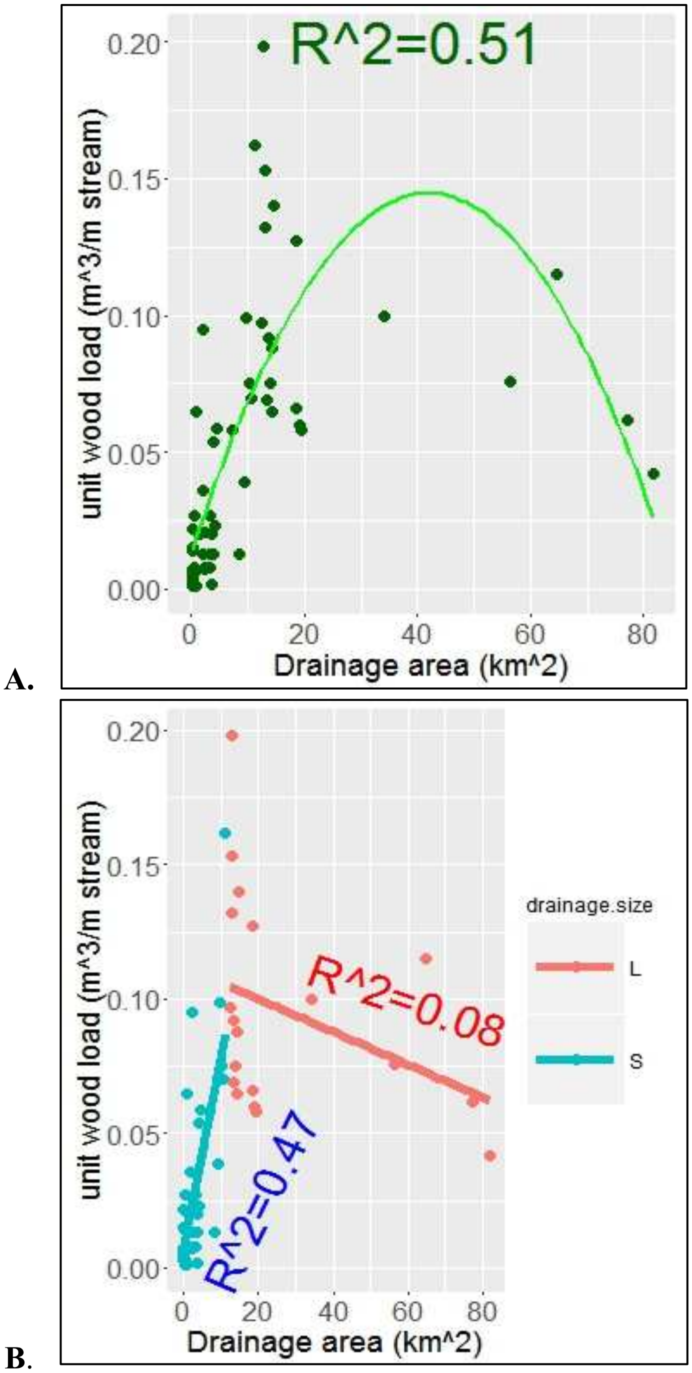
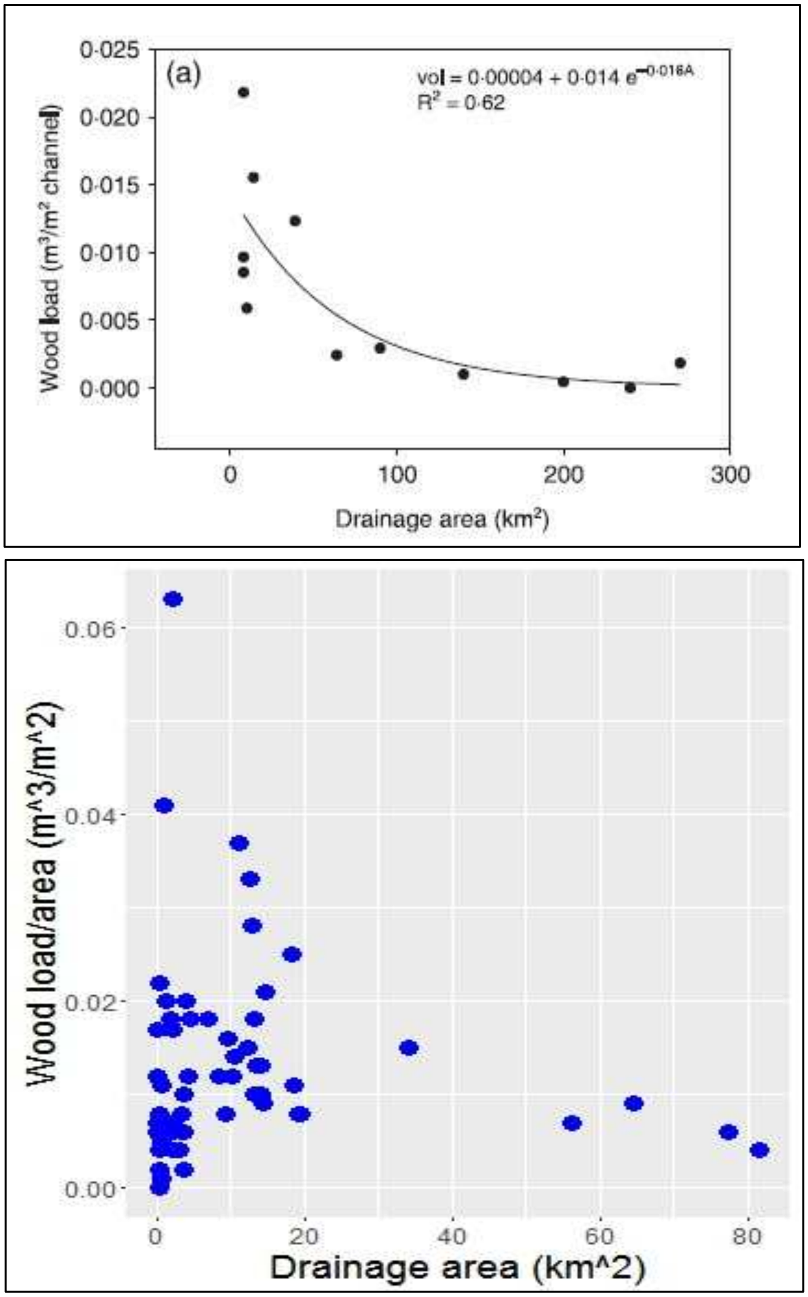


Figure 12. A. Unit wood load (m^3/m) versus drainage area (km^2) with a quadratic fit. The maximum of this fit occurs at 42 km^2. R^2=0.62 for square root transformed data. **B**. The program SegReg (http://www.waterlog.info/segreg.htm) was used to delineate a break in the data at a drainage area of 12.3 km^2. The observed maximum unit wood load occurs in a reach with a drainage area of 12.7 km^2. Data collection at larger drainage areas (especially 40-80 km^2) was limited by basin characteristics. R^2=0.44 and 0.1, respectively, for square-root transformed data. N=58 reaches.

These results support but do not fully corroborate Wohl and Jaeger (2009) (Figure 13 A and B). Their study differs from mine in the range of drainage areas, watersheds, and elevations studied. Wohl and Jaeger included wood in drainage areas of ~8-270 km^2, spread across multiple watersheds in the Colorado Front Range, and including lower elevation sites within the montane vegetation zone and which had experienced historical timber harvest. My sites are in the 0-80 km^2 range, come from sites within a single watershed with no history of timber harvest, and are all within the subalpine vegetation zone, which has a different disturbance regime than the montane zone.

The overlap between the studies is useful. My study suggests that Wohl and Jaeger would have observed an increase in wood load with drainage area up ~12-13 km^2 had they included more sites with smaller drainage areas (Figure 12). Similarly, the Wohl and Jaeger study supplements my lack of data at larger drainage area and suggests that there is a drainage area beyond which wood load systematically decreases. Determining the size of this drainage area remains elusive, however, and may reflect temporal changes in wood distribution in North Saint Vrain between 2009 and 2016 or spatial changes when including reaches with different natural and human disturbance histories. Ability to discern the drainage area at which wood load declines is also difficult because of land-use history in the Front Range. All streams with drainage areas greater than ~ 100 km^2 experienced historical timber harvest. Research since the 2009 Wohl and Jaeger study clearly indicates that sites with historical timber harvest have significantly lower instream wood loads than sites with similarly aged forest that has experienced only natural disturbances (Livers and Wohl, 2016). Consequently, it is not feasible to differentiate the influences of land-use history, change in disturbance regime, and increasing transport capacity for instream wood loads at larger drainage areas in Front Range streams. This was a primary reason that my study sites were confined to the subalpine zone.

Finally, wood/stream area and wood/stream length appear to yield different results with respect to downstream wood load trends. Wood load/area peaks at much smaller drainage areas than wood load/stream length (2.0 km^2 versus 12.7 km^2) (Figure 13B). This indicates that the way in which wood load is standardized is highly important to subsequent analysis, as one method points toward peak wood loads in first-order streams and the other indicates third-order streams as areas of peak storage. Given the quadratic fit and segmented regression for wood/length, and the lack of meaningful statistical relations for the wood/area data (Figure 13B), wood peaking in streams of drainage areas of ~12 km^2 appears to be the more likely scenario. Taken together with the Wohl and Jaeger study, my study suggests a balance of transport and supply, as inferred by Marcus et al. (2002), and indicates that wood load in NSV likely peaks at ~12 km^2 drainage areas and likely declines at larger drainage areas due to high channel transport capacity.



A.

B.

Figure 13. A. Wood load versus drainage area for streams in the North Saint Vrain watershed (both inside and outside the park boundary) and other Front Range sites from Wohl and Jaeger, 2009. **B.** Wood load from this project (Figure 12) was standardized by stream surface area to facilitate comparison between the two studies. In contrast to the analysis accompanying Figure 12, SegReg did not reveal any natural breaks in the data. R^2 for a linear fit was 0.008, suggesting that the small drainage area sites complicate the picture presented in 13A. Wood load/stream area peaks at smaller values than wood load/stream length (2.0 km^2 versus 12.7 km^2). N=11 for 13A, 58 for 13B.

Given instream wood's response to drainage-scale trends, I also sought to analyze how local controls (such as lateral channel confinement, gradient, Montgomery-Buffington stream category, and basal area of the surrounding riparian forest) affect wood volume and distribution. With regard to physical channel characteristics, lateral channel confinement most strongly controls wood volume, with unconfined and partially confined reaches retaining significantly higher wood loads than confined reaches (Figure 14 B). Channels within these reaches are more laterally adjustable and could better allow for wood to implant and stabilize in the channel, as well as having shallower flow depths during peak flows. Channel gradient and Montgomery-Buffington category are weaker controls. In general, higher wood loads are found at lower channel gradients, but this relationship is not systematic, as high wood loads are also found in steeper gradient channels (Figure 14 A). The lack of significant differences in wood loads between different Montgomery-Buffington channel types reflects the ability of wood to stabilize in the channel across a range of gradients and bed materials (Figure 15).

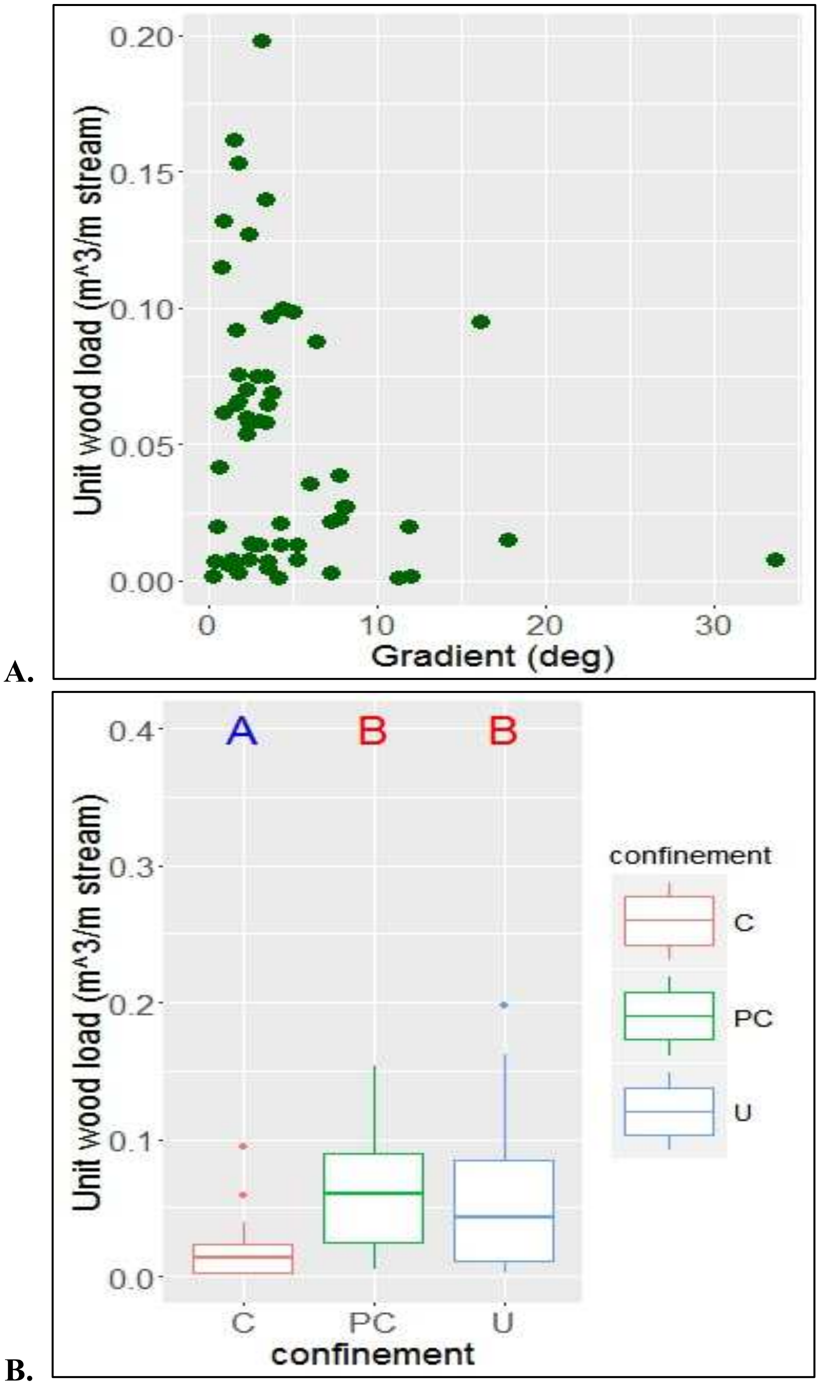


Figure 14. A. Unit wood load (m^3/m) displays few clear trends when plotted against reach-averaged gradient. Wood volume is highest between gradients of 2-3 degrees, but high storage also occurs at steeper gradients. **B.** Wood load (m^3/m) versus lateral channel confinement. Partially confined and unconfined reaches have significantly higher unit wood loads than confined reaches. N=58 reaches for both analyses. For 14B, there are 15 confined reaches, 27 partially confined, and 16 unconfined.

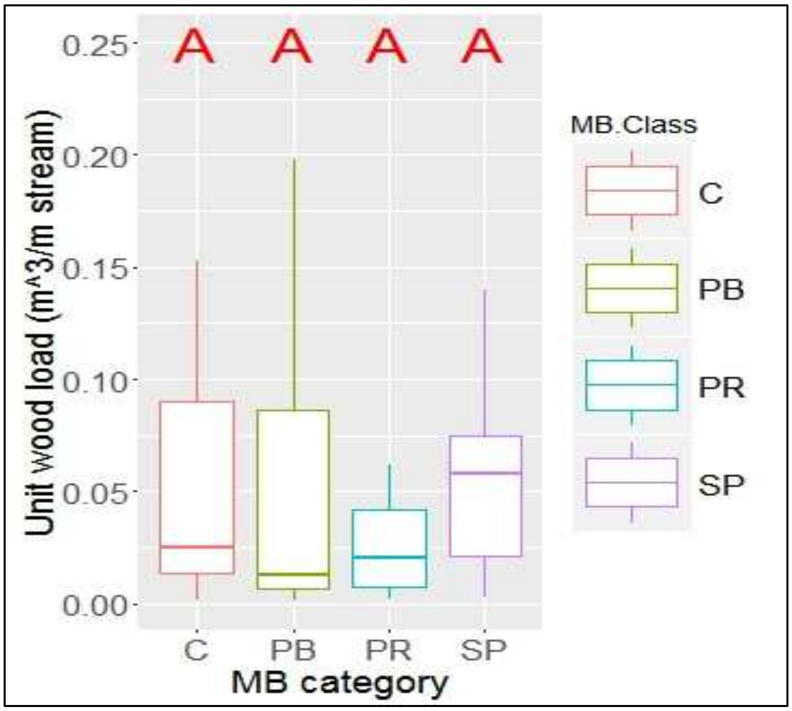


Figure 15. Wood load versus Montgomery-Buffington stream category. There are no significant differences between groups. N=58 reaches; breakdown is as follows: C=12, PB=18, PR=5, SP=23.

Riparian basal area has been related to instream wood loads in previous studies (Richmond and Fausch, 1995; Benda and Sias, 2003). Others have hypothesized that old-growth forest contributes higher volumes of wood than more recently disturbed forest. I, however, do not see evidence for this effect (Figure 16). This suggests that the processes that introduce wood to the channel (lightning, insect outbreak, blowdown) are largely randomly distributed throughout the stream network. Transport of wood from upstream reaches might also strongly influence wood load at some sites, so that basal area of the adjacent forest does not necessarily correlate with wood load.

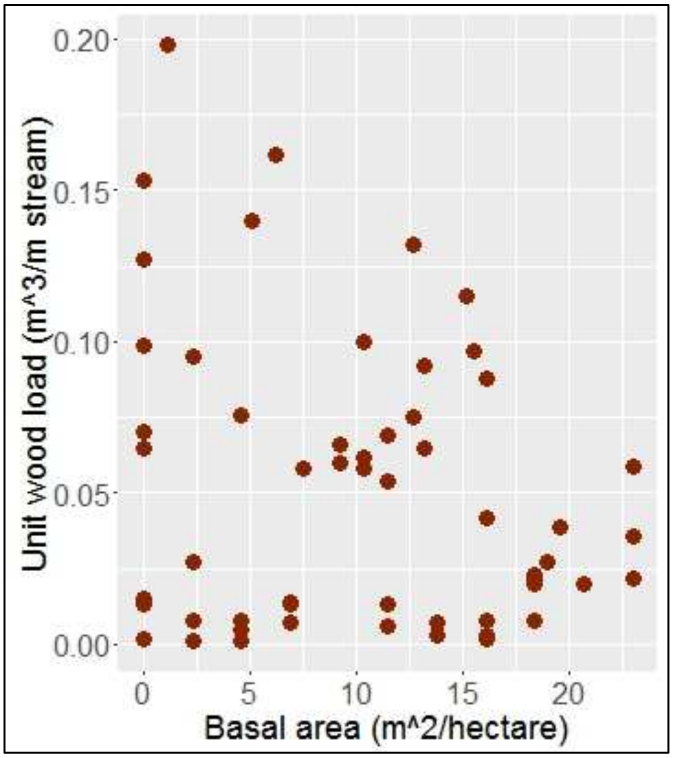


Figure 16. Wood load versus basal area. Basal area was calculated via a conversion from a count of tree cover in the field using a Panama angle gauge forestry tool. N=58 reaches

These results informed a multiple linear regression to assess the balance of controls in determining reach-scale wood load (Table 2). As expected from single variable regression results, drainage area is the strongest control on wood load. Montgomery Buffington (MB) stream category is a secondary control even though it is not an important control on a single variable basis (Figure 15). Only the pool-riffle category is a significant predictor, however, indicating that pool-riffle reaches have significantly lower wood loads than other reaches in this multiple regression model. This means that the single variable boxplots should be taken as a more accurate representation of the effect of different MB categories on wood load. Given that the R^2 from multiple linear regression is smaller than the R^2 of single variable quadratic or linear regression of wood load versus drainage area (Figure 12), it appears reach-scale wood load is highly dependent on drainage area and inclusion of other control variables does not improve prediction of wood loads.

Table 2. Multiple variable linear regression assessing relative importance of predictors in determining reach-scale wood load (response variable). Data were square root transformed for this analysis to help meet regression assumptions. Units are not included because they are physically meaningless after the square root transformation. R^2=0.54 for the model with all possible predictors. The best model has an R^2 of 0.51 and includes sqrt drainage area (+ relationship) and MB category as predictors.

Variable	Importance
sqrt drainage area	1.00
MB category	0.93
sqrt slope	0.46
confinement	0.13
sqrt basal area	0.00

In addition to the total volume of instream wood, the shape of wood and partitioning of wood load between jams and individual pieces may control the extent of sediment storage. Included below are figures that characterize the distribution of different shape characteristics such as D_{50}, the median piece diameter in a reach, and average piece length/average channel width. The length to width ratio is a common metric for the likelihood of jam formation and ability of a log to stabilize in the channel (Gurnell et al., 2002), whereas log diameter can be related to the depth of flow needed for mobilization (Braudrick and Grant, 2000). These characteristics are plotted below versus drainage area to assess whether there are predictable trends moving downstream. Average piece length versus channel width decreases downstream, suggesting that wood may be most geomorphically effective (channel-spanning) at smaller drainage areas (Figure 17). The median diameter of measured pieces displays a fairly strong quadratic relationship; similar to total wood volume, the diameter peaks at drainage areas of ~12 km^2 (Figure 18). The proportion of wood in jams in a reach (volume of jammed wood/total wood load) is thought to be important for predicting sediment storage, as jams may create larger backwaters and induce higher flow resistance than individual pieces (Keller and Swanson, 1979; Manners et al. 2007). The proportion of jammed wood peaks at a drainage area of ~18 km^2, moderately relates to wood load, and does not display discernible trends with gradient (Figures 19 A and B, Figure 20, respectively). This may suggest that flow characteristics are more important for aggregating wood into jams than the total amount of wood in a reach. The proportion of ramp and bridge pieces (number of ramp and bridge pieces measured/total number of measured pieces) versus potential controls was also tested, as these types of pieces are thought to be the most geomorphically effective by creating boundary roughness at the channel margins (Abbe and Montgomery, 2003; Beckman, 2013; Livers, 2016). I did not find clear trends in the proportion of ramps and bridges versus drainage area, wood load, and channel gradient (Figures included in Appendix B). These wood distribution and piece characteristics are later tested as predictors of sediment storage to better characterize how wood influences sediment dynamics.

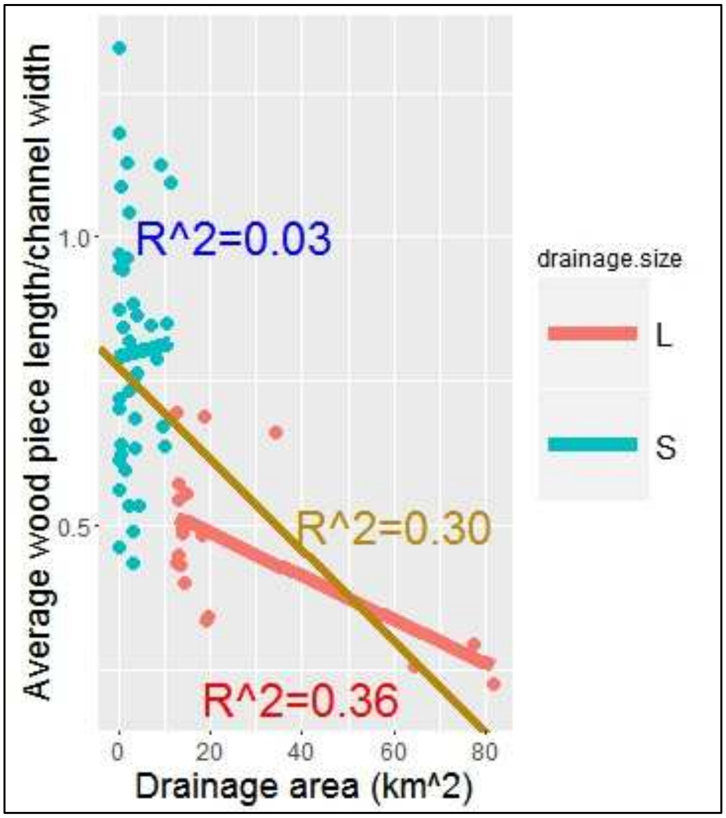


Figure 17. Average wood piece length/channel width versus drainage area. Fit is moderate above drainage areas of 11.5 km^2 (calculated in SegReg), very weak for small drainage areas (below 25 km^2), and moderate when the two datasets are combined. Regardless of how the data are grouped, average piece length/channel width declines with drainage area. R^2=0.02 (blue), 0.41 (red), and 0.41 (gold) for square-root transformed data. N=58 reaches

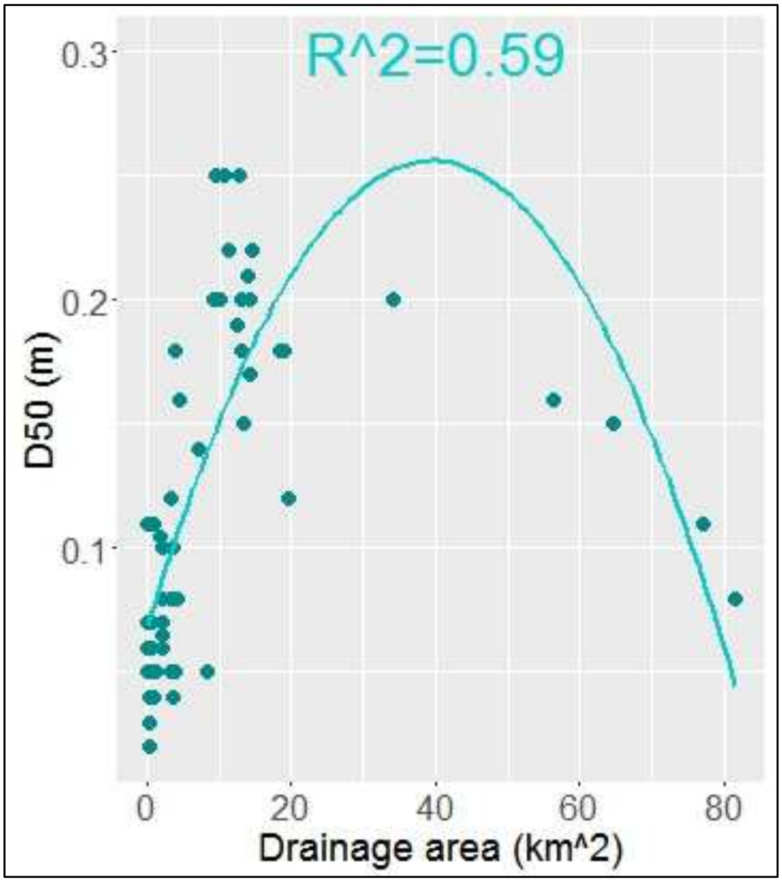


Figure 18. Wood piece D_{50} versus drainage area. The median diameter of wood pieces appears to peak at 12.7 km^2, where maximum unit wood load also occurs (Figure 12B). The fit suggests peak D_{50} at 38 km^2. Data are limited by study site constraints. The quadratic fit, which appears to be driven by the five largest drainage areas, should be taken with caution. R^2=0.62 for square-root transformed data. N=58 reaches

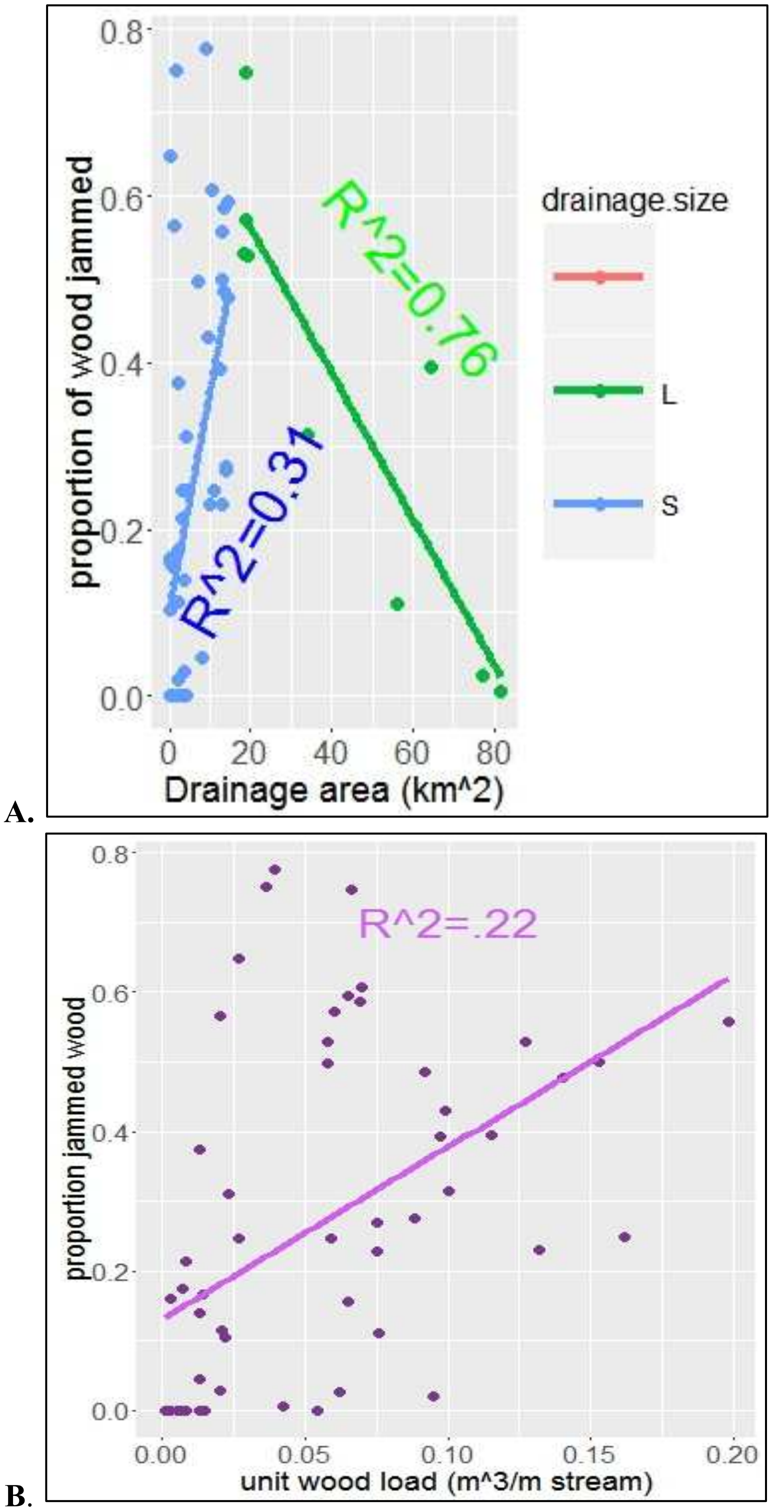


Figure 19. A. The proportion of wood in jams against drainage area follows similar trends to overall wood load versus drainage area. A break in the data at 18 km^2 was found using SegReg. **B.** There is a weak relationship between jammed wood and total wood. The relationship is likely nonlinear but the form is not clear. N=58 reaches.

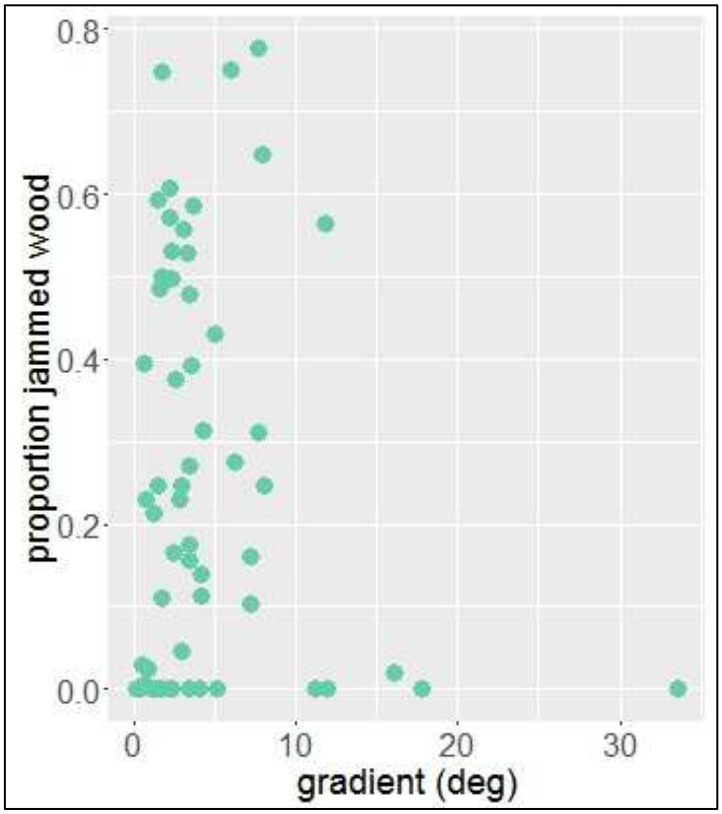
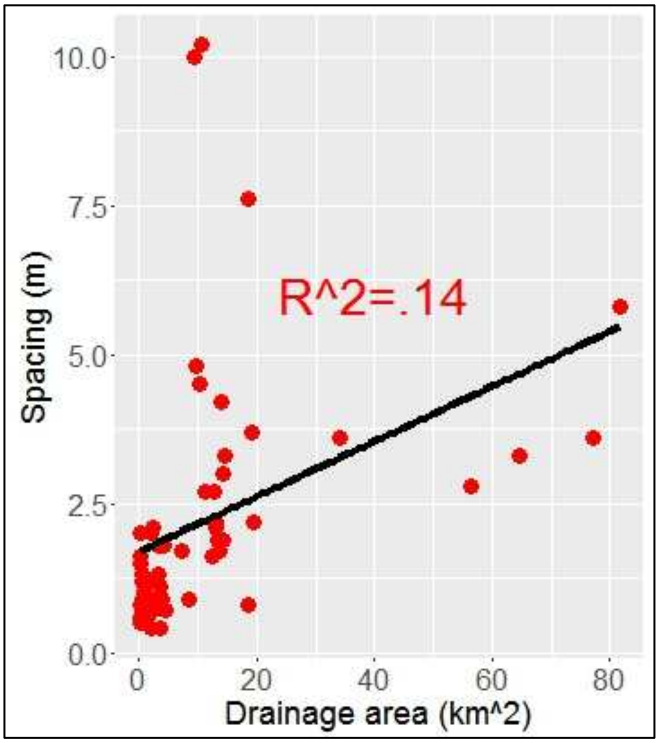


Figure 20. Proportion of jammed wood versus gradient. The highest values, as well as the greatest variability, occur in gradients of ~1-3 degrees. N=58 reaches.

Finally, longitudinal spacing between wood pieces is an indicator of wood distribution that may be important for patterns of sediment storage. Spacing was calculated by dividing stream length in a reach (summing all channel lengths if multithreaded) by the number of jams or dispersed wood pieces in the reach (units are meters). Ideally, spacing would be calculated from GPS points, but the number of pieces and error in the handheld GPS (+/- 9 m) precluded this. Here, spacing is tested as a response variable to drainage area and wood load with the idea that flow characteristics and the amount of instream wood may influence how closely spaced logjams are within a certain reach. Spacing is only moderately related to drainage area and not related to wood load (Figure 21 A and B, respectively). The relationship between spacing and drainage area indicates that smaller channels generally have more closely spaced wood pieces. Larger channels appear to have less frequently occurring wood (greater spacing). Spacing versus wood load suggests that spacing is not highly dependent on the amount of wood in the channel. Together, these results appear to show that the amount of wood in a given reach is more predictable, whereas its spacing may depend on more random factors such as a large jam accumulating the majority of the wood, leaving downstream portions of the reach without much wood. The results may also indicate that my method of measuring spacing is an ineffective way to assess this variable compared to using GPS points during direct field measurements.

A.



B.

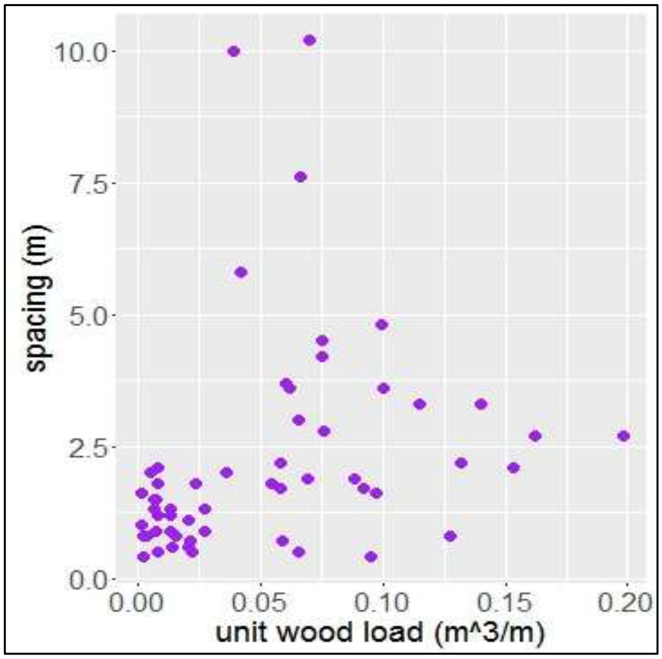


Figure 21. A. Longitudinal spacing of wood versus drainage area; $R^2=0.33$ for square-root transformed data. **B.** Longitudinal spacing versus wood load. $R^2=0.18$ for square-root transformed data. N=58 reaches.

4.3. Controls on coarse sediment storage

H2a: Coarse sediment storage correlates most strongly with wood load.

The previous sections set a framework for how physical channel characteristics, wood volumes, and a combination of the two control coarse sediment storage. Storage appears to be related to a balance of reach and drainage scale predictors. At the drainage scale, the amount of coarse sediment stored by wood follows similar, albeit weaker, trends to wood load versus drainage area (Figure 22). This is a potential indicator that coarse sediment retention is related to wood load, as they follow the same pattern moving downstream. There is direct evidence of this relationship from plotting coarse sediment versus wood load on a reach-averaged scale (Figure 23). I also tested storage versus hypothesized control variables (MB category, lateral channel confinement, and channel gradient). The amount of coarse sediment stored in a given reach does not appear particularly dependent on local gradient or bedform/bed material (Figure 24 A and B). Combined with Figure 25, in which there are differences in coarse sediment storage for different values of lateral channel confinement, the results suggest that lateral adjustability may be important for wood effectively storing coarse sediment. Counterintuitively, channel gradient is not an important predictor of the formation of wedges of coarse sediment that alter the bedforms of the channel. Finally, regarding wood piece characteristics, average piece length/average channel width does not predict coarse sediment storage well (Figure 26 A). This metric is not very indicative of the geomorphic effectiveness of a given piece in storing sediment. Median diameter in a reach (D_{50}) weakly predicts storage (Figure 26 B). This could be due to thicker logs protruding higher into the flow and better causing the resistance necessary to store coarse sediment.

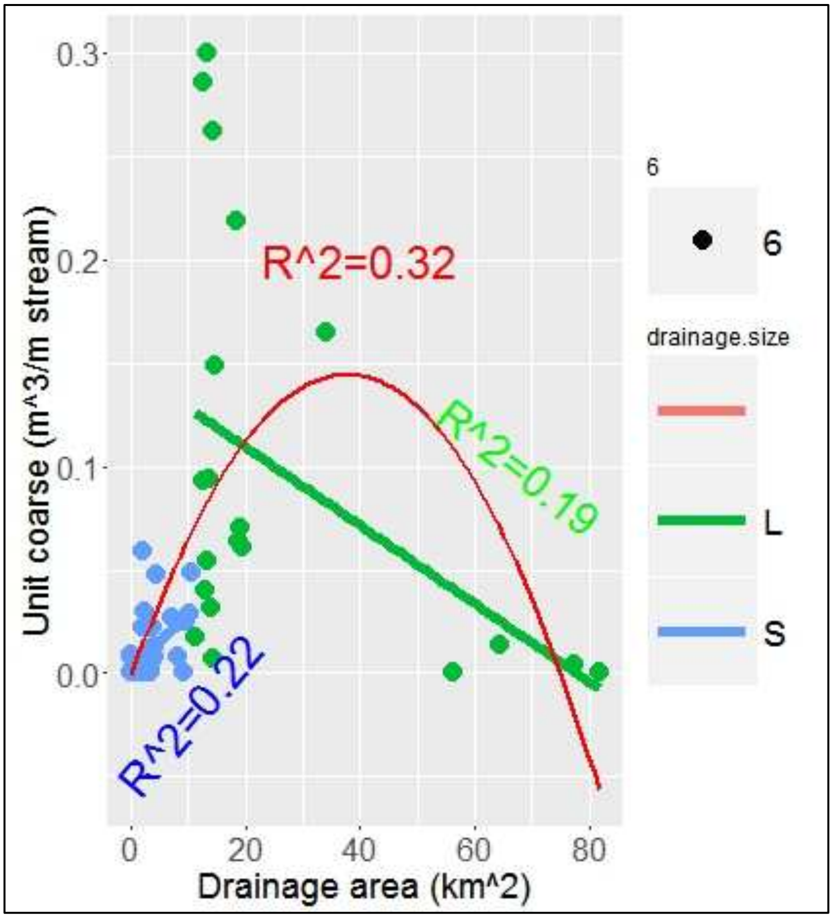


Figure 22. Coarse sediment stored by wood versus drainage area. There are similar, albeit weaker, trends to wood load versus drainage area. A break in the data was found at 11.5 km^2 using SegReg. R^2=0.37 (blue), 0.37 (green), and 0.49 (red) for square-root transformed data.

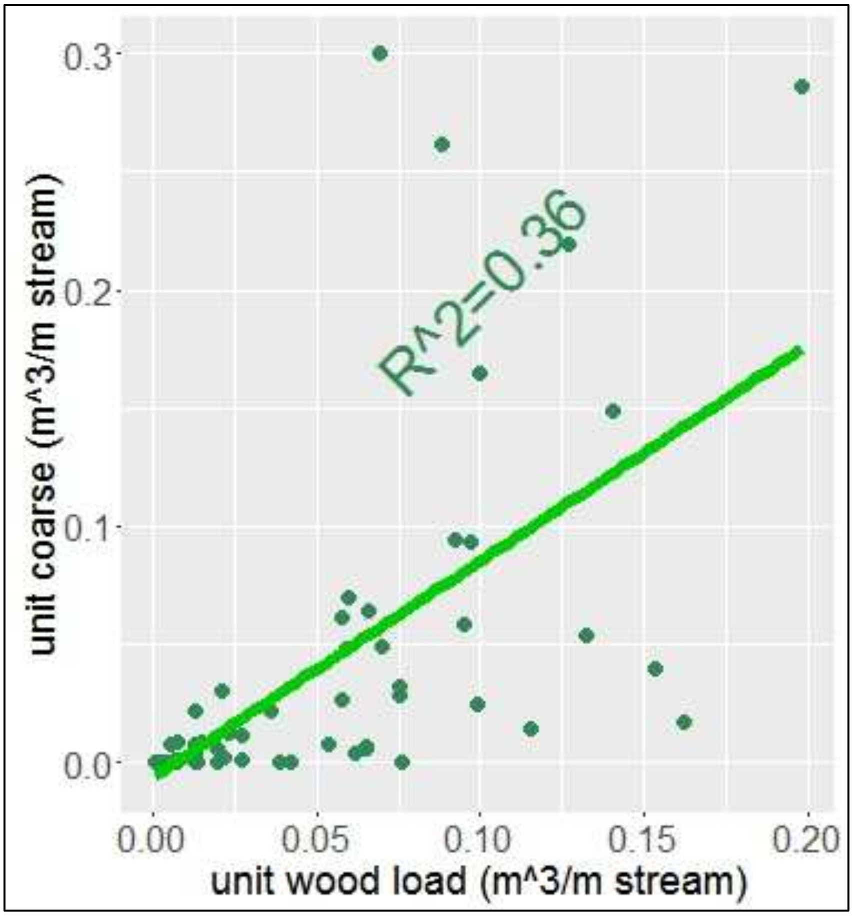
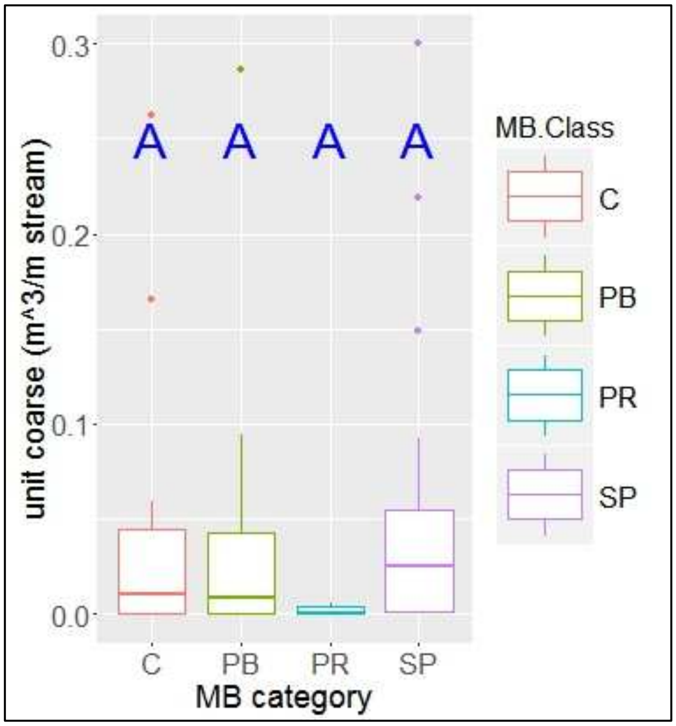


Figure 23. Unit coarse sediment (m^3/m) versus unit wood load. $R^2=0.52$ for square root transformed data. N=58 reaches

A.



B.

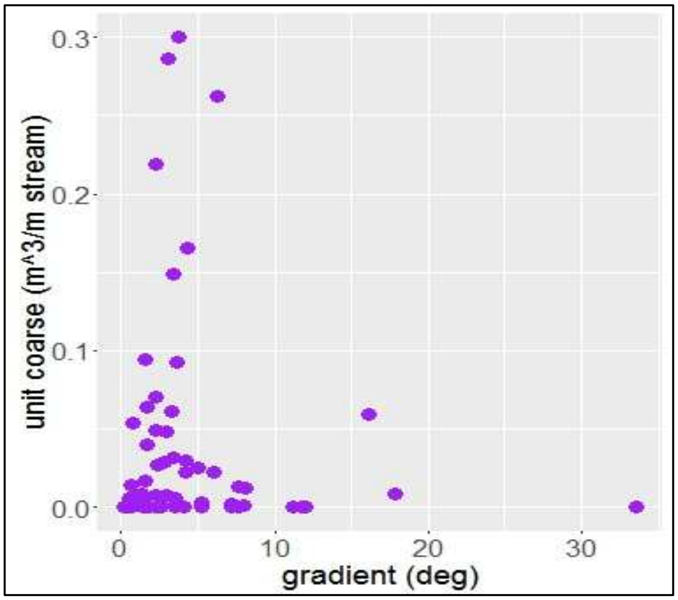


Figure 24. A. Coarse sediment storage versus Montgomery-Buffington category. No significant differences were found between groups. **B.** A plot of coarse sediment storage versus channel gradient does not show a clear, quantifiable trend. Despite this, there appears to be a range of gradients (1.5-3 degrees) at which wood is most effective at storing coarse sediment. N=58 reaches.

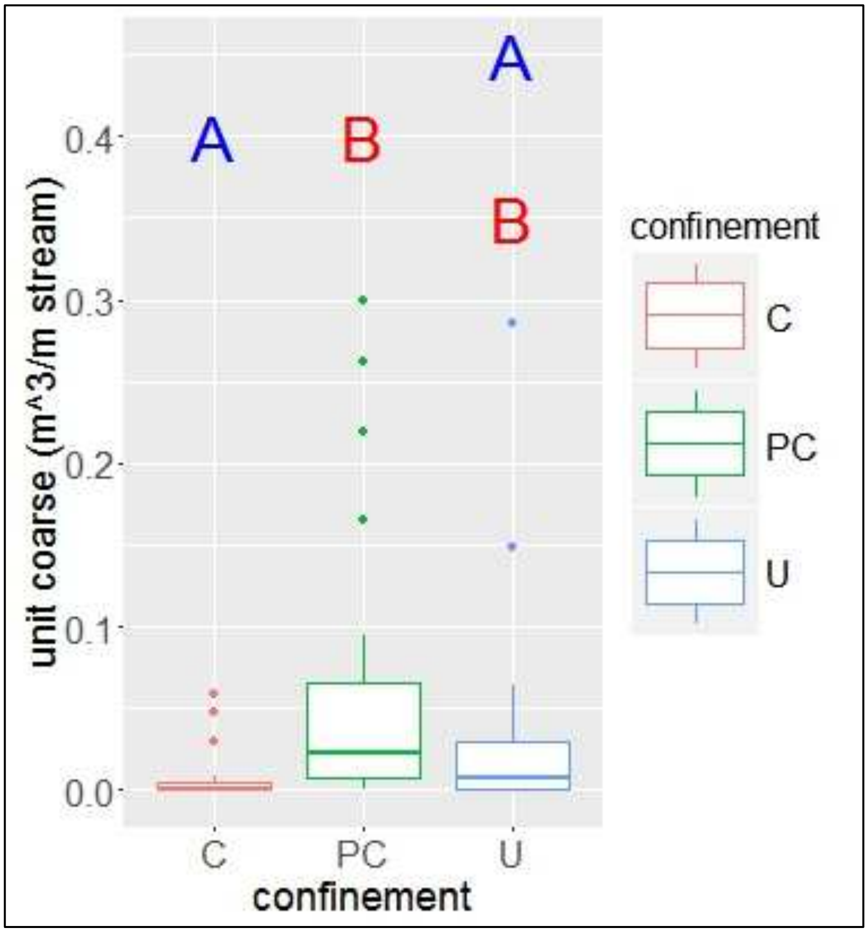


Figure 25. Coarse sediment storage versus lateral channel confinement. Partially confined channels are particularly effective at storing sediment, especially compared to confined reaches. N=58 reaches.

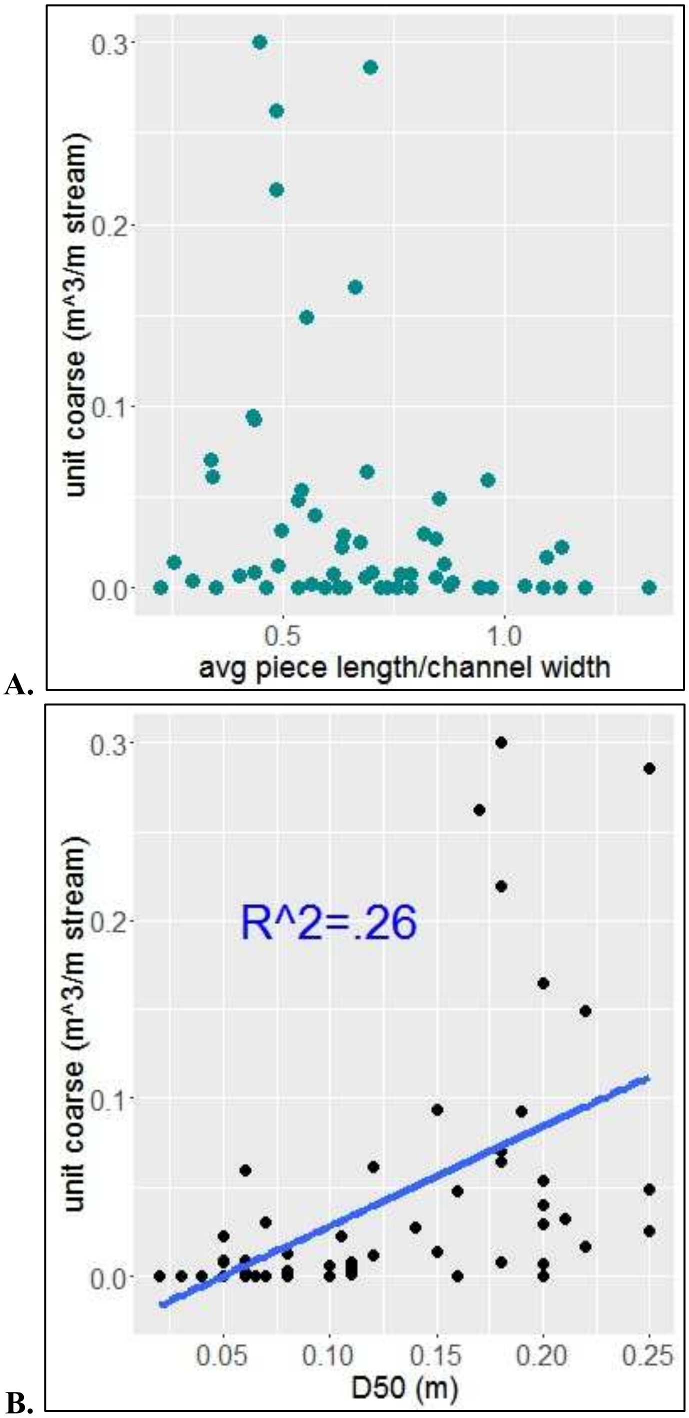


Figure 26 A. Coarse sediment storage versus average piece length/channel width. There does not appear to be a clear relationship. **B.** Stored sediment is moderately related to median diameter of wood pieces in a reach. R^2=0.4 for square-root transformed data. N=58 reaches.

Single variable regressions of stored coarse sediment versus predictors informed a multiple variable regression model to assess whether multiple variables better predict coarse sediment than single variable regressions. This is useful given that none of the relationships in section 4.3.1 are particularly strong. As in the wood load analysis (Table 2), data were square root transformed to meet regression assumptions. Wood load is by far the most important predictor in the model, indicating that stored sediment is highly dependent on a high wood load and not particularly dependent on other factors, such as geomorphic channel parameters (slope, confinement, MB category, drainage area) and wood characteristics (spacing, D_{50}, average length/channel width) (Table 3). However, the proportion of jammed wood and longitudinal spacing of pieces appear to exert minor control on storage. Although R^2 appears to increase appreciably, the strength of fit from multiple regression is not much stronger than the coarse sediment versus wood load single variable regression (R^2=0.52 for square root transformed data, Figure 23). These results fully support Hypothesis 2a, indicating that wood load is the strongest factor in coarse sediment retention and can effectively adjust channel form on a range of channel sizes (drainage area) and geomorphic settings (slope, MB category, confinement).

Table 3. Importance of predictor variables for coarse sediment storage from multiple linear regression model. Importance is calculated by weighing the number of model scenarios in which a variable appears. R^2=0.57 for the best model, which includes sqrt wood load (positive coefficient), sqrt spacing (negative coefficient), and the proportion of jammed wood by volume (positive coefficient) as predictors. R^2=0.62 for the model with all possible predictors included. Units are not included because of their lack of physical interpretability.

Variable	**Importance**
sqrt unit wood load	0.98
proportion jammed (by volume)	0.53
sqrt spacing	0.53
sqrt drainage area	0.36
sqrt (average piece length/average channel width)	0.30
sqrt D_{50}	0.30
proportion ramps and bridges (count)	0.26
sqrt gradient	0.26
confinement (C, PC, U)	0.24
MB category (C, PB, PR, SP)	0.03
sqrt basal area	0.00

When looking at coarse sediment regressions (Figures 22-26), it is apparent that many reaches have no storage of coarse sediment. Although these sites provide a complete picture of coarse sediment retention patterns, it is a useful alternative analysis to remove these zero values to better target what controls storage (Table 4). This modification only very slightly alters the results from the original multiple regression (Table 3). Proportion of jammed wood and spacing no longer appear in the best model, suggesting that their inclusion in the multiple regression in Table 3 is likely more statistically than physically important. Wood load is still the most important predictor of coarse retention; the order of less important predictors shifts slightly. For coarse sediment, removal of zero storage reaches does not change the conclusion that wood load is what drives coarse sediment retention. Moreover, removing sites may remove stream types that are prevalent in the watershed but do not store coarse material (such as cascade and pool-riffle reaches).

Table 4. Multiple regression for reach-scale coarse sediment storage excluding reaches with zero storage. Data were $\log_{10}$ transformed, as this transformation better helped meet regression assumptions than a square root transformation and worked because of the removal of zeros. $R^2=0.44$ for the best model and only includes log unit wood load as a predictor. $R^2=0.59$ for the model with all possible predictors. N=40 after exclusion of sites with zero storage.

Variable	Importance
log unit wood load	0.98
log (average piece length/average channel width)	0.36
proportion jammed	0.33
log gradient	0.29
confinement (C, PC, U)	0.27
proportion ramps and bridges	0.27
log D50	0.22
log drainage area	0.22
log spacing	0.21
MB category (C, PB, PR, SP)	0.08
log basal area	0.00

4.4. Controls on fine sediment storage

H2b: Fine sediment is also most strongly predicted by wood load. Coarse sediment and longitudinal spacing of wood are secondary controls on fine sediment storage.

Fine sediment storage is expected to be more transient and variable than coarse sediment storage. Sand is more easily mobilized and may be more related to wood causing localized scour and deposition than larger scale adjustments in a stream’s longitudinal profile. In a similar vein to the coarse sediment analysis, the following section evaluates different scales and types of controls on fine sediment storage in the network.

Fine sediment corresponds less strongly to wood load than coarse sediment does (Figure 27 A). However, the amount of surrounding coarse sediment appears to exert moderate control on the deposition of fines (Figure 27 B). This relationship is physically reasonable, as coarse sediment can create roughness conducive to storing fines. Fine sediment versus drainage area displays a similar relationship to coarse sediment versus drainage area, with storage peaking in intermediate drainage areas (Figure 28). The weaker fit indicates that drainage-basin-scale changes in discharge are less important for fine sediment storage than coarse sediment and that fine sediment storage may be a product of more localized controls. Sand deposition is therefore more indirectly related to wood load than I had hypothesized.

These results suggest that, on a reach-scale, wood-induced fine sediment storage may be less a product of the amount of wood and more related to channel characteristics (such as lateral channel confinement, channel gradient, and Montgomery-Buffington category) or wood piece characteristics (such as average piece length/channel width, D_{50}, and spacing between pieces) that allow wood to be most effective in obstructing flow and sediment transport. Regarding categorical predictors, there are no significant differences between fine sediment storage and confinement or between storage and Montgomery-Buffington category (Figure 29 A and B). Trends in the data are logical (confined and cascade reaches have low storage, whereas pool-riffle and unconfined reaches have higher storage), suggesting that certain types of reaches are more efficient at retaining fine sediment. However, the high variability indicates effective storage in a range of settings and precludes statistically meaningful differences from emerging. The lack of a relationship between fine sediment and channel gradient corroborates this, indicating wood's ability to effectively retain sand on a range of gradients (Figure 30). Similar to coarse sediment storage, though, there is a gradient range (~1-3 degrees) that has the highest values of fine sediment storage.

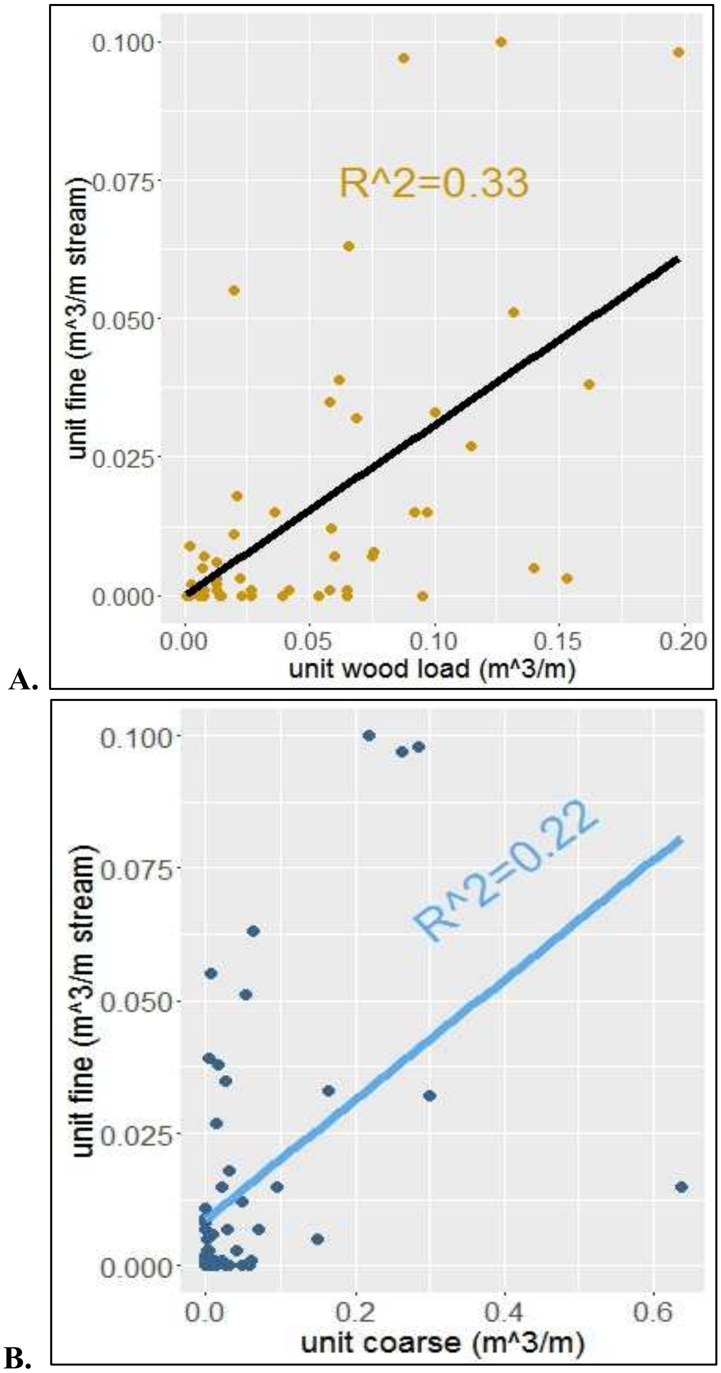


Figure 27. A. Unit fine sediment storage (m^3/m) versus unit wood load. R^2=0.35 for square-root transformed data **B.** Unit fine versus unit coarse storage. R^2=0.44 for square root transformed data. N=55 reaches (3 of 58 reaches only had coarse sediment measurements taken).

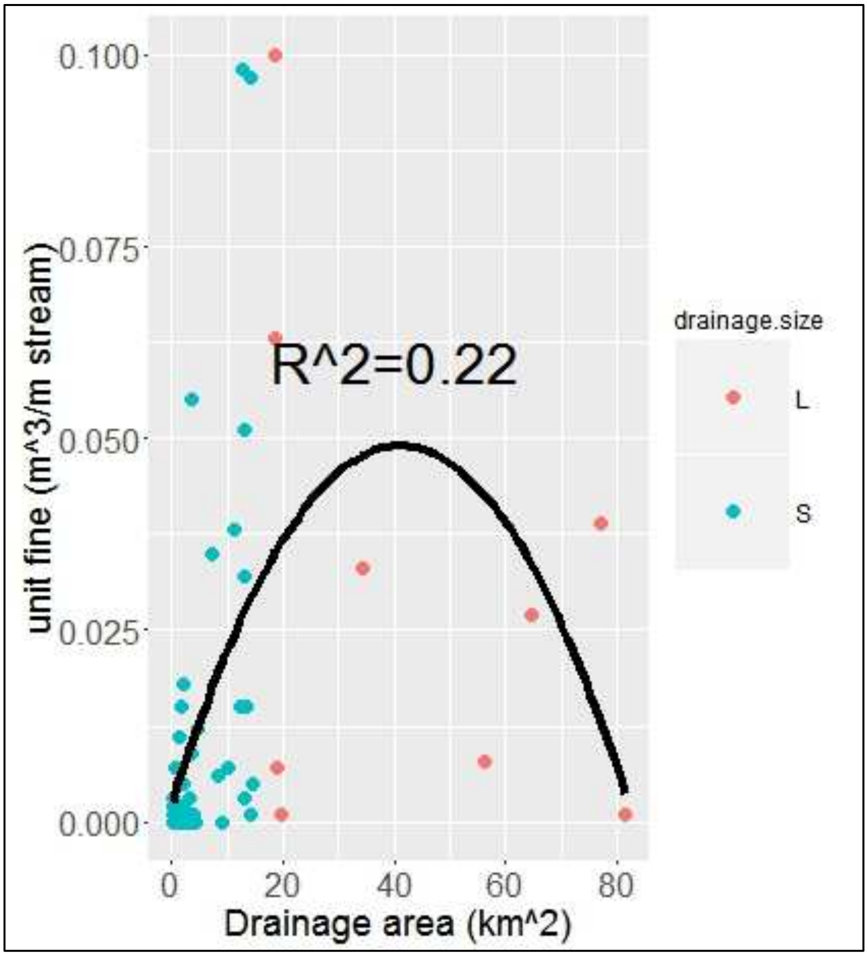


Figure 28. Fine sediment storage versus drainage area. A natural break in the data was found with SegReg at 10.7 km^2 (blue versus red dots) but no strong relationships were found through performing this segmentation. There is a moderate quadratic relationship between fine sediment and drainage area with the fit estimating peak values at 41 km^2. Observed maximum storage occurs at 18 km^2. R^2=0.34 for square-root transformed data. N=55 reaches.

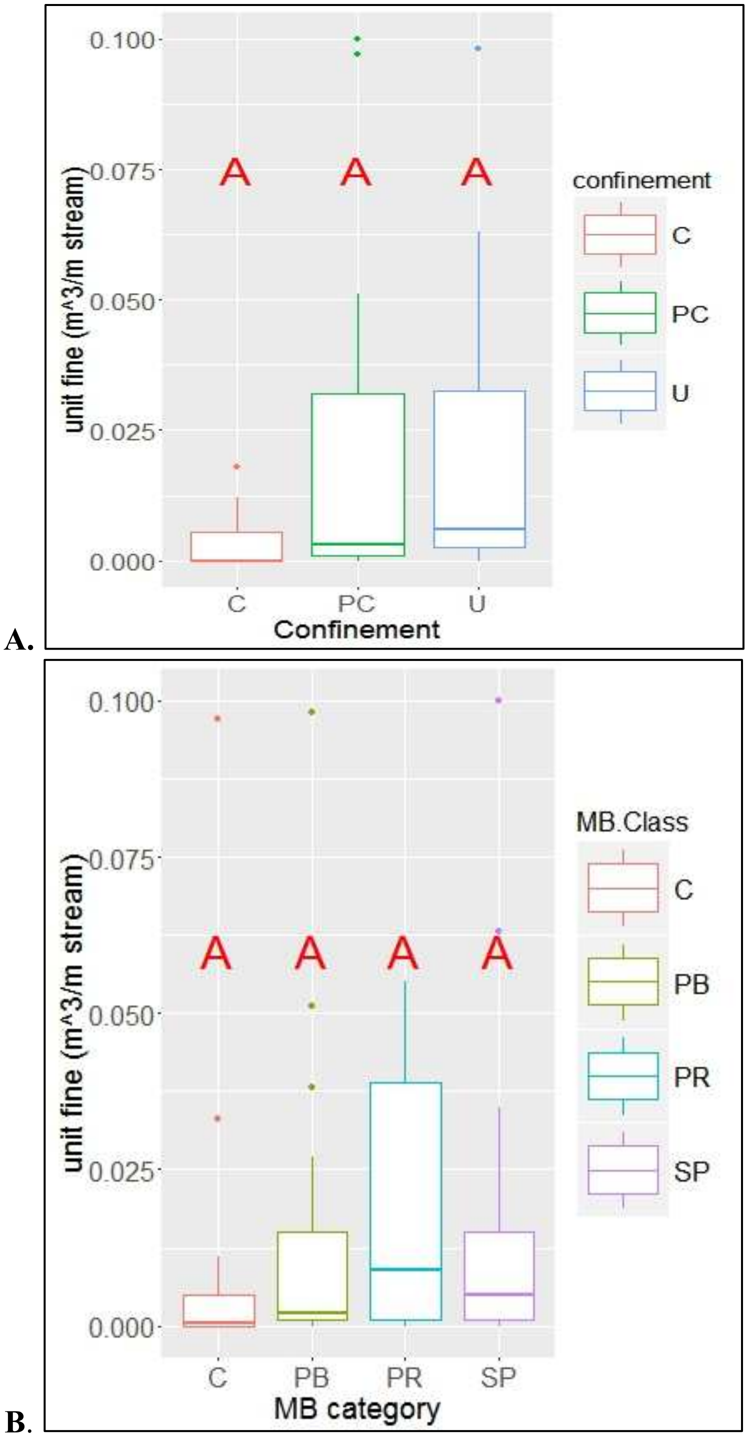


Figure 29 A. Unit fine sediment storage (m^3/m) versus lateral channel confinement. No significant differences were found between categories. **B.** Fine storage versus MB category; no significant differences were found. N=55 reaches.

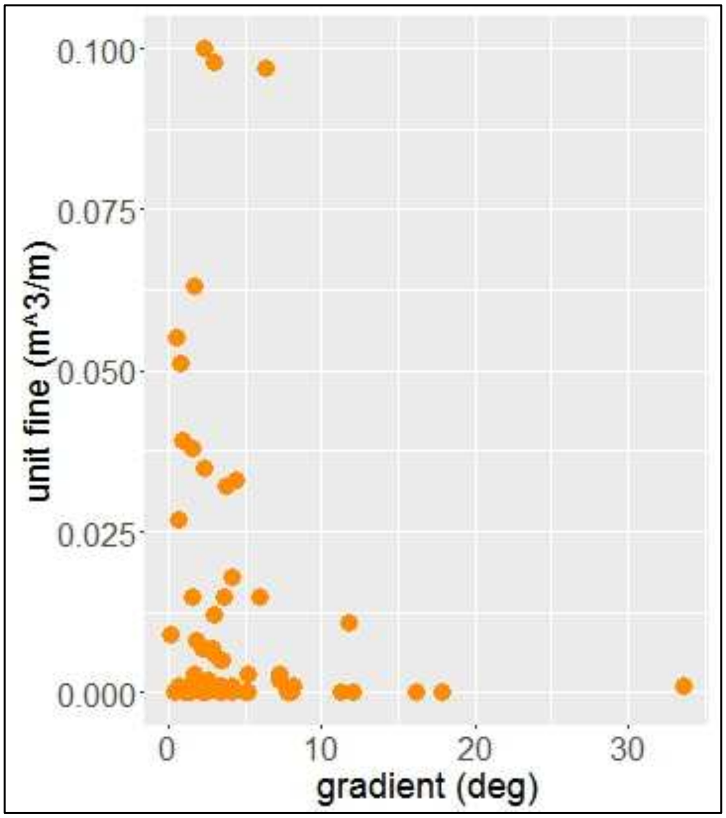


Figure 30. Unit fine sediment volume (m^3/m) versus channel gradient. No clear relationship was found between the two variables. N=55 reaches.

Fine sediment is not strongly correlated to wood distribution or wood piece characteristics. There is a slight negative relationship with respect to longitudinal spacing of pieces, but no clear trend (Figure 31). Although close spacing was predicted to decrease mobilization and increase retention of fines, there is no evidence for spacing controlling the distribution of fine sediment. This is consistent with field observations, though, as both tightly spaced jams and widely separated, large jams were sometimes observed to be effective in storing fine sediment. Regarding reach-scale piece characteristics, fine sediment has no relationship with average piece length/average channel width and a very weak positive correlation with D_{50} (Figure 32 A and B). This suggests that diameter causes more vertical flow resistance in the water column than lateral, channel-spanning wood. Most importantly, though, the weak relationships between fine sediment storage and these reach-averaged wood piece metrics indicate that fine sediment may be more strongly influenced by local, jam, or piece-scale factors than reach-scale controls.

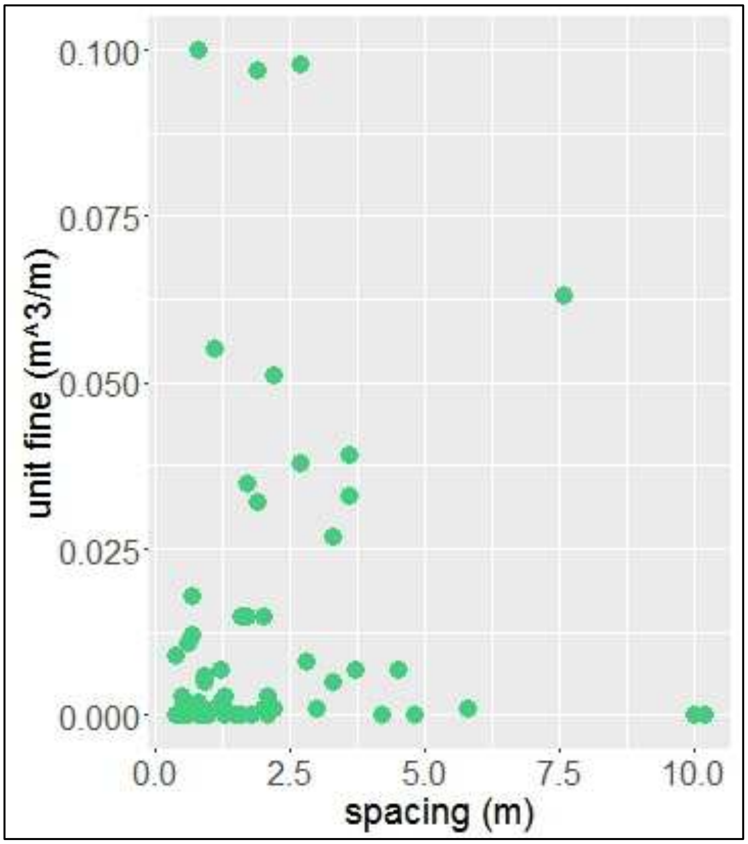


Figure 31. Unit fine sediment storage (m^3/m) versus longitudinal spacing (reach length/number of jams or wood pieces). Although storage is highly variable regardless of spacing, storage is generally lower at reaches with infrequent jams (high spacing). N=55 reaches

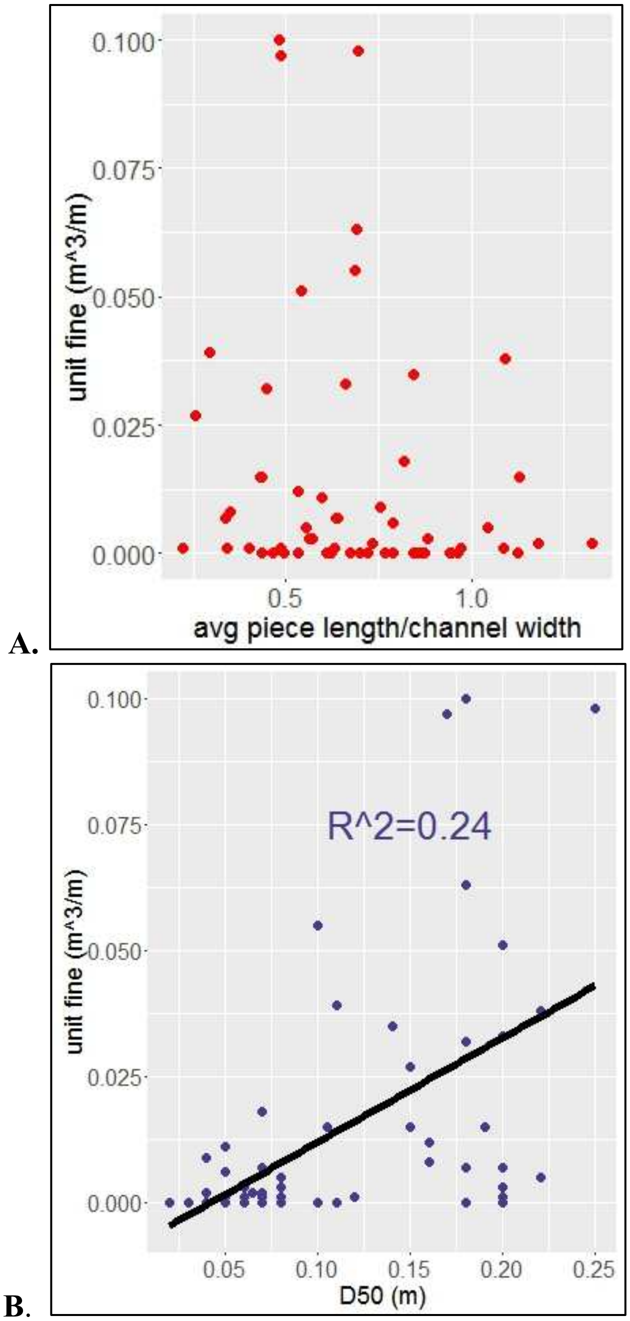


Figure 32. A. Fine sediment storage versus average wood piece length/average channel width. B. Fine sediment storage versus median wood diameter (D_{50}). R^2=0.28 for square-root transformed unit fine sediment versus D_{50}. N=55 reaches.

Taken together, the results for fine sediment storage indicate stronger controls from coarse sediment, wood load, and drainage area than channel characteristics or wood piece metrics. These results are somewhat confusing, as the correlation between coarse and fine sediment indicates localized roughness and resistance as important factors for fine sediment retention, whereas the relationship between fine sediment and drainage area suggests larger-scale flow regime controls.

A multiple variable linear regression was conducted to delineate the types of controls most predictive of fine sediment storage on a given reach. The results from multiple regression are depicted in Table 5 and reveal coarse sediment to be the strongest predictor of fine sediment storage. However, gradient and average piece length/channel width are also relatively important predictors. The number of important predictors in this analysis (compared to one predictor, wood load, dominating coarse sediment multiple regression) indicates that different scales of factors influence fine sediment storage. Although some of these important predictors (such as spacing and average piece length/channel width) did not predict fine sediment storage well on an individual basis, multiple regression sorts through their relative contributions. This type of analysis predicts fine sediment storage much better than any of the single variable regressions (R^2 improves to 0.6 compared to ~0.2-0.3). Hypothesis 2b is partially supported by these results. Interestingly, coarse sediment is a much more important predictor of fine sediment storage than wood load. This suggests coarse sediment as the primary form of resistance in causing sand deposition. Wood is storing this coarse sediment (Figure 23 and Table 3), but its role in fine sediment storage is less direct than hypothesized. To test this, coarse sediment was removed as a predictor from the regression model; wood load became the most important predictor (results shown in Appendix C). This confirms that wood is important in creating backwaters of fine sediment storage, but that it exerts an underlying control rather than a direct one. Drainage area is the second most important predictor in the model, indicating that fine sediment is not only controlled by local factors. Although there is not a clear pattern of downstream fining in NSV, there may be an optimal drainage area for storage of fines (Figure 28). Close longitudinal spacing of wood, as expected, limits downstream mobilization of fines and increases cumulative retention on the reach scale. Finally, average wood piece length/ average channel width moderately predicts fine sediment storage, indicating that channel-spanning wood pieces may be most effective in inducing fine deposition. Taken together, these results suggest a more complicated feedback of different levels of controls for fine sediment deposition.

Table 5. Importance for predictor variables in fine sediment multiple regression. Importance is calculated by weighing the number of models in which a predictor appears. R^2=0.60 for the best model (chosen with AICc selection) and includes sqrt unit coarse sediment (positive coefficient), sqrt drainage area (positive coefficient), sqrt channel gradient (negative coefficient), sqrt wood piece spacing (negative coefficient), and sqrt average length wood piece/channel width (positive coefficient) as predictors. R^2=0.69 for the model with all possible predictors. Units are not included because they are physically meaningless after the square root transformation. N=55 reaches.

Variable	Importance
sqrt unit coarse	1.00
sqrt drainage area	0.85
sqrt (average piece length/average channel width)	0.71
sqrt gradient	0.62
sqrt spacing	0.48
proportion of ramps and bridges (count)	0.32
sqrt basal area	0.30
Confinement (C, PC, U)	0.28
proportion jammed (volume)	0.23
sqrt unit wood load	0.23
sqrt D_{50}	0.23
MB category (SP, PR, C, PB)	0.15

As in the coarse sediment analysis, many reaches did not store any fine sediment. Reaches without fine sediment (and without coarse sediment because the amount of coarse sediment is a hypothesized control) were removed from the subsequent analysis (Table 6). This can potentially better target the factors involved in fine sediment storage. Results changed somewhat in this scenario, as coarse sediment became a less important predictor. Given the single variable regression between fine sediment and coarse sediment (Figure 27B), it is feasible that the abundance of sites without fine storage caused the relationship between fine and coarse to appear stronger than it is. Drainage area becomes less important in this scenario, also indicating that zero values may have had a large effect on this relationship (Figure 28). Regardless of whether zero storage reaches are included, factors such as localized coarse sediment storage and wood piece characteristics (average piece length/average channel width) are more important than total wood load to storage of fines.

Table 6. Fine sediment multiple regression after removing zero storage reaches. Because there are no longer zeros, data were $\log_{10}$ transformed to help meet regression assumptions. This better met regression assumptions than a square root transformation. R^2=0.59 for the best model and includes log average piece length/average channel width, log unit coarse sediment, log gradient, log and drainage area as predictors. R^2=0.69 for the model with all predictors. N=30 reaches.

Variable	**Importance**
log average piece length/average channel width	0.87
log unit coarse	0.87
log gradient	0.76
log drainage area	0.58
log spacing	0.34
proportion ramps and bridges	0.22
proportion jammed	0.22
log unit wood load	0.21
log D_{50}	0.19
MB category (SP, PR, C, PB)	0.05
confinement (C, PC, U)	0.03
log basal area	0.00

4.5. Controls on POM storage

H2c: POM storage correlates most strongly with wood load, followed by fine sediment, basal area, spacing, and confinement.

There is weak evidence to support H2c from a multiple regression model. Confinement, basal area, and coarse sediment were found to be relatively important predictors of POM storage (Table 7). Although POM has been tied to the amount of wood and fine sediment, with wood creating an obstruction and fine sediment a depositional surface (Bilby and Likens, 1981; Raikow et al. 1995; Jones and Smock, 1991), neither of these variables was a very important predictor. This may indicate that coarse sediment (which is strongly controlled by wood, Figure 23 and Table 3) is the most important source of local resistance for inducing POM storage. The amount of wood is likely a factor in POM storage, but POM dynamics may be controlled by more localized factors (such as coarse sediment) behind jams or wood pieces. Similar to the fine sediment analysis, this idea was tested by removing coarse sediment as a predictor. Wood load becomes the fourth most important predictor in this scenario, highlighting its underlying role in creating resistance and pools conducive to storage (results shown in Appendix C). Lateral channel confinement and basal area as the strongest predictors suggest that floodplain-channel connectivity and transport and POM source characteristics are important in determining the amount of POM in a reach. Figure 33 displays the relationship between POM and lateral channel confinement, indicating that more extensive floodplains may allow for more effective POM transport to and storage within the channel. Taken together, these results suggest that POM storage is dependent on floodplain-channel transport and in-channel roughness in the form of wood-stored coarse sediment. This partially supports Hypothesis 2c, as POM is not highly correlated to fine sediment, spacing, or wood load. Reviewing the conceptual model (Figure 4), the relationship in which coarse sediment controls fine sediment storage and fine sediment controls POM storage is not as straightforward as expected. Fine sediment may offer a depositional surface for POM, but it does not appear to be as effective as coarse sediment in creating roughness that induces POM deposition.

The individual graphs of POM versus secondary predictors (basal area and coarse sediment) are shown in Appendix D because these graphs do not display visually or statistically informative trends.

Table 7. Multiple regression and importance results for POM storage versus predictors. Importance is calculated by weighing the number of models in which a predictor appears. R^2=0.3 for the best model (chosen by AICc selection), which includes lateral channel confinement, sqrt basal area (positive coefficient), and sqrt unit coarse sediment volume (positive coefficient) as predictors. R^2=0.48 for the model with all possible predictors. N=58 reaches.

Variable	**Importance**
confinement (C, PC, U)	0.75
sqrt basal area	0.73
sqrt unit coarse	0.62
sqrt spacing	0.47
sqrt gradient	0.43
proportion jammed wood	0.35
sqrt unit wood load	0.35
proportion ramps and bridges	0.33
sqrt unit fine	0.32
sqrt drainage area	0.28
sqrtD_{50}	0.24
sqrt	0.23
MB category (SP, C, PB, PR)	0.17

Given the abundance of reaches with no POM storage, a multiple regression was calculated with the zeros removed (Table 8). This modification appreciably changes interpretation of controls on POM storage. Confinement, basal area, and coarse sediment volume become much less important predictors, but wood piece size relative to channel size becomes especially important. In addition, fewer predictors emerge as more important than others.

Interestingly, however, the overall strength of the model improves (R^2 increases to 0.56 from 0.3). Overall, these incongruous results demonstrate that it is difficult to predict reach-scale POM storage, potentially because of its high mobility and transience. Despite this, a comparison of Tables 7 and 8 is valuable in showing that exclusion of sites with zero storage matters in assessing POM storage. As in the fine sediment storage analysis, controls outside of total wood load are most important in POM storage.

Table 8. POM multiple regression after removing reaches without POM storage. A $\log_{10}$ transformation was used to help meet regression assumptions. This transformation better met assumptions than a square root transformation and worked due to the lack of zero values. R^2=0.56 for the best model and included log average wood piece length/channel width, proportion jammed, and confinement as predictors. R^2=0.84 for the model with all possible predictors. N=25 reaches.

Variable	Importance
log (average piece length/average channel width)	0.64
proportion jammed (volume)	0.50
confinement (C, PC, U)	0.36
proportion ramps and bridges (count)	0.24
log drainage area	0.22
log unit coarse	0.19
log unit fine	0.18
log D_{50}	0.17
log spacing	0.16
log unit wood load	0.15
log gradient	0.12
basal area	0.12
MB category (SP, C, PB, PR)	0.03

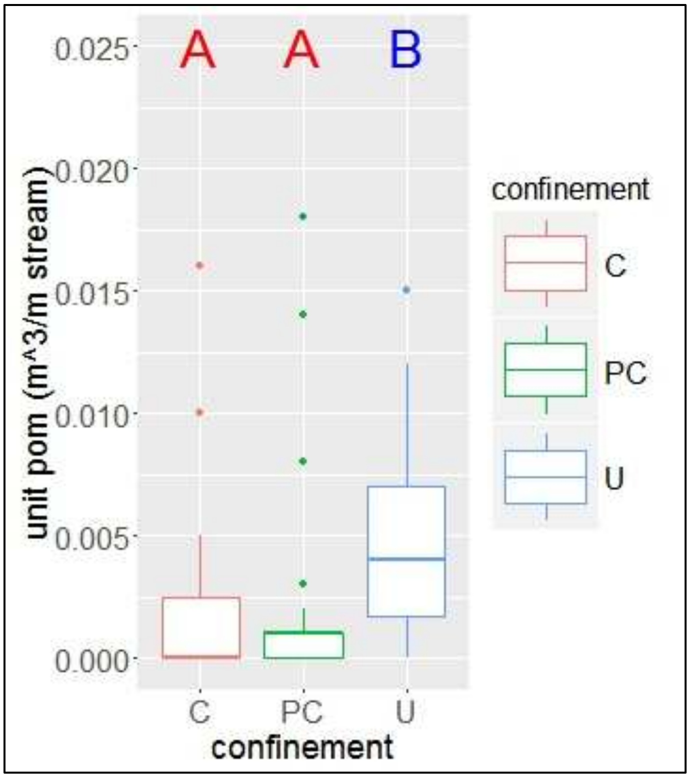


Figure 33. Unit POM storage (m^3/m) versus channel confinement. Unconfined reaches store significantly higher POM volumes than confined or partially confined reaches.

4.6. Jam-scale controls on material storage (coarse, fine, POM)

4.6.1 Analysis excluding Livers, 2016 data

Hypothesis 3a: On the scale of a single jam, sediment and POM storage are inversely correlated with porosity and permeability. Fine sediment storage correlates more strongly than coarse sediment storage with porosity and permeability. POM storage correlates more strongly than fine sediment with porosity and permeability.

Hypothesis 3b: Sediment and POM storage are positively correlated with jam volume (specifically jam volume/average channel width). The relationship should be progressively stronger for progressively finer material.

The following analyses do not contain data from Livers, 2016 due to difficulty in matching measurements at the jam scale. Coarse and fine sediment and POM storage were not related to jam porosity or permeability. Figures are included in Appendix E, but there is no discernible relationship between these variables. This reflects the fact that jams are complicated, three-dimensional structures and quick, field estimation of porosity and permeability is not an effective metric for assessing the amount of material stored behind a jam. I also did not find evidence for relatively stronger relationships between finer material (fine sediment and POM) and porosity and permeability, as storage was highly variable at all estimated porosity and permeability values. Therefore, there is no evidence to support H3a. Based on field observations, porosity and permeability appear to influence storage. “Leakier” jams appear to store less material. However, visual assignment of porosity and permeability misses the true values of these variables and cannot capture the subsurface, three-dimensional porosity and permeability that may be influencing storage.

Regarding hypothesis 3b, there is a moderate relationship between jam volume and storage. A standard outlier test was conducted given that a few jams store much more material than the rest of the surveyed jams. Many outliers (Q1-1.5IQR, Q3+1.5IQR) and extreme outliers (Q1-3IQR, Q3+3IQR) were found, likely because of the prevalence of zero or no storage jams. However, only the very extreme values were removed (the highest two for coarse, three for fine, and one for POM; these values appeared to be strongly driving the regression). Original plots are included in Appendix F. Both the complete dataset of jams (Figures 34A, 35A, 36A) and only jams with stored material (Figures 34B, 35B, 36B) are plotted. For both scenarios, the strength of the relationship is moderate and comparable for fine and coarse sediment and much weaker for POM, which is the opposite of the expected result (Figures 34-36). Therefore, there is no evidence to support Hypothesis 3B. The lack of strong results at this scale may indicate that reach-scale processes are more important in determining sediment storage, even behind a single jam. It also may reflect the study design, as jam dimensions and characteristics were not intensively surveyed. Because of the nature of the study, I may have been too optimistic in attempting to glean useful data at this smaller scale.

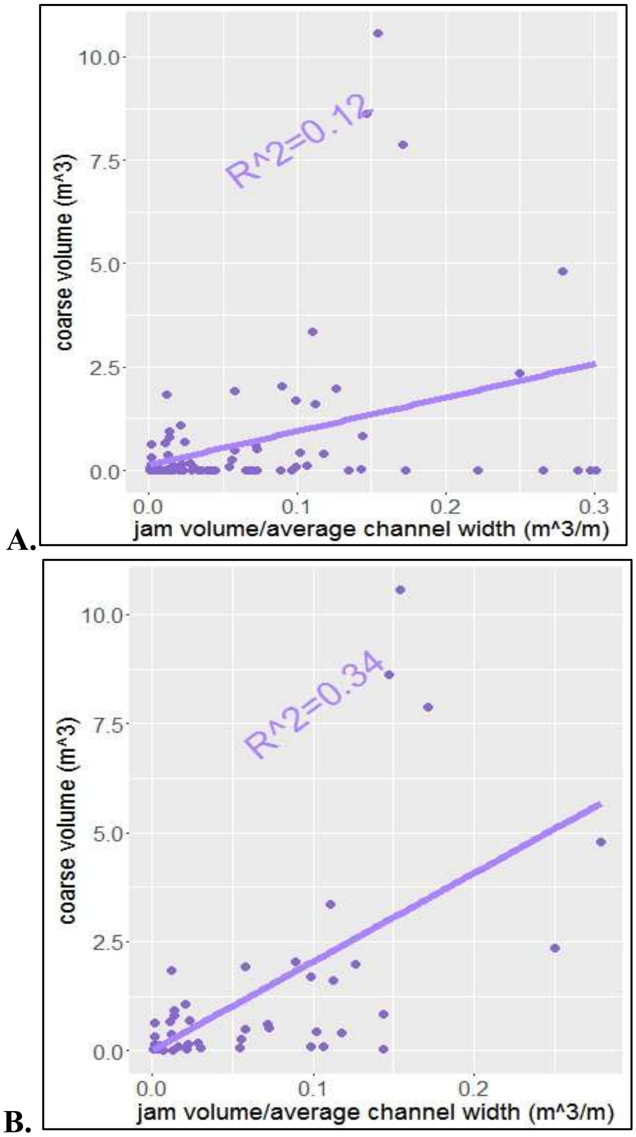


Figure 34 A. Coarse sediment volume versus jam volume/average channel width. Data are for 96 jams on 31 reaches in NSV. **B.** The same analysis as A with jams of zero coarse storage excluded. N=45 jams on 18 reaches. The two highest coarse sediment volume values were removed but outliers remain.

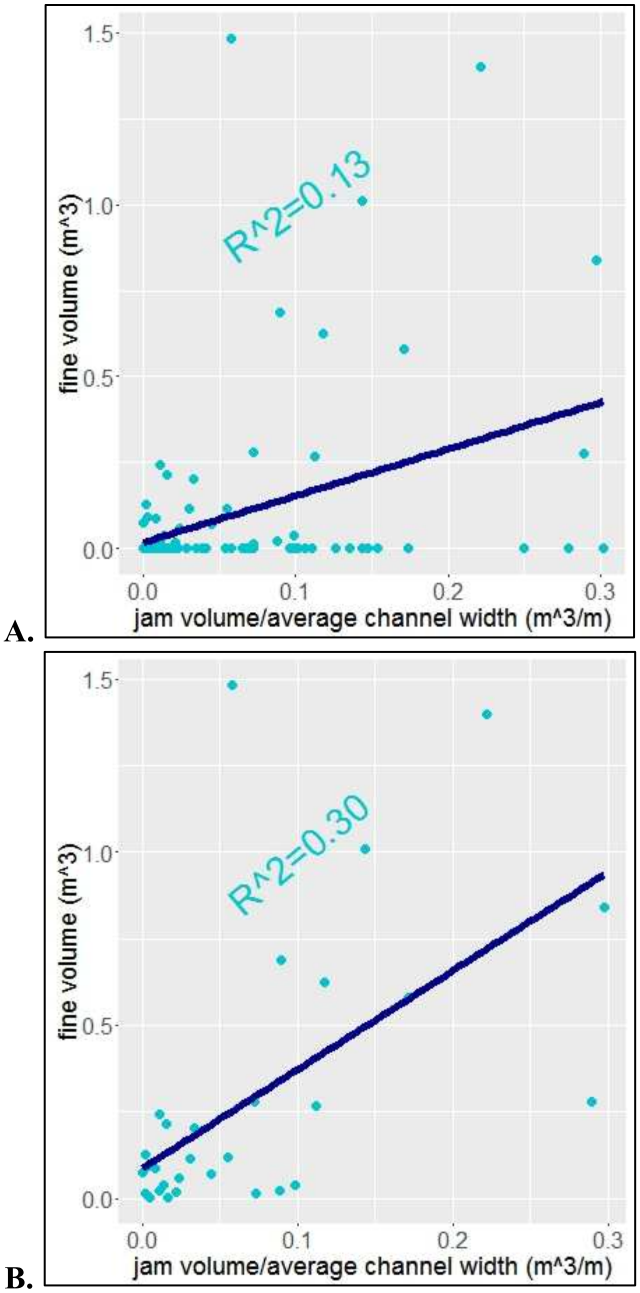


Figure 35. A. Fine sediment volume versus jam volume/average channel width. N=95 reaches on 31 reaches. **B.** The same analysis excluding jams without fine sediment storage. N=32 jams on 17 reaches. The three largest fine sediment volume values were removed but outliers remain.

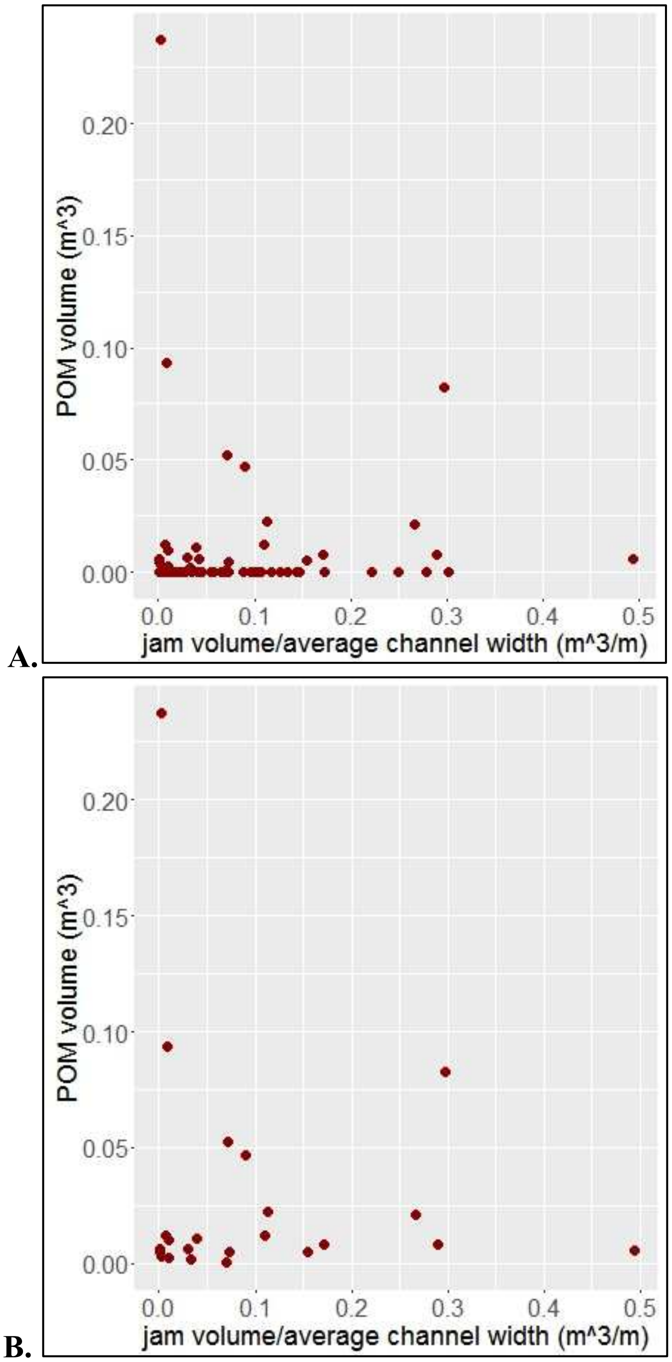


Figure 36. A. POM volume versus jam volume/average channel width. Data are for 97 jams on 31 reaches in NSV. **B.** POM volume versus jam volume/average channel width excluding jams without POM storage. N=24 jams on 12 reaches. The highest POM value was removed but outliers remain.

4.6.2. Pseudo jam-scale analysis including jams from Livers, 2016

Data from Livers (2016) capture key, typically multithreaded sites from NSV and include detailed jam measurements and POM surveys. As mentioned earlier, relating the sediment I measured at a jam to the wood volume from a jam (via matching up GPS coordinates from Livers, 2016) was not possible. However, I conducted a "pseudo" jam-scale analysis with the available data. I calculated average jam volume and average coarse and fine sediment and POM storage by jams (excluding storage from non-jam pieces) for each reach. I also excluded reaches without jam-induced sediment storage from this analysis. Although this method is not truly a jam-by-jam analysis (as in 4.6.1), it adds an additional perspective on how jam characteristics influence storage. Essentially, it contains higher number of reaches and jams than the analyses in 4.6a but does not correlate storage at a single jam to the jam itself.

Again, average jam volume/average channel width was used as a predictor of storage and indicator of a jam's effectiveness relative to channel size. Only jams storing material were used for this analysis. Overall, results are not highly linear and are very scattered (even compared to those in 4.6a). There is evidence that the relationship between jam volume and material storage increases with increasingly finer material (i.e., correlations are strongest between average jam volume and average POM volume, moderate between average jam volume and average fine sediment volume, and weakest between average jam volume and average coarse sediment volume) (Figure 36 A and B, Figure 37). This somewhat supports Hypothesis 3b and the conceptual model (Figure 4). However, it contradicts the true jam-scale analysis from the previous section. Taken together, these analyses partially support Hypothesis 3b. It appears that, on a reach-averaged scale, larger jams are needed to store finer material. Because sediment retention, especially coarse sediment, is part of larger scale bed adjustment processes, logjams and wood pieces acting together on a reach may be more important than a single logjam for this type of storage. There is high variability for all types of storage in this analysis, however, further indicating that the study design or processes acting beyond the scale of a single jam preclude clear jam-scale prediction of sediment storage.

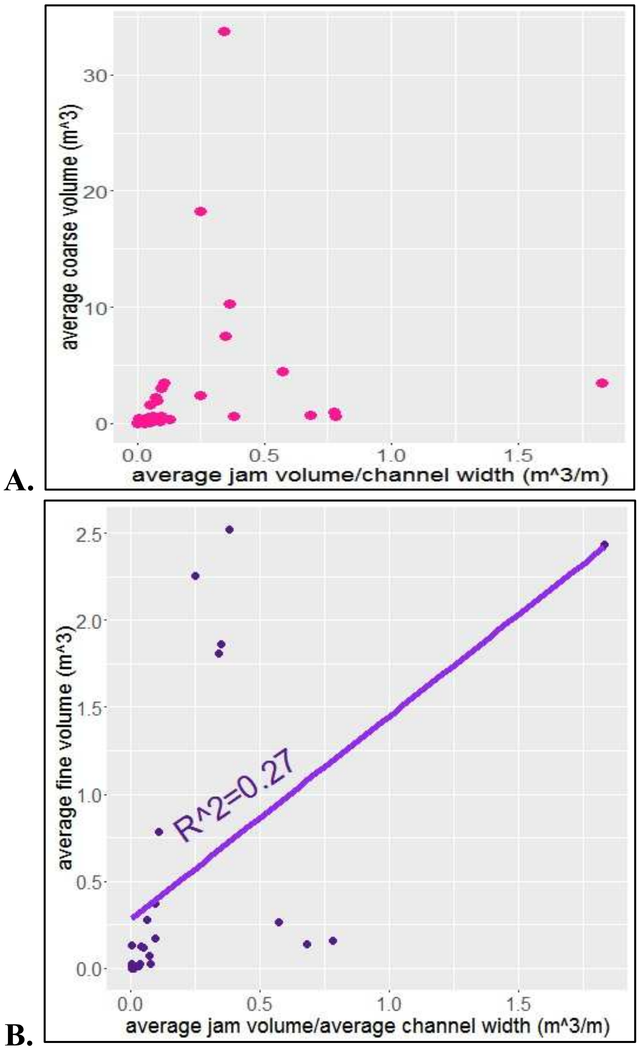


Figure 36. A. Reach-averaged coarse sediment volume versus average jam volume/channel width. N=29 reaches. No linear relationship was found for the data. Data include those from Livers (2016), which brings in an additional 110 jams for this reach-averaged analysis. **B.** Reach-averaged fine sediment volume versus average jam volume/channel width. A weak linear relationship was found but appears to be driven by the point with the highest average jam volume/average channel width. N=24 reaches, including data from Livers (2016).

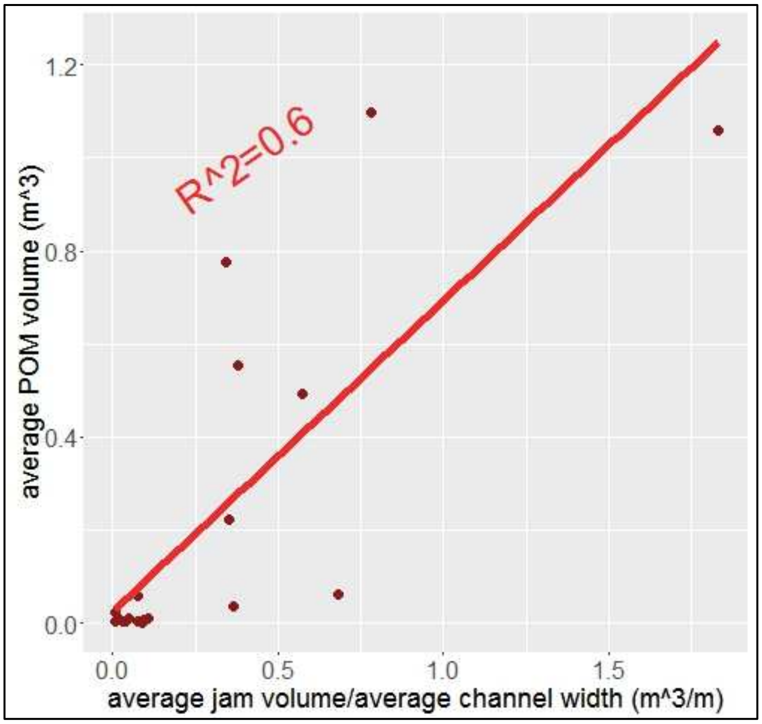


Figure 37. Reach-averaged POM volume versus average jam volume/channel width. N=20 reaches; this includes jam data from Livers (2016).

4.7. Drainage basin analysis of wood, sediment, and POM storage

4.7.1 A note about threshold drainage area selection and mapping of first order streams

Whether in the field or in ArcGIS, mapping small streams is difficult. Contributing area for channel initiation for Front Range streams ranges from 0.01 km^2 to 0.6 km^2 (Henkle et al. 2011). As mentioned in section 3.5, three scenarios were chosen for contributing area at channel initiation (0.1 km^2, 0.25 km^2, 0.5 km^2) based on field observations and analysis of topographic maps. This setup was two-pronged: to find a contributing area that best represented the NSV stream network and to assess the sensitivity of drainage-scale storage estimates to the choice of contributing area. A 0.25 km^2 contributing area was chosen as most representative of the NSV stream network based on (i) the relatively high rate of success in mapping first-order streams as judged by comparing GIS-generated channel initiation sites against those mapped in the field (8 of 11, 73%) and (ii) the avoidance of creating too dense a stream network in which streams that were not observed in the field (and are likely just small depressions in the forest floor) are mapped (Figure 38). The maps and the tradeoffs for the 0.1 km^2 and 0.5 km^2 scenarios are presented and explained in Appendix G.

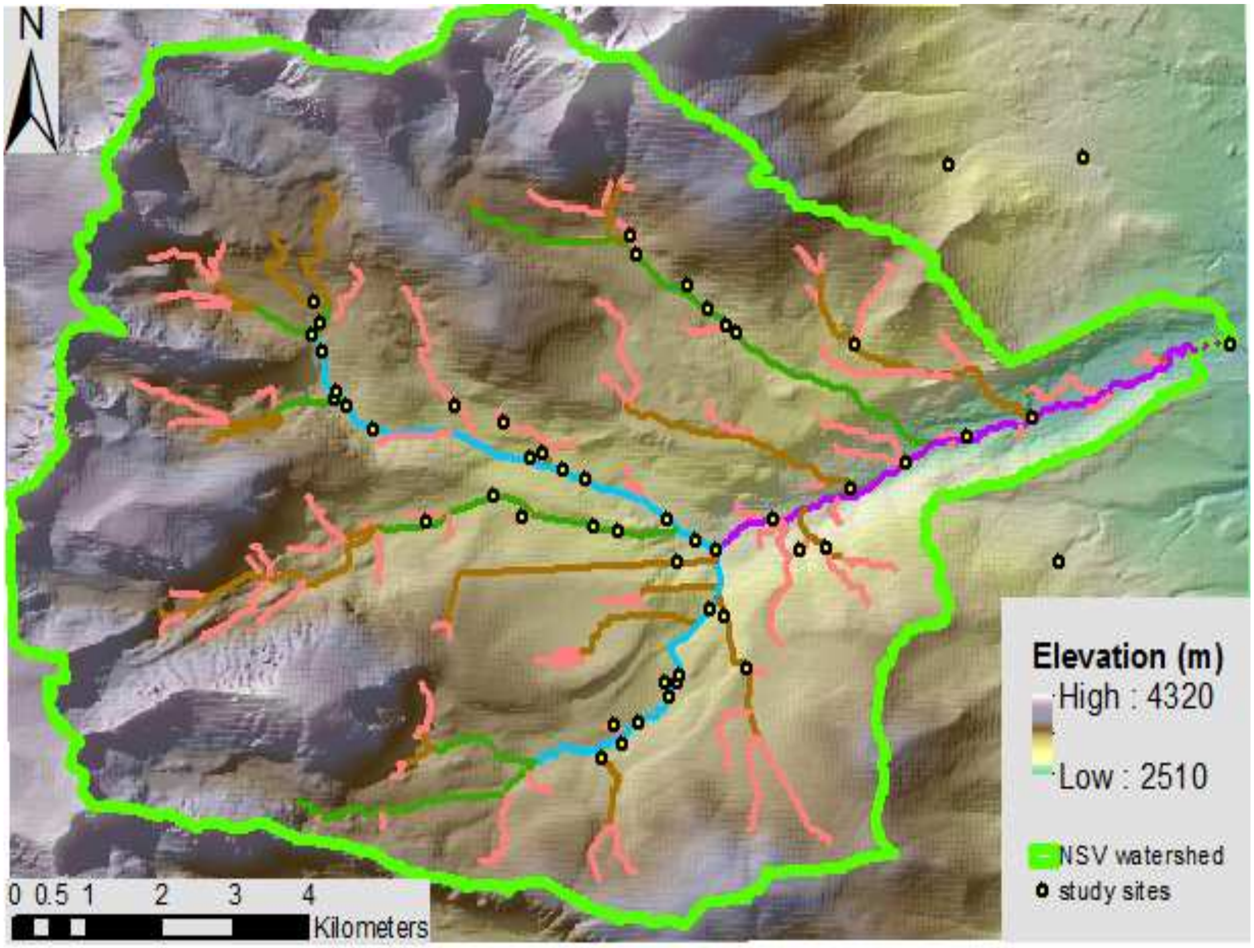


Figure 38. NSV watershed created in ArcGIS using a 0.25 km^2 threshold drainage area for channel initiation. Streams were clipped at treeline to avoid extrapolating estimates to the alpine zone (no instream wood). However, stream order retains the original streams (including alpine zone), because this area also contributes to streamflow generation. This scenario (as opposed to using a 0.1 km^2 or 0.5 km^2 threshold) best captured first order streams (8 of 11 mapped to the generated network), yet avoided an unrealistically dense stream network (as in the 0.1 km^2 case). Stream segment colors indicate stream order and match those in Figures 42-45. N=48 reaches; 11 first order (red), 9 second order (brown), 12 third order(green), 12 fourth order (blue), and 4 fifth order (purple).

4.7.2. Average material storage by stream order

The previous sections illuminate the complex interactions among wood, sediment, and POM within North Saint Vrain Creek. Storage is typically an interplay of different scales and types of controls (i.e., fine sediment is strongly related to both localized coarse sediment and drainage area, Table 5). Although stream order (or drainage area) is commonly not the primary control on storage, separating storage by stream order is the most feasible way to extrapolate these findings, as cumulative storage on different stream orders can be easily calculated in ArcGIS (average storage by stream order (m^3/m) *total stream length (m)=m^3 material). This analysis is restricted to sites within the NSV watershed with an outlet at the RMNP boundary (N=48 reaches).

Average wood load is significantly higher in third- and fourth-order streams than in first- or second-order reaches (Figure 39). Average coarse sediment displays differences among stream orders, with average storage maximized in third-order streams (Figures 40A). Fine sediment storage is evenly spread among stream orders and there are no significant differences between groups (Figure 40B). Average POM storage is more variable and does not correlate strongly with stream order (Figure 41).

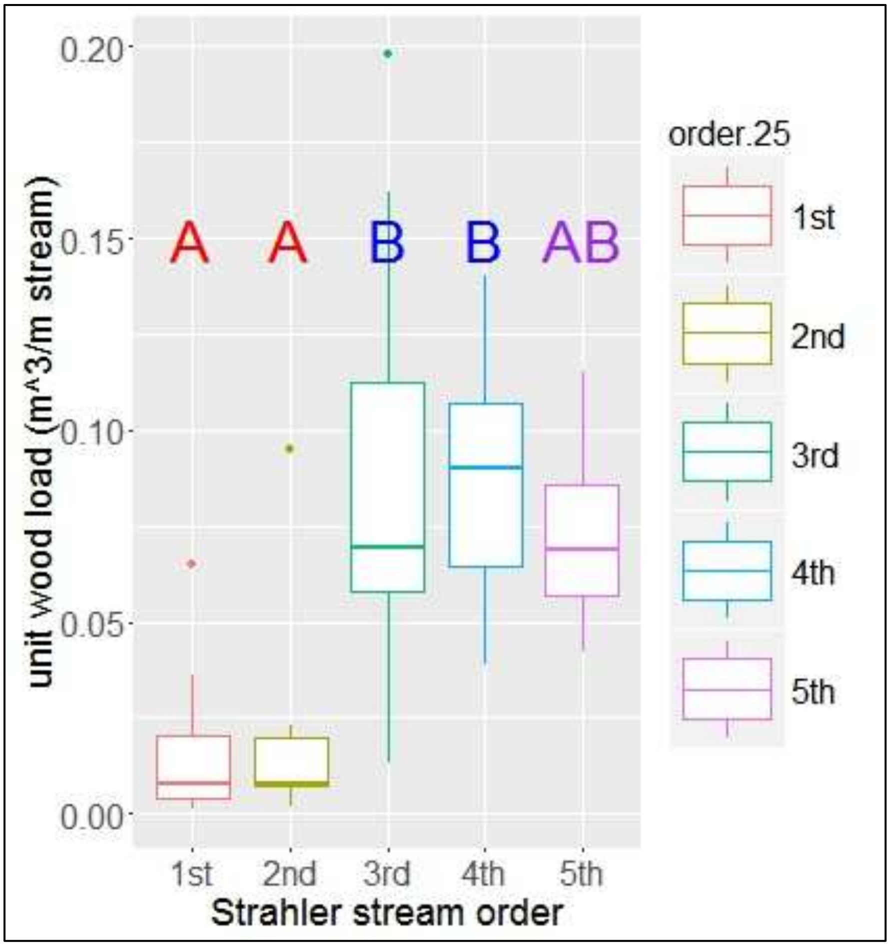


Figure 39. Wood load versus stream order. Stream order was calculated using a 10 m DEM in ArcGIS with a 0.25 km^2 threshold contributing area for channel initiation. N=48 reaches.

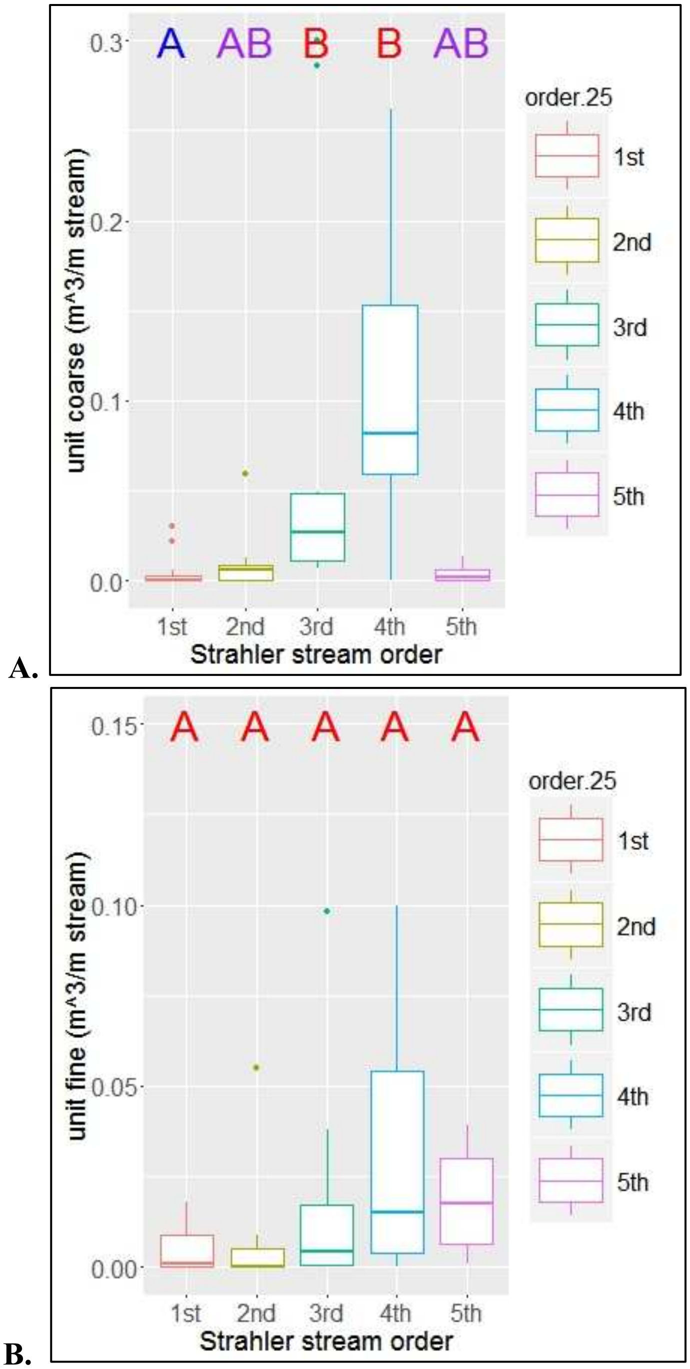


Figure 40. A. Coarse sediment storage versus stream order. Storage peaks in third-order streams and is significantly higher than in first-order streams. **B.** Fine sediment storage versus stream order. There are no significant differences between groups. Stream order was calculated using a 10 m DEM in ArcGIS with a 0.25 km^2 threshold contributing area for channel initiation. N=48 reaches.

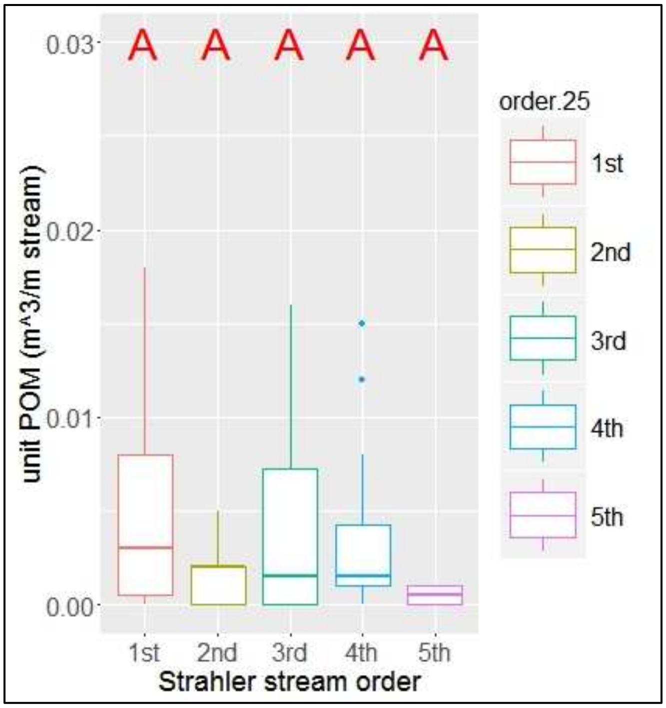


Figure 41. POM storage versus stream order. Storage is highly variable and there are no significant differences between groups. Stream order was calculated using a 10 m DEM in ArcGIS with a 0.25 km^2 threshold contributing area for channel initiation. N=48 reaches.

4.7.3 Cumulative estimates of wood, sediment, and POM storage and sensitivity to choice of contributing area

Hypothesis 4: Cumulative storage of wood, coarse, fine, and POM is highest in third order streams.

Figures 42-45 reveal that cumulative instream wood loads and the cumulative volume of material stored by wood differ in various parts of the drainage basin. All the following analysis is based on the 0.25 km^2 contributing area scenario (rationale for this in Section 4.7.2). Third-order streams are a hotspot of wood and coarse sediment storage (34% and 41% respectively). Fourth-order streams also have a large cumulative effect, storing 21% of wood and 37% of coarse sediment (Figures 42 and 43). This is a disproportionate effect with respect to stream length, as third- and fourth-order streams comprise 15% and 8% of total stream length, respectively.

Cumulative fine sediment storage, in contrast, displays a more evenly balanced trend within the drainage basin (Figure 44). Twenty-one percent of fine sediment storage occurs in first-order streams, 19% in second order, 23% in third order, 26% in fourth order, and 10% in fifth-order streams. The largest cumulative portion in fourth-order streams may indicate that these streams tend to be found in lower gradient segments of the valley where average substrate size is finer. In general, fine sediment does not accumulate in any one segment of the watershed. Localized factors promote retention throughout the drainage basin.

Finally, cumulative POM retention is highest in first-order streams (Figure 45). This is a roughly proportional effect (60% in 46% of the stream network). This finding indicates that, although POM storage was observed behind large jams in third- to fourth-order streams, smaller storage features may be important on a cumulative basis. This could indicate that (i) local forest characteristics are more important than drainage-scale trends in determining POM storage, (ii) the relatively small hydraulic forces present in first-order channels allow POM to be retained, or (iii) high rates of POM replenishment through litterfall after peak flow, combined with low transport capacity, quickly ‘restock’ stored POM after periods of transport. First-order streams are not greatly incised, are connected to the forest floor, and commonly contain roots of living trees that serve as persistent POM retention structures.

Sensitivity of these estimates to the choice of threshold contributing area was assessed by calculating percent difference. Storage estimates are highest for the 0.1 km^2 scenario, intermediate for the 0.25 km^2 scenario, and lowest for the 0.5 km^2 scenario, which makes sense given the density of the stream network under these different conditions. Overall, wood, coarse sediment, and fine sediment estimates are somewhat sensitive to these scenarios, but values are generally similar (percent differences of ~15-40%, Figures 42-44). POM storage estimates are more sensitive to these scenarios, with values ranging from 35-85% (Figure 45). The largest differences for all types of storage occur between the 0.1 km^2 and 0.5 km^2 scenarios. These results indicate that cumulative storage estimates are somewhat sensitive to the method by which a stream network is created in ArcGIS and that careful thought should go into how well a digitally created stream network matches field observations when analyzing different scenarios. An alternative analysis (assessing differences in stored material/stream surface area- m^3/m^2, as opposed to stored material/stream length- m^3/m) was conducted at 0.25 km^2. Results are presented in Appendix H; interpretation of storage hotspots is the same despite slight differences in the proportion of storage.

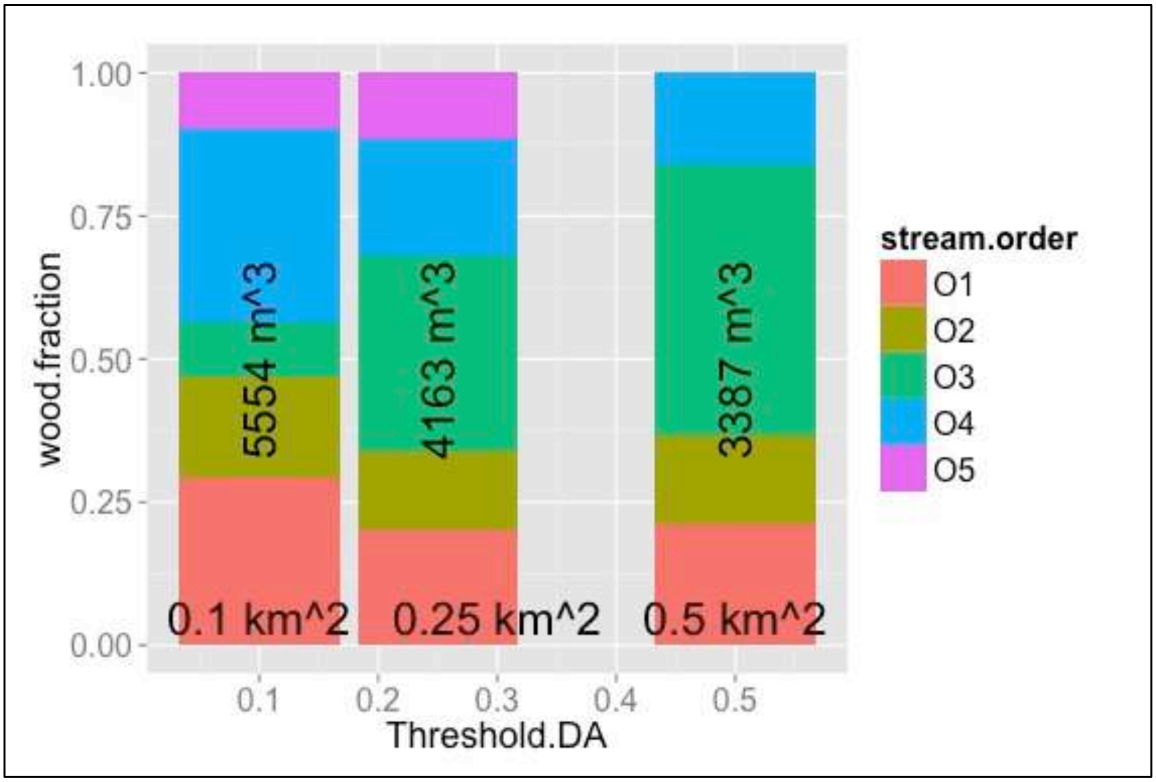


Figure 42. Network-scale wood load and distribution estimates. Wood load total estimates in NSV (vertical text on bars) are somewhat sensitive to the choice of contributing drainage area for channel initiation used to build a stream network in ArcGIS. Percent differences are 28.6% between 0.1 km^2 and 0.25 km^2, 48.5% between 0.1 km^2 and 0.5 km^2, and 20.6% between 0.25 km^2 and 0.5 km^2. The distribution of cumulative stored wood varies between these scenarios, with fourth-order streams storing the highest wood loads (34%) for 0.1 km^2 threshold drainage area, third order containing the highest wood loads (34%) for 0.25 km^2 threshold drainage area, and third-order streams storing the most wood (47%) for a 0.5 km^2 threshold drainage area.

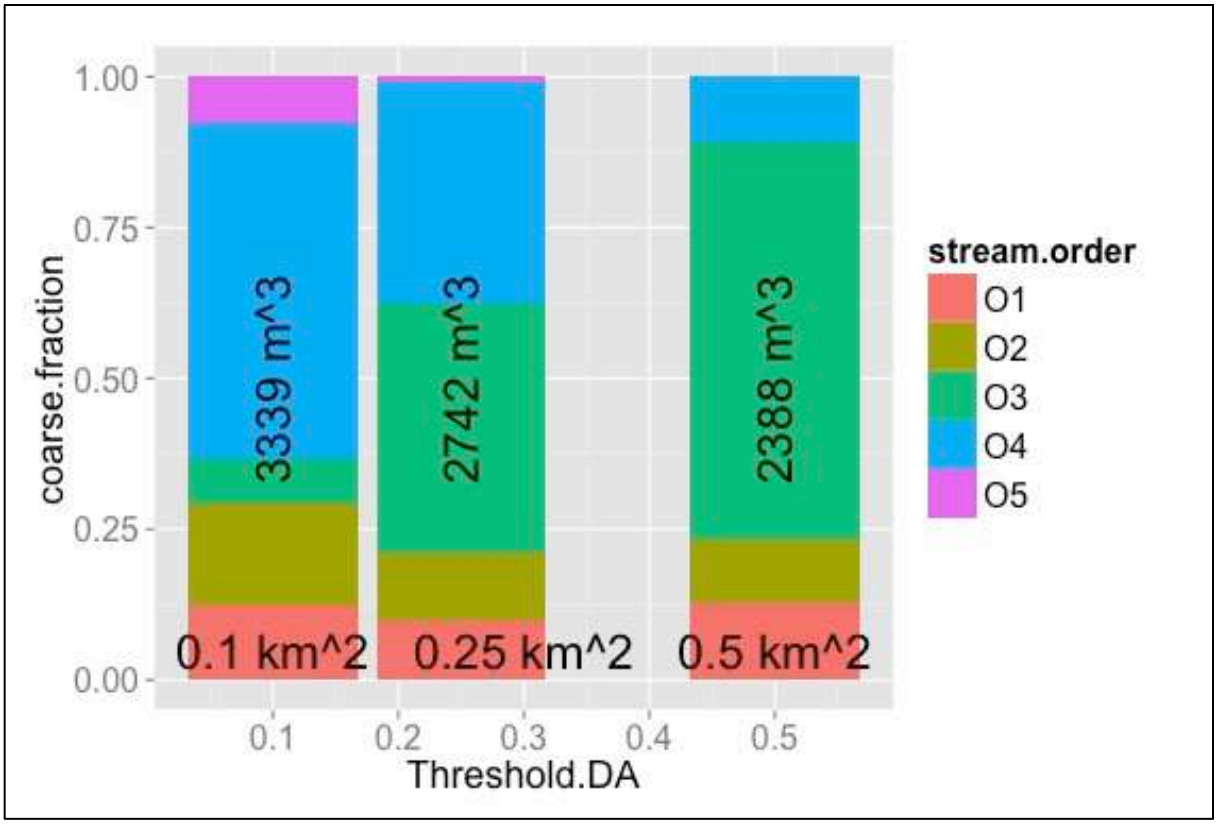


Figure 43. Coarse sediment storage distribution at the network scale. Basin-scale storage estimates (shown on bars) are slightly sensitive to threshold drainage area for channel initiation. Percent differences are 19.6% between 0.1 km^2 and 0.25 km^2, 33.2% between 0.1 km^2 and 0.5 km^2, and 13.8% between 0.25 km^2 and 0.5 km^2. The distribution of coarse sediment is sensitive to these scenarios. Under the 0.1 km^2 scenario, 56% of total coarse sediment storage occurs in fourth-order streams; under 0.25 km^2, 41% occurs in third-order streams; and under 0.5 km^2, 66% of storage is concentrated in third-order streams.

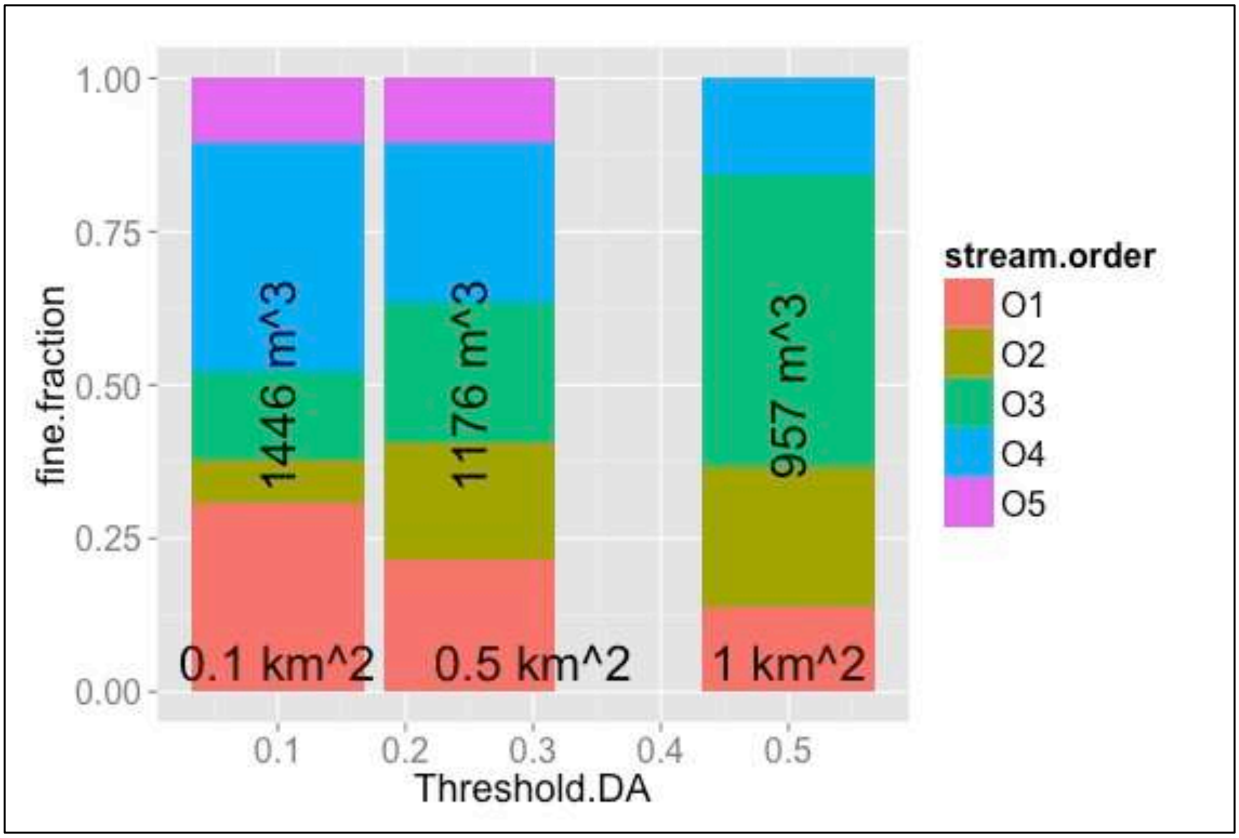


Figure 44. Fine sediment storage distribution at the network scale. The basin-scale storage estimate (shown on bars) is somewhat sensitive to threshold drainage area choice. Percent differences are 20.6% between 0.1 km^2 and 0.25 km^2, 40.7% between 0.1 km^2 and 0.5 km^2, and 20.5% between 0.25 km^2 and 0.5km^2. The distribution of storage is somewhat sensitive to these scenarios. Cumulative storage is highest in fourth-order streams for networks created with 0.1 km^2 and 0.25 km^2 contributing areas (37% and 26% of total storage, respectively). For the 0.5 km^2 scenario, the bulk of storage is in third-order streams (48%).

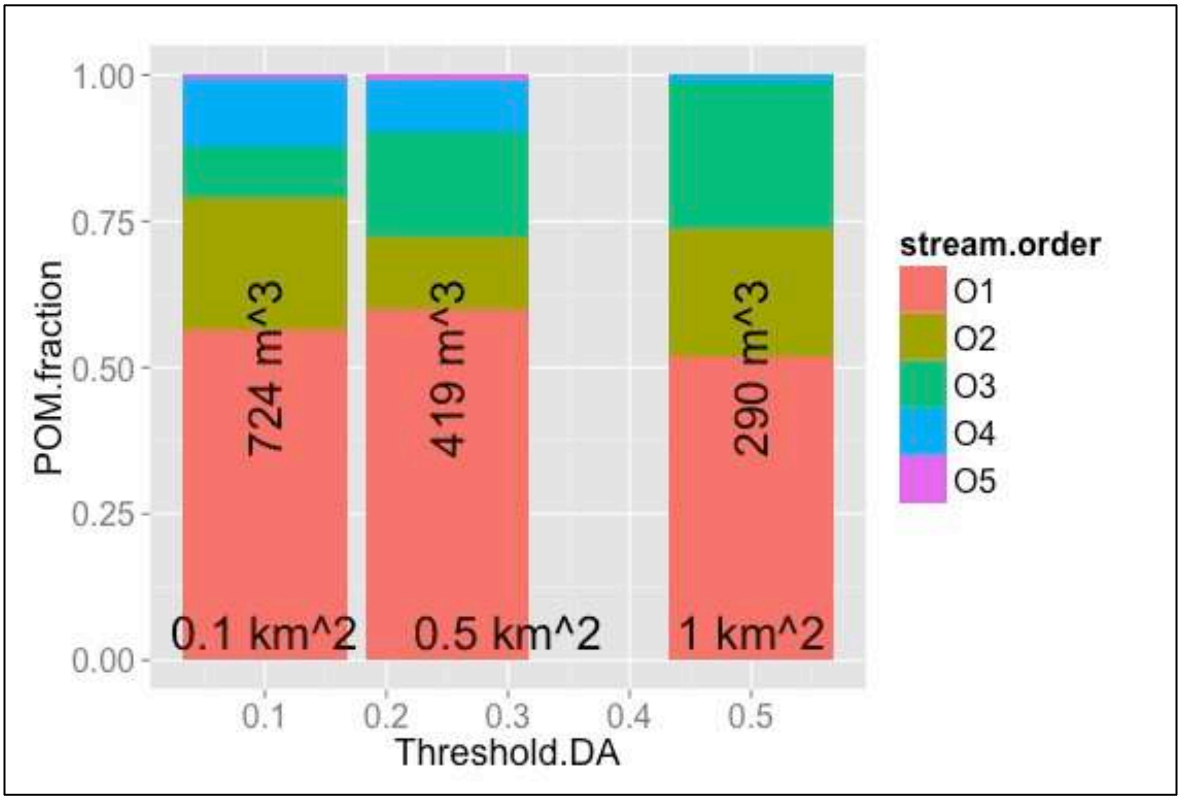


Figure 45. Network-scale distribution of stored POM. The total amount of stored POM in NSV (shown on bars) is sensitive to the choice of contributing area for channel initiation when creating a stream network in ArcGIS. Percent differences are 53.4% between 0.1 km^2 and 0.25 km^2, 85.6% between 0.1 km^2 and 0.5 km^2, and 36.4% between 0.25 km^2 and 0.5 km^2. The distribution of stored POM is also not highly sensitive to these scenarios. Regardless of the contributing area scenario, the majority of POM storage occurs in first-order streams (56%, 60%, 52%, for 0.1 km^2, 0.25 km^2, and 0.5 km^2, respectively).

5. CONCLUSIONS

5.1 Summary

This project investigated controls on wood loads and material (coarse and fine sediment and POM) storage on streams of different sizes flowing through valleys of varying lateral channel confinement with different Montgomery-Buffington bedforms and surrounding riparian forest basal area. Although wood distribution in NSV has been investigated, wood loads in small (first- and second-order streams) and geomorphic effects in both these streams and larger streams (especially in relation to physical channel characteristics and wood piece characteristics) have not been well studied.

Because coarse sediment is less frequently mobilized than fine sediment or POM, a wide range of types of wood and reaches can retain coarse sediment. Wood is therefore the most important control (relative to channel and wood piece characteristics) on coarse sediment retention. Reach-scale fine sediment responds strongly to reach-scale coarse sediment, suggesting the possibility of localized coarse sediment inducing fine sediment retention. However, given fine sediment's mobility, flow properties at a given reach (related to drainage area) and wood's effectiveness relative to channel width are also important in determining the ability of a reach to trap fine sediment. Finally, the POM results suggest that lateral inputs of material should also be considered. Although wood ultimately stores POM, the source and transport of POM (basal area and confinement controlling litterfall transport) appear to be important in determining reach-scale POM storage. This study suggests that total wood load, wood piece characteristics, channel characteristics, and surrounding forest characteristics all contribute to how much material is stored by instream wood. Although some of these factors are more important than others for storage of a given type, none of these factors acts in isolation.

Across all types of material, wood appears to exert control on storage (revealed by direct relationships of wood and material storage or an indirect relationship in which a feature created by wood exerts strong control).

The major contribution of this project to wood and sediment studies is the translation of reach-scale controls to cumulative storage estimates. This component of the thesis indicates where storage hotspots occur and how the magnitude of storage relates to cumulative length of a given stream order in the network. Although the specific factors influencing storage are complex (especially the range of scales controlling fine sediment distribution and storage), different parts of the network display different geomorphic effects related to instream wood. Although comprising only 15% of the stream network, third-order reaches store 41% of total coarse sediment and 34% of total wood. Fourth-order streams are the largest cumulative zones of fine sediment storage, retaining 26% of the total estimate in 8% of the total stream length. However, fine sediment storage is balanced, with first-, second-, and third-order streams also contributing appreciably to overall fine sediment storage. First-order streams are the largest contributors to total POM storage, retaining an estimated 60% of total stored POM in 46% of the stream network.

Jam-scale results were inconclusive, as retention of POM and fine and coarse sediment was correlated to neither porosity nor permeability. Material storage was moderately related to jam volume. However, there is not clear evidence for progressively finer material (POM) being more strongly affected by jam volume. The lack of results on the jam scale may indicate that transport, deposition, and retention are related to factors beyond a single jam, such as total wood load and drainage-scale transport of wood and sediment. In the case of POM, lateral valley bottom litterfall inputs may better determine the amount of POM behind a jam than the size of the obstructing jam. Essentially, a jam does not act in isolation. However, the nature of the study may have also precluded effective jam-scale analysis. Because I sought to characterize a high number of study reaches, I did not intensively survey jam dimensions, as did Beckman (2013) and Livers (2016). Although my targeting of the largest pieces and calculating overall jam dimensions appeared to work on a reach-scale, this strategy may have inadequately characterized jam volume in relation to sediment retention behind a single jam.

5.2 Limitations

The conclusions of this work are limited by a few key factors. I was aware of such limitations going into the field season and into this analysis, but it is worth stating where results may not be broadly applicable. Overall, the methods I used were simple and quick. Because I sought to characterize many study reaches, variables such as gradient and lateral channel confinement were measured with a laser rangefinder. This method sacrifices some detail in measuring physical channel characteristics. Wood load was also quickly assessed, especially with respect to jams. By making simplifying volume assumptions and measuring the ten or so biggest pieces in a jam, wood load estimates are a minimum. This may explain why jam scale analysis did not yield any sort of trend with respect to material stored by a single jam. When measuring sediment volumes, pebble counts were not performed and grain size distributions not assessed. Coarse and fine are relative terms. This could potentially prevent interpretation of relative sediment mobility, especially sediment at the sand-gravel transition. Delineating the extent of stored sediment and whether sediment was stored by wood (or was just bed material surrounding a piece of wood) sometimes proved difficult, especially in small streams. Despite these difficulties, the study effectively captured the key elements of different types of channels. Gradient was calculated with sufficient accuracy to represent differences between cascade, step-pool, plane-bed, and pool-riffle sequences, whereas wood load was assessed in a way that fairly represented the amount of wood in different channel types.

Another key limitation of this study is its snapshot style of analysis. Because fieldwork was conducted over the course of a summer, I do not attempt to estimate the duration of storage. In first-order streams, especially, the turnover of stored POM is not clear. This study is not able to disentangle whether POM accumulates and mobilizes on annual scales or whether storage and replenishment occur on longer time scales. Coarse sediment is more stable but likely also has cyclical turnover. For 12 of my reaches, I used wood and POM data from sites from Livers (2016). I operated on the assumption that wood loads and POM were consistent between reaches on this timescale, given that all data I used were taken after the 2013 floods. This obviously has the potential to introduce error given the geomorphically dynamic nature of rivers, especially with respect to wood and POM transport. The largest logjams appeared stable in this time frame and I expect that reach-scale wood loads were relatively consistent. POM is a trickier issue; because of its transient, highly mobile nature, POM results should be taken with caution. Moreover, I try not to make broad statements of carbon cycle implications tied to POM results, as I did not sample carbon content. The volume of POM stored by wood has ecological implications, but I refrain from making estimates and positing implications due to the nature of my study.

Finally, using stream order to scale up results to a drainage basin estimate of storage may not be a broadly applicable technique. Stream order varies with drainage area differently in rectangular, parallel, or trellis stream networks than in the dendritic North Saint Vrain. Essentially, stream order is a proxy for drainage area (which drives changes in wood and sediment storage); this metric may not scale as well with drainage area in other types of basins. Therefore, this type of analysis may be most applicable to dendritic networks.

5.3 Management implications and recommendations for future work

I restrict the following management implications to snowmelt-dominated streams in the Southern Rockies, as instream wood processes vary between climatic and hydrologic regimes. Wood obviously plays an important role in sediment retention; this effect is cumulatively highest in third-order streams. High cumulative sediment storage effects can be achieved by retaining large logjams and closely spaced individual pieces. Although storage is lower on high gradient cascade reaches, wood can still exert strong geomorphic effects on steep sections, especially in the case of sediment storage. Fine sediment is more dependent on wood piece characteristics (such as spacing and average piece length/average channel width) than on overall wood load. Even with this, a high wood load appears to play a strong underlying role in all types of storage. Therefore, wood recruitment processes should not be interrupted or altered, especially near third-order streams. Recruitment appears effective in a range of forest ages and types (therefore, although old-growth forest should be prioritized, disturbances such as fire and insect outbreaks can be important sources of wood to the channel). Most importantly, floodplain decay and wood buildup should be allowed to occur naturally, as this is an important input of wood to the stream. If anything, this project reveals the importance of first-order streams. Because lateral roots in first-order streams are such an important POM storage mechanism, protecting these streams from development and incursions is extremely important. Although this is not an issue within Rocky Mountain National Park, small Front Range streams on US Forest Service and other land should be protected from road building and extensive backcountry campsite use. When trees are cleared for backcountry sites, the removal of a litterfall input source and lateral root storage mechanism might impact downstream transport of POM and catchment-scale carbon cycling.

Future work on wood and sediment in NSV could build upon this research by looking at these processes over multiple years. A longer-term study on which reaches retain the most wood and material associated with wood would be useful in a changing, more variable climate. Understanding how wood transport, storage, and wood's geomorphic effectiveness change with smaller snowpack, earlier snowmelt, increased fire frequency and severity, and future insect outbreaks would be important in predicting water resources and sediment budgets both within the catchment and downstream. This project especially highlighted the difficulty of jam-scale analysis. There is some relationship between a jam's "leakiness" and how much material it stores, but a quick method for accurately assessing porosity and permeability remains elusive. Better understanding of these variables could be important in implementing and engineering logjams in restoration efforts.

The ability of this research to translate to other types of river systems is not completely clear. Therefore, similar reach and basin-scale analyses should be conducted in non-snowmelt dominated systems in a range of different forest types and drainage network shapes. The development of a comprehensive dataset that identifies hotspots of sediment storage would be very useful for management and wood-based restoration in a range of settings. It is especially important that future efforts at least roughly differentiate between stored fine and coarse sediment. Given fine sediment's impacts as a pollutant, separating fine and coarse sediment is useful in understanding how different watersheds store fine sediment and buffer downstream accumulation of high concentrations of fine sediment.

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7. APPENDIX

A. Table of study reaches. Orange reaches were at drainage areas too small for detection in USGS StreamStats and were not included in the analysis. Green reaches were removed from analysis due to visible geomorphological alteration from the 2013 floods or due to their position at low elevations/different forest types (section 5.1). Fine sediment data were not collected at reaches highlighted with pink.

Name	Type	GPS coordinates	Drainage area (km^2)	MB cat
Fisher	NSV trib	40.202452, 105.579159	0.00	PB
Cloud	NSV trib	40.223562, 105.644598	0.00	SP
Chipmunk	NSV trib	40.216953, 105.638896	0.00	*NA
Delaware	Hunter's trib	40.226468, 105.592408	0.10	PB
Badger	Cony trib	40.176517, 105.605396	0.11	PB
Diorite	Rock Creek trib	40.202021, 105.485915	0.12	C
Gibcat	NSV trib	40.202021, 105.485915	0.14	PR
Otter	Cony trib	40.16026, 105.53862	0.18	PB
Granite	Rock Creek Trib	40.178177, 105.602578	0.18	SP
Tiger	NSV trib	40.210216, 105.619136	0.23	C
Squirrel	Cony trib	40.183391, 105.594817	0.26	SP
Red Fox	Fox Creek trib	40.195958, 105.549147	0.26	SP
Hungry Rancher	Cabin trib	40.227421, 105.486750	0.29	SP
Shale	Rock Creek Trib	40.20150, 105.48621	0.29	PB
Jockey	Horse Creek Trib	40.226393, 105.467703	0.31	SP
Cabin Creek trib	trib	40.237761, 105.562700	0.31	C
Illinois	Hunter's trib	40.219506, 105.588575	0.47	PB
Snowshoe Hare	NSV trib	40.196537, 105.577082	0.52	C
Ermine	Cony trib	40.183347, 105.597186	0.54	PB
Maine	Hunter's trib	40.229760, 105.600403	0.78	C
Screech Owl	Ouzel trib	40.200866, 105.612922	0.86	SP

Marten	NSV trib	40.196537, 105.578655	1.24	C
Long's	Cabin Trib	40.236350, 105.493705	1.53	SP
Lynx	NSV trib	40.212430, 105.622775	1.87	SP
Serval	NSV trib	40.197317, 105.595556	2.05	C
Barbaro	Horse Creek main	40.238429, 105.546111	2.13	PB
Willow	main	40.189028, 105.541578	2.20	SP
Rhode Island	Camper's creek	40.218589, 105.573663	2.23	SP
Muskrat	Cony trib	40.177162, 105.603963	2.26	SP
Thundercat	NSV trib	40.222749, 105.640266	3.19	PB
Lightning	NSV main	40.219819, 105.639914	3.24	C
Gneiss	Rock Creek main	40.161074, 105.541463	3.34	SP
Wolf	Sandbeach	40.202498, 105.579192	3.53	PR
Pika	Cony trib	40.184282, 105.586568	3.60	PR
Sandstone	Rock Creek trib	40.171914, 105.529604	3.76	PB
Storm	NSV trib	40.220863, 105.637217	3.91	SP
Mink	Cony Trib	40.190716, 105.590693	4.12	C
Mertensia	NSV trib	40.213904, 105.637297	4.46	SP
Andesite	Rock creek main	40.173324, 105.525866	7.05	SP
Massachusetts	Hunter's main?	40.228961, 105.600012	8.27	PB
Thunder	NSV main	40.218096, 105.638945	9.18	C
Hunt C	Hunt main	40.222025, 105.591626	9.67	SP
Ouzel U	Ouzel main	40.20014, 105.62627	10.21	SP
Hunt U	Hunt main	40.220011, 105.588721	10.60	PB
Ouzel b	Ouzel main	40.202970, 105.617914	11.20	PB
Pennsylvania	Cony main	40.179106, 105.600299	12.44	SP
Ouzel A	Ouzel main	40.200276, 105.605740	12.73	PB
Ouzel C	Ouzel main	40.199612, 105.60274	12.96	CC
Cony U	Cony main	40.182634, 105.596631	13.09	PB
Ouzel below bridge	main	40.200321, 105.597638	13.19	SP
Idaho	Cony main	40.184177, 105.595432	13.48	PB
NSV highest	main	40.21397, 105.63716	13.97	SP
Cony C	main	40.190983, 105.591654	14.13	C
NSV hst-high	main	40.212387, 105.635603	14.26	PB
NSV High	main	40.21018, 105.63180	14.65	SP

Cony High	main	40.196874, 105.590419	18.40	SP
NSV L	main	40.20683, 105.61285	18.64	SP
Gray's	NSV main	40.206079, 105.610170	19.03	PB
Torrey's	NSV main	40.203022, 105.607633	19.49	SP
NSV PC	main	40.198353, 105.593287	34.22	C
Yukon	N fk BT	40.488119, 105.501527	36.29	SP
Alaska	N fk BT	40.472716, 105.465297	45.10	PB
NSV CCC	main	40.226188, 105.486714	56.25	SP
Cabin creek main	main	40.200749, 105.583378	56.25	SP
NSV above lot	main	40.206499, 105.567830	64.54	PB
NSV below lot	main	40.209128, 105.560423	77.24	PR
Beaver Meadow	NSV main	40.211054, 105.552433	81.65	PR
Bright	NSV main	40.21507, 105.45619	199.07	PB

Name	**gradient (deg)**	**VW/CW**	**confinement**	**basal area (m^2/ha)**	**reach length (m)**	**avg channel width (m)**
Fisher	0.40	3.70	PC	6.89	10.00	0.87
Cloud	5.10	4.54	PC	13.78	12.70	1.27
Chipmunk	14.50	1.00	C	25.25	10.00	0.66
Delaware	3.50	4.82	PC	4.59	10.00	0.75
Badger	1.10	5.37	PC	11.48	10.30	1.03
Diorite	17.80	1.00	C	0.00	13.00	1.30
Gibcat	0.40	1.52	C	6.89	10.60	1.06
Otter	1.70	8.33	U	16.07	10.00	0.50
Granite	7.20	17.20	U	22.96	13.00	1.30
Tiger	12.00	1.00	C	16.07	11.40	1.14
Squirrel	2.50	10.70	U	6.89	17.00	1.70
Red Fox	7.20	1.00	C	13.78	10.00	0.78
Hungry Rancher	3.60	1.00	C	0.00	13.00	1.30
Shale	4.10	1.00	C	4.59	14.70	1.47
Jockey	8.00	1.00	C	2.30	12.00	1.20

Cabin Creek trib	18.50	1.00	C	9.18	12.50	1.25
Illinois	1.50	14.60	U	11.48	16.60	1.66
Snowshoe Hare	33.60	1.00	C	4.59	10.00	0.75
Ermine	2.30	21.70	U	2.30	17.20	1.72
Maine	11.20	1.00	C	2.30	10.00	0.78
Screech Owl	3.50	3.75	PC	0.00	16.00	1.60
Marten	11.80	1.00	C	20.66	10.00	1.03
Long's	3.90	4.65	PC	9.18	23.00	2.30
Lynx	6.00	6.40	PC	22.96	20.00	2.00
Serval	16.10	1.00	C	2.30	15.00	1.50
Barbaro	2.60	1.86	C	6.89	19.00	1.90
Willow	5.20	5.80	PC	16.07	19.00	1.90
Rhode Island	3.50	40.00	U	13.78	60.00	1.19
Muskrat	4.20	1.00	C	18.37	12.30	1.23
Thundercat	1.30	3.74	PC	18.37	20.30	2.03
Lightning	8.10	7.10	PC	18.94	130.00	3.50
Gneiss	5.20	3.32	PC	11.48	21.30	2.13
Wolf	0.20	1.00	C	0.00	10.00	0.95
Pika	0.50	23.00	U	18.37	20.00	2.00
Sandstone	4.20	4.17	PC	6.89	20.70	2.07
Storm	2.20	2.53	PC	11.48	27.30	2.73
Mink	7.70	4.77	PC	18.37	20.00	2.00
Mertensia	3.00	1.00	C	22.96	66.00	3.30
Andesite	2.35	4.13	PC	10.33	32.00	3.20
Massachusetts	3.00	115.00	U	0.00	10.80	1.08
Thunder	7.70	1.90	C	19.51	50.10	5.01
Hunt C	5.00	4.00	PC	0.00	124.00	6.20
Ouzel U	2.87	12.50	U	12.63	195.00	6.50
Hunt U	2.20	6.50	PC	0.00	51.30	5.13
Ouzel b	1.53	13.00	U	6.20	200.00	4.40
Pennsylvania	3.63	3.34	PC	15.50	65.00	6.50
Ouzel A	3.05	9.40	U	1.15	60.30	6.03
Ouzel C	1.72	5.54	PC	0.00	55.00	5.50
Cony U	0.80	*	PC	12.63	75.00	7.50

Ouzel below bridge	3.73	6.80	PC	11.48	115.00	6.80
Idaho	1.60	3.50	PC	13.20	72.50	7.25
NSV highest	3.40	*	U	*	150.00	7.50
Cony C	6.30	2.63	PC	16.07	70.00	7.00
NSV hst-high	1.55	13.37	U	13.20	75.00	7.50
NSV High	3.40	*	U	5.05	500.00	6.80
Cony High	2.30	5.65	PC	0.00	130.00	5.04
NSV L	1.72	*	U	9.18	120.00	6.00
Gray's	2.20	5.85	PC	9.18	78.50	7.85
Torrey's	3.33	2.22	PC	7.46	71.50	7.15
NSV PC	4.35	2.94	PC	10.33	67.00	6.70
Yukon	3.60	3.55	PC	7.46	80.00	8.00
Alaska	3.50	6.24	PC	2.30	70.00	7.00
NSV CCC	1.78	3.30	PC	4.59	115.00	11.50
Cabin creek main	2.00	5.26	PC	5.74	113.00	11.30
NSV above lot	0.70	51.00	U	15.15	125.00	12.50
NSV below lot	0.90	3.34	PC	10.33	112.50	11.25
Beaver Meadow	0.63	5.24	PC	16.07	115.00	11.50
Bright	0.93	2.05	PC	3.06	186.00	18.60

Name	wood load (m^3)	unit wood load (m^3/m)	wood/area(m^3/m^2)	coarse (m^3)	unit coarse (m^3/m)	coarse/area (m^3/m^2)
Fisher	0.01	0.00	0.00	0.00	0.00	0.00
Cloud	0.16	0.01	0.01	1.86	0.15	0.12
Chipmunk	0.06	0.01	0.01	0.00	0.00	0.00
Delaware	0.05	0.01	0.01	0.00	0.00	0.00
Badger	0.06	0.01	0.01	0.09	0.01	0.02
Diorite	0.20	0.02	0.01	0.11	0.01	0.01
Gibcat	0.08	0.01	0.01	0.00	0.00	0.00
Otter	0.03	0.00	0.01	0.00	0.00	0.00
Granite	0.28	0.02	0.02	0.03	0.00	0.00
Tiger	0.02	0.00	0.00	0.00	0.00	0.00
Squirrel	0.23	0.01	0.01	0.00	0.00	0.00
Red Fox	0.03	0.00	0.00	0.00	0.00	0.00
Hungry Rancher	0.02	0.00	0.00	0.00	0.00	0.00

Shale	0.01	0.00	0.00	0.00	0.00	0.00
Jockey	0.32	0.03	0.02	0.01	0.00	0.00
Cabin Creek trib	0.05	0.00	0.00	0.04	0.00	0.00
Illinois	0.10	0.01	0.00	0.00	0.00	0.00
Snowshoe Hare	0.08	0.01	0.01	0.00	0.00	0.00
Ermine	0.14	0.01	0.00	0.00	0.00	0.00
Maine	0.01	0.00	0.00	0.00	0.00	0.00
Screech Owl	1.04	0.07	0.04	0.09	0.01	0.01
Marten	0.20	0.02	0.02	0.00	0.00	0.00
Long's	0.18	0.01	0.00	0.00	0.00	0.00
Lynx	0.71	0.04	0.02	0.43	0.02	0.02
Serval	1.42	0.09	0.06	0.89	0.06	0.08
Barbaro	0.24	0.01	0.01	0.00	0.00	0.00
Willow	0.14	0.01	0.00	0.00	0.00	0.00
Rhode Island	0.43	0.01	0.01	0.04	0.00	0.00
Muskrat	0.26	0.02	0.02	0.36	0.03	0.05
Thundercat	0.15	0.01	0.00	0.19	0.01	0.01
Lightning	3.56	0.03	0.01	1.62	0.01	0.01
Gneiss	0.28	0.01	0.01	0.06	0.00	0.00
Wolf	0.02	0.00	0.00	0.00	0.00	0.00
Pika	0.39	0.02	0.01	0.12	0.01	0.01
Sandstone	0.27	0.01	0.01	0.45	0.02	0.02
Storm	1.46	0.05	0.02	0.21	0.01	0.01
Mink	0.47	0.02	0.01	0.26	0.01	0.01
Mertensia	3.90	0.06	0.02	3.19	0.05	0.03
Andesite	1.84	0.06	0.02	0.87	0.03	0.02
Massachusetts	0.14	0.01	0.01	0.08	0.01	0.01
Thunder	1.94	0.04	0.01	0.00	0.00	0.00
Hunt C	12.30	0.10	0.02	3.16	0.03	0.01
Ouzel U	14.62	0.07	0.01	5.72	0.03	0.01
Hunt U	3.59	0.07	0.01	2.52	0.05	0.02
Ouzel b	32.38	0.16	0.04	3.48	0.02	0.01
Pennsylvania	6.28	0.10	0.01	41.44	0.64	0.20
Ouzel A	11.94	0.20	0.03	17.28	0.29	0.10
Ouzel C	8.42	0.15	0.03	2.18	0.04	0.01
Cony U	9.92	0.13	0.02	4.04	0.05	0.01
Ouzel below bridge	7.89	0.07	0.01	34.46	0.30	0.09
Idaho	6.64	0.09	0.01	6.81	0.09	0.03
NSV highest	11.27	0.08	0.01	4.82	0.03	0.01

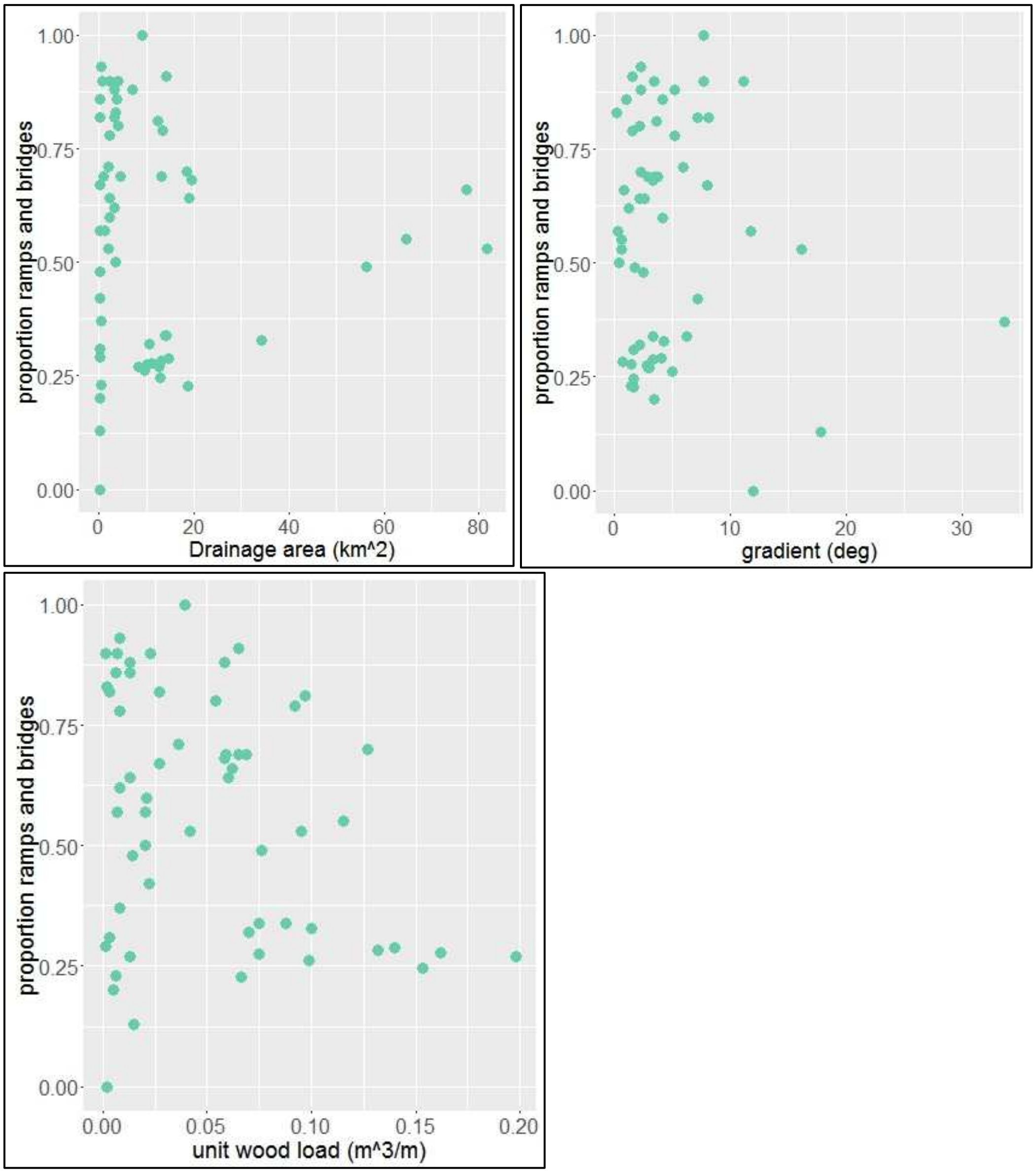
Cony C	6.19	0.09	0.01	18.33	0.26	0.07
NSV hst-high	4.86	0.06	0.01	0.55	0.01	0.00
NSV High	69.90	0.14	0.02	74.59	0.15	0.04
Cony High	16.57	0.13	0.03	28.43	0.22	0.09
NSV L	7.87	0.07	0.01	7.64	0.06	0.02
Gray's	4.71	0.06	0.01	5.49	0.07	0.02
Torrey's	4.12	0.06	0.01	4.40	0.06	0.02
NSV PC	6.67	0.10	0.01	11.05	0.16	0.05
Yukon	1.08	0.01	0.00	0.00	0.00	0.00
Alaska	1.91	0.03	0.00	0.01	0.00	0.00
NSV CCC	8.69	0.08	0.01	0.00	0.00	0.00
Cabin creek main	2.11	0.02	0.00	0.00	0.00	0.00
NSV above lot	14.33	0.11	0.01	1.80	0.01	0.00
NSV below lot	7.03	0.06	0.01	0.49	0.00	0.00
Beaver Meadow	4.82	0.04	0.00	0.00	0.00	0.00
Bright	4.74	0.03	0.00	0.00	0.00	0.00

Name	**fine (m^3)**	**unit fine (m^3/m)**	**fine/area(m^3/m^2)**	**pom (m^3)**	**unit pom (m^3/m)**	**pom/area (m^3/m^2)**
Fisher	0.00	0.00	0.00	0.01	0.00	0.00
Cloud	0.00	0.00	0.00	0.00	0.00	0.00
Chipmunk	0.00	0.00	0.00	0.01	0.00	0.00
Delaware	0.01	0.00	0.00	0.00	0.00	0.00
Badger	0.00	0.00	0.00	0.00	0.00	0.00
Diorite	0.00	0.00	0.00	0.00	0.00	0.00
Gibcat	0.00	0.00	0.00	0.02	0.00	0.00
Otter	0.02	0.00	0.00	0.05	0.01	0.00
Granite	0.04	0.00	0.00	0.01	0.00	0.00
Tiger	0.00	0.00	0.00	0.01	0.00	0.00
Squirrel	0.00	0.00	0.00	0.10	0.01	0.00
Red Fox	0.02	0.00	0.00	0.00	0.00	0.00
Hungry Rancher	0.00	0.00	0.00	0.00	0.00	0.00
Shale	0.00	0.00	0.00	0.01	0.00	0.00
Jockey	0.00	0.00	0.00	0.00	0.00	0.00
Cabin Creek trib	0.00	0.00	0.00	0.00	0.00	0.00
Illinois	0.00	0.00	0.00	0.17	0.01	0.00
Snowshoe Hare	0.01	0.00	0.00	0.00	0.00	0.00
Ermine	0.12	0.01	0.00	0.02	0.00	0.00
Maine	0.00	0.00	0.00	0.00	0.00	0.00

Screech Owl	0.00	0.00	0.00	0.00	0.00	0.00
Marten	0.11	0.01	0.01	0.03	0.00	0.00
Long's	0.25	0.01	0.00	0.01	0.00	0.00
Lynx	0.30	0.01	0.01	0.37	0.02	0.00
Serval	0.00	0.00	0.00	0.07	0.00	0.00
Barbaro	0.03	0.00	0.00	0.00	0.00	0.00
Willow	0.00	0.00	0.00	0.00	0.00	0.00
Rhode Island	0.28	0.00	0.00	0.22	0.00	0.00
Muskrat	0.22	0.02	0.01	0.13	0.01	0.00
Thundercat	0.01	0.00	0.00	0.03	0.00	0.00
Lightning	0.09	0.00	0.00	0.01	0.00	0.00
Gneiss	0.06	0.00	0.00	0.00	0.00	0.00
Wolf	0.09	0.01	0.01	0.02	0.00	0.00
Pika	1.10	0.05	0.03	0.05	0.00	0.00
Sandstone	0.02	0.00	0.00	0.00	0.00	0.00
Storm	0.00	0.00	0.00	0.00	0.00	0.00
Mink	0.00	0.00	0.00	0.00	0.00	0.00
Mertensia	0.82	0.01	0.00	1.08	0.02	0.00
Andesite	1.12	0.04	0.01	0.00	0.00	0.00
Massachusetts	0.07	0.01	0.01	0.00	0.00	0.00
Thunder	0.00	0.00	0.00	0.00	0.00	0.00
Hunt C				0.09	0.00	0.00
Ouzel U	1.39	0.01	0.00	0.80	0.00	0.00
Hunt U				0.05	0.00	0.00
Ouzel b	7.69	0.04	0.01	1.23	0.01	0.00
Pennsylvania	0.99	0.02	0.00	0.04	0.00	0.00
Ouzel A	5.93	0.10	0.02	0.67	0.01	0.00
Ouzel C	0.17	0.00	0.00	0.02	0.00	0.00
Cony U	3.84	0.05	0.01	0.63	0.01	0.00
Ouzel below bridge	3.62	0.03	0.00	1.55	0.01	0.00
Idaho	1.09	0.02	0.00	0.04	0.00	0.00
NSV highest				0.50	0.00	0.00
Cony C	6.77	0.10	0.01	0.00	0.00	0.00
NSV hst-high	0.04	0.00	0.00	0.12	0.00	0.00
NSV High	2.66	0.01	0.00	5.77	0.01	0.00
Cony High	13.03	0.10	0.02	0.30	0.00	0.00
NSV L	7.57	0.06	0.01	1.85	0.02	0.00
Gray's	0.58	0.01	0.00	0.12	0.00	0.00
Torrey's	0.09	0.00	0.00	0.24	0.00	0.00

NSV PC	2.18	0.03	0.00	0.06	0.00	0.00
Yukon	0.00	0.00	0.00	0.00	0.00	0.00
Alaska	0.00	0.00	0.00	0.00	0.00	0.00
NSV CCC	0.97	0.01	0.00	0.10	0.00	0.00
Cabin creek main	0.00	0.00	0.00	0.00	0.00	0.00
NSV above lot	3.32	0.03	0.00	0.00	0.00	0.00
NSV below lot	4.34	0.04	0.00	0.08	0.00	0.00
Beaver Meadow	0.13	0.00	0.00	0.00	0.00	0.00
Bright	0.00	0.00	0.00	0.00	0.00	0.00

B. Proportion of ramps and bridges versus potential controls (section 4.2)



C. Removal of coarse sediment as predictor in fine sediment and POM multiple regressions (section 4.4.1, 4.5.1)

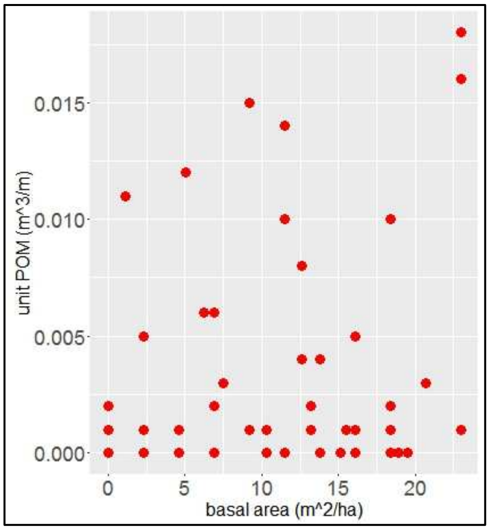
Fine sediment multiple regression after removal of coarse sediment as a predictor. The best model only includes wood load (positive coefficient) as a predictor (R^2=0.49). R^2=0.56 for the model with all possible predictors

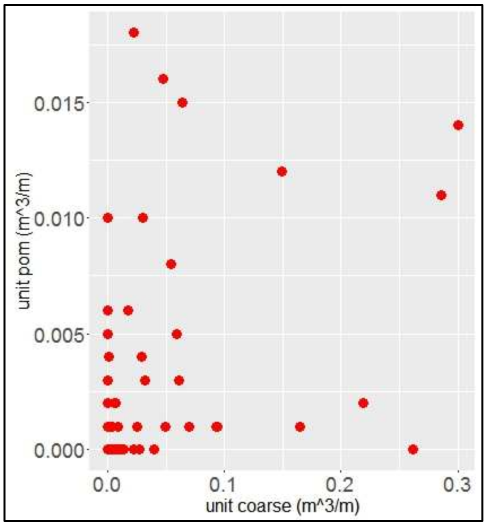
Variable	**Importance**
sqrt unit wood load	0.69
sqrt drainage area	0.58
sqrt spacing	0.55
sqrt D_{50}	0.48
proportion ramps and bridges (count)	0.43
sqrt gradient	0.42
sqrt (average piece length/average channel width)	0.37
proportion jammed (volume)	0.37
sqrt basal area	0.28
confinement (C, PC, U)	0.11
MB category (SP, PB, PR, C)	0.09

POM multiple regression after removal of coarse sediment as a predictor. The best model includes confinement, basal area (positive coefficient), spacing (negative coefficient), and wood load (positive coefficient) (R^2=0.31). R^2=0.45 for the model with all possible predictors.

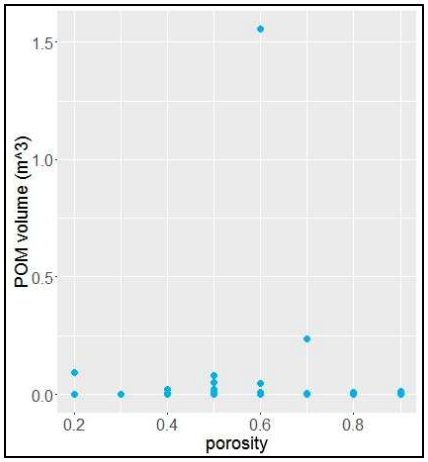
Variable	**Importance**
sqrt BA	0.75
sqrt spacing	0.58
confinement (C, PC, U)	0.56
sqrt unit wood load	0.50
sqrt unit fine	0.47
proportion jammed (volume)	0.43
sqrt gradient	0.42
proportion ramps and bridges (count)	0.39
sqrt drainage area	0.34
sqrt D50	0.29
sqrt (average piece length/average channel width)	0.23
MB category (SP, PR, PB, C)	0.16

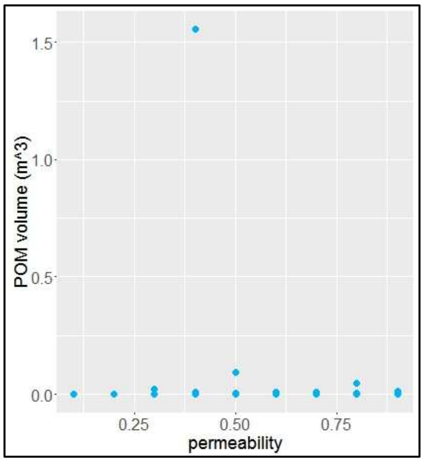
C. POM versus secondary predictors (section 4.5.1)

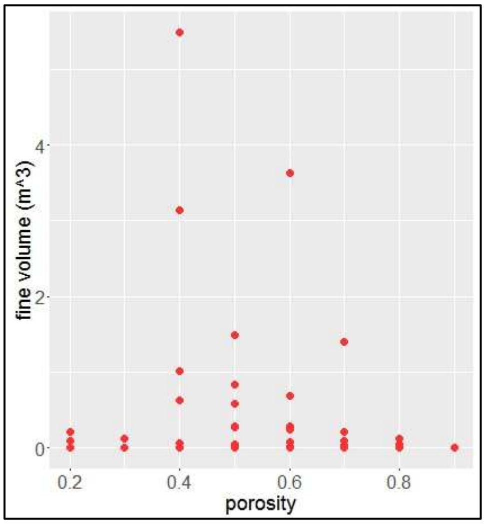


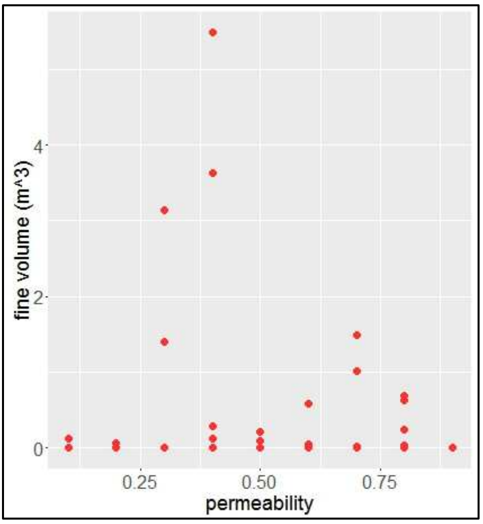


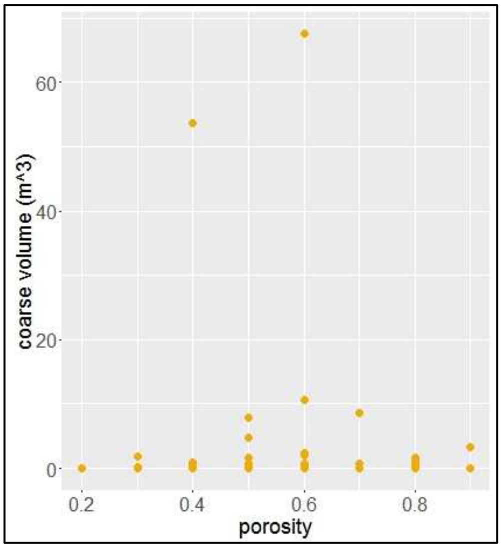
D. Jam-scale material storage versus estimated porosity and permeability (section 4.6.1)

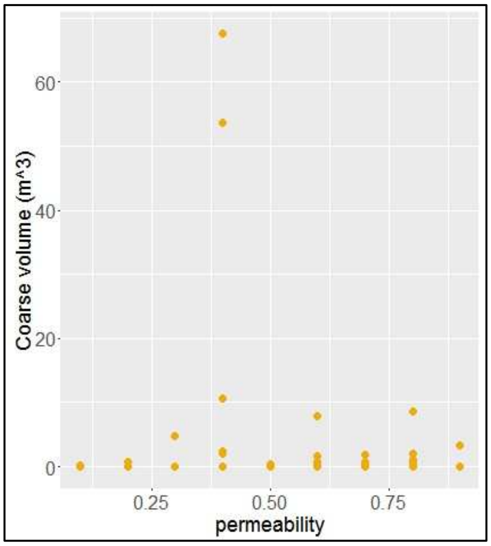




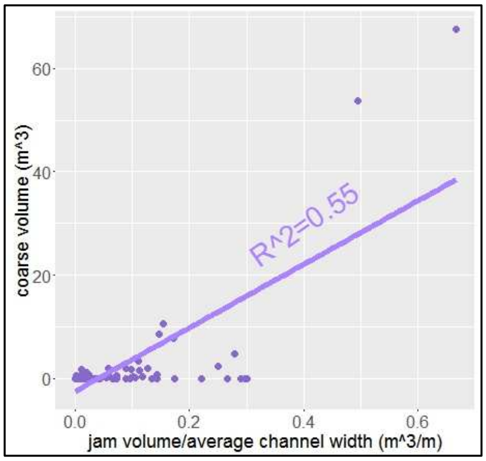


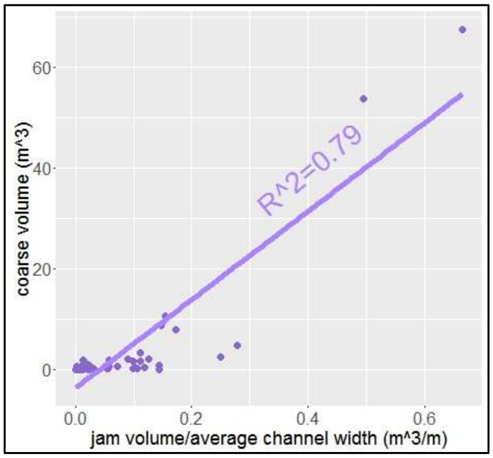


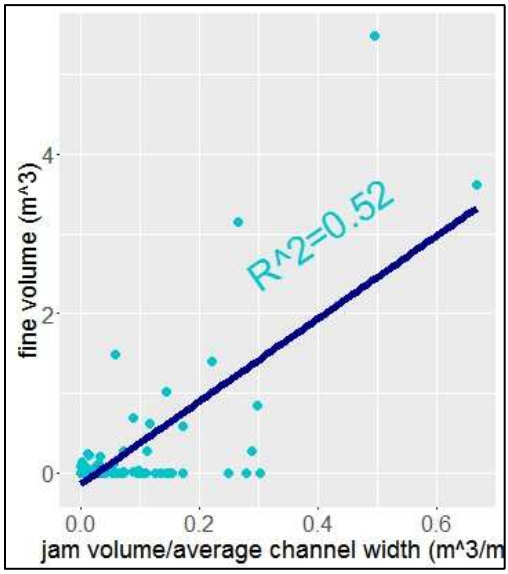


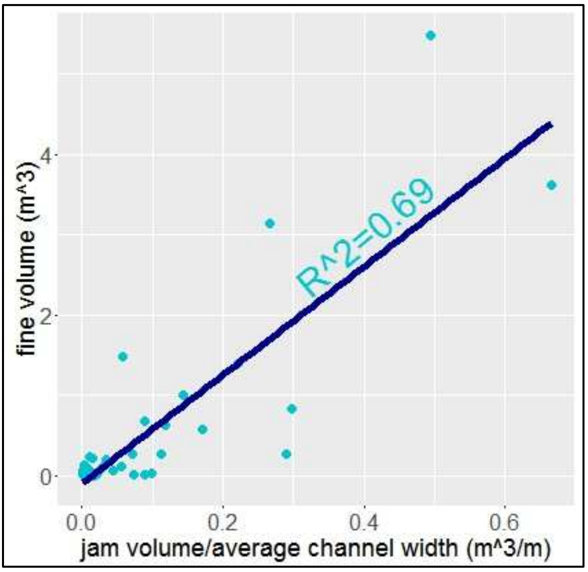


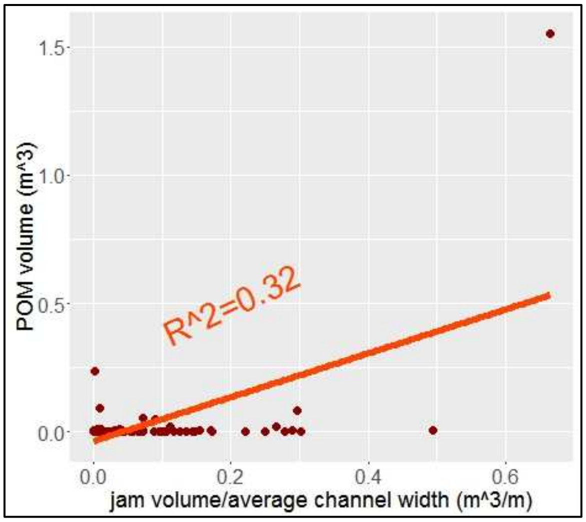
E. Results for 4.6.1 (jam-scale analysis) before removal of outliers. The highest two values were removed for coarse, the highest three for fine, and the highest for POM. There were outliers and extreme outliers outside of these removed data points, but these were not removed because they would reduce the sample size greatly and because jam storage can be highly variable (i.e. both high and low storage are physically reasonable).

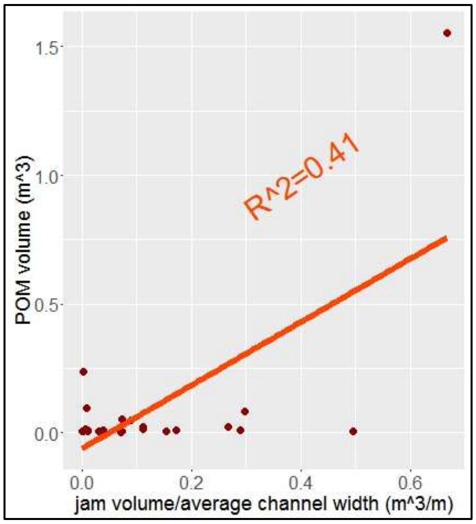

R^2=0.55
coarse volume (m^3)
60
40
20
0
0.0
0.2
0.4
0.6
jam volume/average channel width (m^3/m)


R^2=0.79
coarse volume (m^3)
60
40
20
0
0.0
0.2
0.4
0.6
jam volume/average channel width (m^3/m)

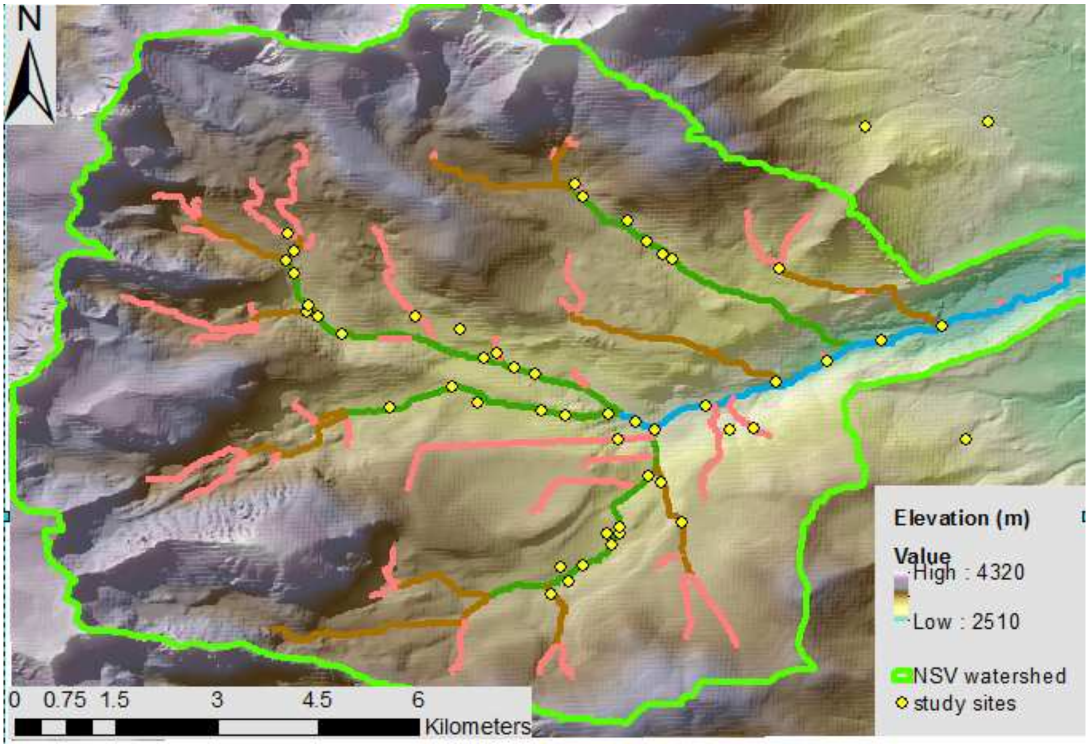

R^2=0.52
fine volume (m^3)
4
2
0
0.0
0.2
0.4
0.6
jam volume/average channel width (m^3/m


R^2=0.69
fine volume (m^3)
4
2
0
0.0
0.2
0.4
0.6
jam volume/average channel width (m^3/m)



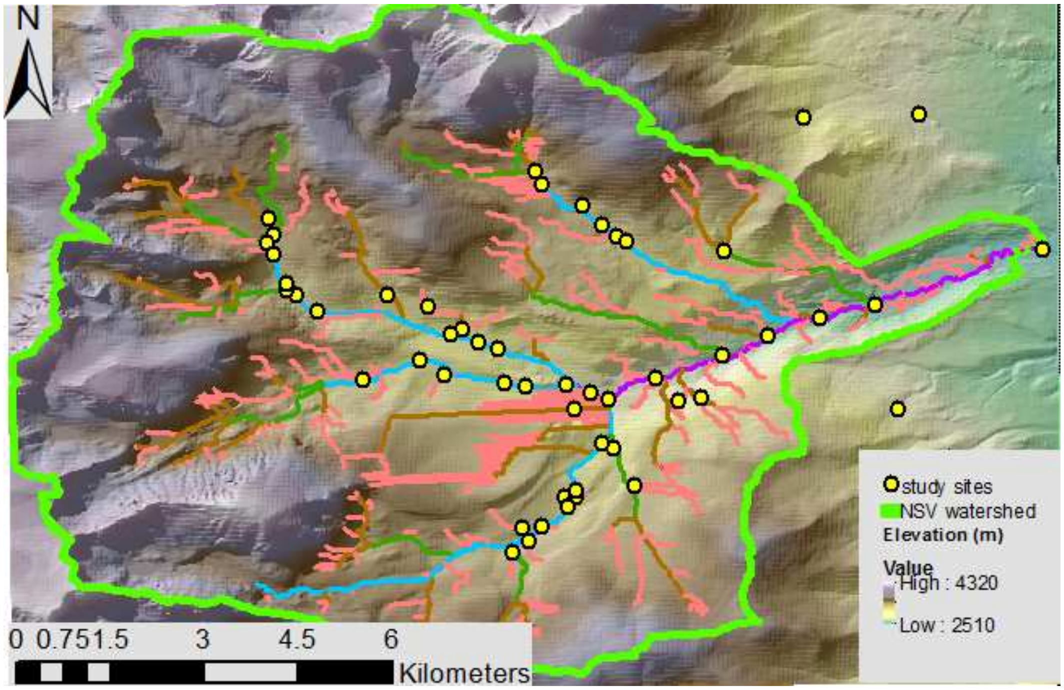


F. Maps excluded from 4.7.2 and used in sensitivity analysis (4.7.3)



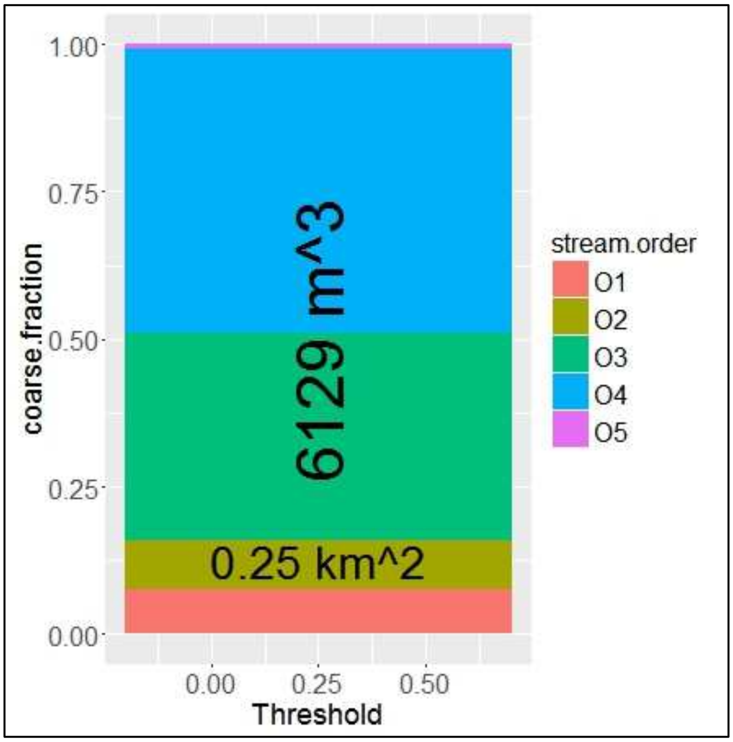
NSV map created in ArcGIS using a 0.5km^2 threshold contributing area for channel initiation. Streams were clipped to treeline to exclude extrapolation to alpine streams (no wood). There are 15 first order streams, 8 second order streams, 20 third order, and

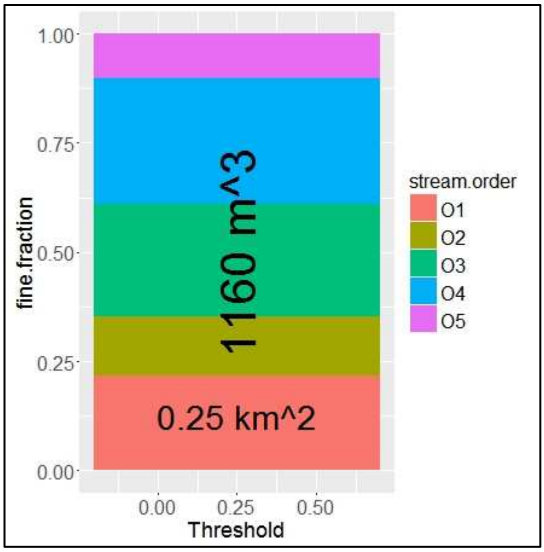
5 fourth order. Eight of the 15 first order streams do not correspond to a mapped stream. Due to this, and a density of streams too low compared to observed observations, this map was not chosen as representative of the NSV stream network. However, storage values were extrapolated for a sensitivity analysis. N=48 reaches.

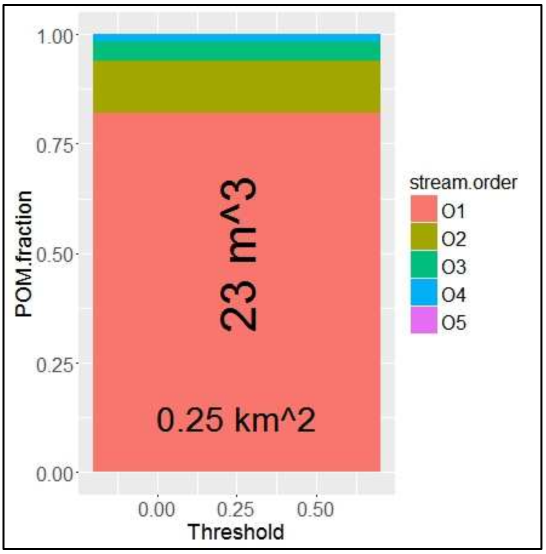


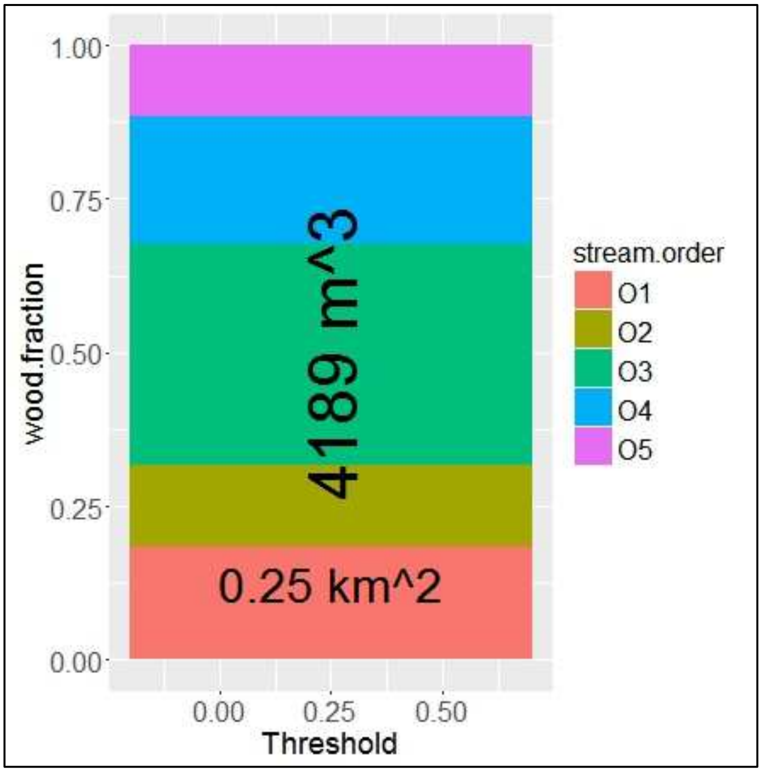
NSV map created in ArcGIS using a 0.1km^2 threshold contributing area for channel initiation. Streams were clipped to treeline to exclude extrapolation to alpine streams (no wood). There are 9 first order streams, 6 second order streams, 8 third order, 20 fourth order, and 5 fifth order. All but one of the first order streams were mapped to a point in the stream network. However, due to an unrealistically high density of streams (drawing streams in areas that do not mesh with field observations), this scenario was not chosen as representative of the NSV network. Storage values were extrapolated for a sensitivity analysis. N=48 reaches.

G. Analysis of storage distribution and hotspots standardized by stream surface area (m^3/m^2). Total surface area at a given stream order was calculated by multiplying total stream length by average channel width (m^2). Average storage by stream order (m^3/m^2) was then multiplied by total surface area at each stream order to scale up results. While the numbers differ, interpretation of where storage hotspots occur does not. This analysis was only conducted for the 0.25 km^2 contributing area scenario.




1.00
0.75
0.50
0.25
0.00
fine.fraction
1160 m^3
0.25 km^2
0.00
0.25
0.50
Threshold
stream.order
O1
O2
O3
O4
O5


1.00
0.75
0.50
0.25
0.00
POM.fraction
23 m^3
0.25 km^2
0.00
0.25
0.50
Threshold
stream.order
O1
O2
O3
O4
O5


1.00
0.75
0.50
0.25
0.00
wood.fraction
4189 m^3
0.25 km^2
0.00
0.25
0.50
Threshold
stream.order
O1
O2
O3
O4
O5