Wood Budget for Countyline to A Street Levee Modification Project, White River, WA

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Glossary of Key Terms *(in order of appearance)*

Large wood (LW): dead pieces of trees ≥1 m (3.28 feet) in length and ≥10 cm (3.94 inches) in diameter.

Project site: The parcel boundaries encompassing the Countyline-A Street Floodplain Reconnection Project on the White River.

Upstream source area: The 28 km-long river segment upstream from the project site, ending at the Lake Tapps diversion. This segment includes a 6-km reach of the White River between A-Street Bridge and the upstream end of the TransCanada facility entirely confined by levees and revetments and therefore treated simply as a flume-like transport reach.

Patch: a class of biogeomorphic landform with distinctive, internally homogeneous forest structure.

Potential wood loading (PWL): the quantity of wood in the stems of riparian forests that is ≥1 m in length and ≥10 in diameter, excluding branches and rootwads. This value is given as a quantity per unit area.

Wood budget: A quantitative accounting of changes in wood storage in a river channel, in the form of a mass balance, as a function of primary inputs and outputs over time and space (Benda and Sias 2003). ($\Delta S = [L_i - L_o + Q_i - Q_o - D] * t$)

Wood storage (S): the quantity of large wood stored in a river reach, measured as volume or number of pieces. This value may be given as a quantity per unit length or area. A change in wood storage (ΔS) refers to the quantity of wood lost or gained in a specific location over a specified time interval; units are in quantities per reach length per time.

Total lateral recruitment (L_i): the total quantity of wood added to the river from the forest per unit reach-length per time. In this study, this value refers only to wood originating from standing riparian forests toppled by bank undercutting associated with channel migration, widening, and avulsions. In this study, additional sources of wood are not considered; downed wood on the forest floor, exhumation of buried wood, trees toppled by fires and windstorms, and wood delivered by landslides, debris flows or avalanches.

Total lateral outputs (L_o): the total quantity of wood lost from the active channel of the river through overbank deposition and the abandonment of jams by the river.

Fluvial transport input (Q_i): the quantity of wood transported by the river across the upstream boundary (cross-section) of a river reach in a given year.

Fluvial transport output (Q_o)*:* the quantity of wood transported by the river across the downstream boundary (cross-section) of a river reach in a given year.

Decay (*D*): the quantity of wood lost to physical breakdown (e.g., fragmentation) and biological processing (e.g., by microbes, fungus, and invertebrates) in a year.

Size classes (for trees and logs): Alphanumeric codes (24 classes) that refer to the length and large-end diameter of logs or diameter at breast-height and the height of trees (Montgomery 2008).

		Diameter				
		10-20 cm	20-40 cm	40-80 cm	80-160 cm	160-320 cm
Length		3.9-7.9 inches	7.9-15.7 inches	15.7-31.5 inches	31.5-63.0 inches	63.0-126.0 inches
1- 2 m	3.3-6.6 ft	B2	B3	B4	B5	B6
2-4 m	6.6-13.1 ft	C2	C3	C4	C5	C6
4-8 m	13.1-26.2 ft	D2	D3	D4	D5	D6
8-16 m	26.2-52.5 ft	E2	E3	E4	E5	E6
16-32 m	52.5 -105.0 ft	F2	F3	F4	F5	F6
> 32 m	>105.0 ft	G2	G3	G4	G5	G6

Common Conversions:

1 centimeter (cm) = 0.3937 inches (in)

1 meter (m) = 3.2808 feet (ft) *or* 1.0936 yards (yd)

1 kilometer (km) = 3280.840 ft *or* 0.6214 miles (mi)

1 hectare = 10,000 square meters (m^2) *or* 2.4711 acres *or* 11,959.901 square yards (yd^2)

1 cubic meter = 35.3147 cubic feet (ft^3) *or* 1.308 cubic yards (yd^3)

Summary

This study is intended to provide a better understanding of how much wood is transported by the White River to the Countyline to A Street Levee Modification Project site, how the project may affect wood storage on site, and the amount of wood that may reach sites downstream.

Study Goal:

- To estimate fluvial transport inputs of large wood to the project site from the upstream source area.
- To estimate changes in large wood storage at the project site following the installation of engineered logjams (ELJs) and subsequent floodplain adjustments.
- To estimate the fluvial transport output from the project site to downstream areas.

Methods *(refer to glossary for terms)*:

I estimated a quantitative wood budget for the upstream source area and the project site by following the methods of Benda and Sias (2003).

- Potential wood loading was estimated for five forest patch types in the upstream source area and for four patch types at the project site. Thirty-seven plots were surveyed with the point-centered quarter technique; including 1,480 trees over 5.9 km of transects.
- In the upstream source area, total lateral wood recruitment was based on measurements of erosion from channel migration between 2005 and 2010. These estimates were based on overlay analyses in ArcGIS.
- At the project site, total lateral wood recruitment combines two potential sources: an abrupt pulse resulting from channel avulsion into existing trees on the project site, and gradual inputs from future bank undercutting during and after the avulsion.
- Average fluvial transport output was estimated for the upstream source area and for the project site as a function of the total lateral wood recruitment (L_i), the proportion of pieces shorter than the active channel width (Φ), and the distance a piece of wood can travel before disintegrating (ξ; lifetime transport distance).

Total Lateral Wood Recruitment in Upstream Source Area:

Wood recruitment occurs when trees fall into the river and become large wood. From 2005-2010, 60 hectares of forest was eroded through natural channel migration – 12 hectares per year (0.09% of the forested valley). This estimate represents a period of relatively high flows and probably overestimates the long-term average.

- Total lateral wood recruitment (L_i yr^{-1}) to the channel in the upstream source area was estimated to be 5,819 m^3 or 5,854 pieces per year (or 200-600 m^3 km^{-1} yr^{-1} among locations).

- Old terraces contribute 47% of the volume despite composing only 17% of the eroded area. They supply 86% of all long (5-class) and 44% of the large diameter (G-class logs); those than can function as key pieces; see glossary for easy-to-read table of log class dimensions.
- Relatively young (developing) floodplains disproportionately affect the number of pieces that entered the channel each year; they contributed 40% of pieces but composed only 25% of the eroded area.
- Total lateral wood recruitment peaked at three locations where the river was meandering through old terraces on the outside bend – known as ‘wood hotspots’ (Latterell and Naiman 2007).
- Black cottonwood dominated total lateral wood recruitment by volume throughout the upstream source area.
- Total lateral wood recruitment, by number of pieces, declined with increasing distance upstream, as expansive broadleaf forests give way to conifer forests in a narrower valley.

<u>Fluvial Transport Inputs to Project Site from Upstream Source Area</u>:

The estimated long-term average fluvial transport input rate of large wood from the upstream source area (Q_o) to the project site is 640 m^3 yr^{-1} or 644 pieces yr^{-1}.

- Most (83%) of the pieces are predicted to 10-30 cm in diameter).
- Five percent, or 25 pieces, are expected to reach 80-160 cm in diameter.
- Approximately eight percent, or 44 pieces, are expected to be over 32 m long.

<u>Total Lateral Wood Recruitment to Project Site From Channel Relocation and Subsequent Migration</u>:

If the White River mainstem completely avulses into the project site – a conservative assumption – up to 6.1 hectares of forest could be eroded by the river and enter the channel as large wood.

- This could produce a pulse of wood from standing forests estimated at 2,733 m^3 in total volume and containing 1,144 pieces.
- Red alder and cottonwood would compose roughly 64% and 28% of the pieces respectively.
- The majority would be smaller than 16 meters long and 40 cm in diameter.
- An estimated 201 downed trees (725 m^3) could also be captured by the channel. Most (57%) of these would be 16-32 meters long and 20 to 80 cm in diameter (82%).
- Additional channel migration in subsequent years could potentially produce 344 m^3 yr^{-1} (107 pieces) from standing forests; this amount will likely diminish below 262 m^3 yr^{-1} (82 pieces) over a decade or more.

<u>Estimated Fluvial Transport Outputs from Project Site</u>:

A complete channel avulsion into the project site could potentially generate quantities of large wood up to 2,780 m^3 (1,312 pieces) from the project site – via fluvial transport. After avulsion, fluvial transport outputs may decline from 226 m^3 (173 pieces) to 209 m^3 (168 pieces) within roughly a decade.

Project Site Wood Budget and Net Effect of Project on Fluvial Transport Inputs to Downstream Reaches:

The project site may accumulate an estimated 1,530 m^3 (108 m^3 per channel width) following a complete channel avulsion, and approximately 700 m^3 in each of the subsequent years for roughly 10 years.

- Consequently, under these assumptions, the project site is projected to accumulate roughly 7,000 m^3 of large wood – or 473 m^3 per channel width – over the first decade; exceeding the threshold for "good" levels of wood loading, based on regional reference streams (Fox et al. 2003). Streams must contain more wood than three-quarters of the natural streams of comparable size in western Washington to considered to achieve a "good" habitat quality rating (Fox et al. 2003).
- The project site is predicted to retain between 37 to 77% of the large wood that enters the site from upstream and from erosion of forests on the project site, depending on the year.
- If an abrupt channel avulsion occurs, the export of wood to downstream reaches could potentially quadruple (2,140 m^3 above the background of 640 m^3).
- However, the project should reduce the amount of wood reaching downstream reaches to <35% of pre-project levels, on average (by year 2 after completion).
- At some point, the project site is likely to saturate – or reach maximum loading – but when this will occur cannot be predicted with confidence.

Conclusions:

The wood budget presented in this report requires many simplifying assumptions that limit the reliability and scope of the findings; conclusions should be treated as reasonable estimates, not precise forecasts of future events. This report is simply intended to guide decision making with a synthesis of the best available information.

- This study indicates that the White River will likely deliver a substantial quantity of wood to the project site.
- This study suggests that, if a complete channel avulsion occurs, the project may initially elevate, but eventually reduce the amount of wood reaching downstream reaches; at least until wood loading in the project reach approaches levels similar to unmodified river channels.

I. INTRODUCTION

The Countyline-A Street Levee Modification Project (see Vicinity Map), on the White River within the Cities of Sumner, and Pacific, Washington, will remove an existing levee and construct a setback levee, and engineered logjams (ELJs). The purpose of the project is to reduce flood risks and enhance and restore salmonid habitat by reconnecting the river with its floodplain. The project design team needs a better understanding of how much wood is transported into the project site by the river. They also need to know how the project may affect wood recruitment and storage on site, and the amount of wood that reaches downstream areas. This information will help inform the engineered logjam design. This study is intended to help address these needs.

Specifically, this large wood study has three goals:

GOAL 1: To estimate fluvial transport inputs of large wood to the project site from the upstream source area.

GOAL 2: To estimate changes in large wood storage at the project site following the installation of engineered logjams and channel re-location.

GOAL 3: To estimate the potential fluvial transport output of large wood from the project site to downstream reaches.

The methods used in this study are based on a published framework for estimating changes in wood storage in a river channel, in the form of a mass balance, as a function of primary inputs and outputs over time and space: a wood budget (Benda and Sias 2003). The basic form of this equation is:

$$\Delta S = [L_i - L_o + Q_i - Q_o - D] * t \qquad \textit{(EQUATION 1)}$$

where,

ΔS	Change in storage
L_i	Total lateral recruitment (or inputs)
L_o	Total lateral outputs
Q_i	Fluvial transport inputs
Q_o	Fluvial transport outputs
D	Decay
t	Time

This study has four *objectives:*

OBJECTIVE 1: Estimate potential wood loading (PWL) in forests of the upstream source area and at the project site.

OBJECTIVE 2: Estimate total lateral recruitment from channel migration (L_i) in upstream source area with airphoto analysis.

OBJECTIVE 3: Estimate wood flux (Q_o) from upstream source area to the project site (equivalent to Q_i).

OBJECTIVE 4: Estimate a wood budget for the project site to estimate change in storage (ΔS) on-site and fluvial wood transport (Q_o) from the project site to downstream areas.

II. METHODS

Study Area

This study focuses on the Countyline to A Street Levee Modification Project (hereafter, project site) on the White River and an upstream source area (for large wood) extending 28 km upstream to the Lake Tapps diversion. This reach appears to regulate the quantity of wood entering the project site through fluvial transport. Accordingly, and for the sake of efficiency, the study excludes approximately 13 km of the White River from more detailed analyses. The exclusion is primarily based on two assumptions:

- ASSUMPTION 1. The 5 km of the White River between A-Street bridge and the upstream end of the Transcanada facility are assumed to contribute and store negligible amounts of wood. Wood storage and recruitment was not estimated for this segment. This assumption is reasonable because the reach is entirely confined by levees and revetments that virtually eliminate lateral wood recruitment. In 2010, the reach contained three natural logjams that could potentially trap fluvially transported wood, but the potential effect of these jams was ignored. These jams were not present in 2005, suggesting that some wood storage may occur in this reach; estimates of fluvial transport outputs of large wood from the upstream source area may be slightly overestimated.

- ASSUMPTION 2. No wood (or a negligible amount, from the standpoint of this study) enters the upstream source area between the Lake Tapps Diversion dam and Mud Mountain dam (approx. 8 km). This assumption was substantiated by a comparison of channel positions – based on aerial photos from 2005 and 2009 – which suggested very little lateral wood recruitment occurred in this reach. If the excluded reach between the two dams actually does contribute wood to the upstream source area, the fluvial transport output from the upstream source area may be slightly underestimated.

OBJECTIVE 1 METHOD: Potential wood loading (PWL)

PWL was estimated for five patch types in the upstream source area and for four patch types at the project site (Table 1; Appendix 1). Individual patches were identified in 2010 color infrared photos and from lidar maps. Sampling in the upstream source area was spread over a river segment approximately three kilometers long. Sampling at the project site was performed at the same locations as previously located wetland survey cross-sections. In each case, we attempted to locate plots to fit entirely within the boundaries of a relatively homogeneous and distinct stand (Figure 1). On-the-ground photos of each plot are provided in Appendix 1.

Patches were defined according to relevant typologies from river ecology literature (Latterell et al. 2006), and on the basis of idiosyncratic features related to human modifications, where necessary. Patches in the upstream source area were formed by relatively natural successional and geomorphic processes, in spite of historical logging and flood control by Mud Mountain Dam. This means that many examples of similar patch types exist on the landscape, even if contemporary patches differ from those that may have been present prior to human impacts. One exception was the isolated conifer patch; the name was ascribed (for the purposes of this study) to the fir-dominated stands growing behind the TransCanada levee. Patch types in the project site were more unique and artificial (i.e., from channelization) so they were simply differentiated on the basis of the relative stem density and height (Table 1).

Table 1. Patch type descriptions

Reach	Patch type	*n*	Mean Age	Dominant species	Landform & Hydrology
Upstream source area	Developing floodplain	9	20	Cottonwood and red alder	Thin alluvial deposits inundated multiple times during the wet season
	Established floodplain	5	32	Cottonwood	Deeper alluvial deposits inundated at least during annual peak flows
	Terrace	6	75	Cottonwood and Douglas-fir	High landform with deep mineral soils mostly isolated from overbank flows
	Old Terrace	4	130	Western redcedar and cottonwood	High landform isolated from overbank flows
	Isolated Conifer (behind levee)	5	63	Douglas-fir	Thin alluvial deposits on gravel and cobble artificially disconnected from flows by levee
Project site	Tall dense floodplain	4	78	Cottonwood	Low, wet alluvial deposits backwatered during floods behind levee
	Tall sparse floodplain	1	60	Cottonwood	Low, wet alluvial deposits backwatered during floods behind levee
	Short floodplain	2	90	Cottonwood and red alder	Low, wet alluvial deposits backwatered during floods behind levee
	Open water wetland	1	60	Cottonwood	Submerged landform under standing water

Point-centered quarter (PCQ) surveys (Mitchell 2007) were used to survey forests and estimate PWL in each patch type. The results from PCQ surveys were used to estimate absolute stem density (λ; stems or pieces per hectare), absolute density of large wood size classes (Montgomery 2008) and total wood volume per unit area by patch (m^3 ha^{-1}). A 100 m (328 ft) tape was extended in a straight line through developing and established floodplains. In all other patch types, two 100 m tapes were extended in parallel and separated by 10-20 m (or 33-66 ft), to avoid sampling of the same trees repeatedly. Starting locations were selected non-randomly near the edge of each patch without known bias. Unintentional bias could have potentially influenced the starting point selection, but the effect of any such bias is probably minimal because the observer can only see a very small portion of the trees that will be included in the sample, owing to the substantial length of the transect. Transects were oriented to remain within a discrete patch, resulting in many different orientations in the upstream source area (Fig. 1). Transects at the project site were extended roughly perpendicular to flow for ease of access; these locations had previously been cleared of thorny vegetation, which limited otherwise limited access.

Plot centers were located at 10 randomly generated points spread across either one or two 100 m tapes, depending on the patch type. At each plot center, the area around the point was visually divided into four quadrants and the closest stem (live or dead) ≥ 10 cm (0.33 ft) at D_{130} (diameter at breast height, or approximately 130 cm above the ground) was identified. The distance from the plot center to the perimeter of each tree was measured with a TruPulse laser rangefinder (to 0.1 m; 0.33 ft).

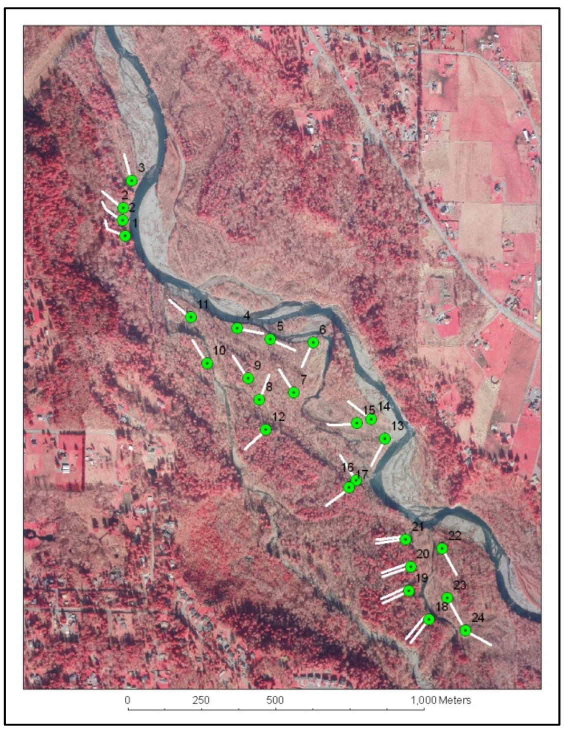
Instead of measuring D_{130}, as is the usual convention, tree height and diameter and height was visually estimated according to alphanumeric size classes (24 classes; A-G and 2-5) for large wood (Montgomery 2008).

- LENGTH CODES: **B** (1- 2 m); **C** (2-4 m); **D** (4-8 m); **E** (8-16 m); **F** (16-32 m); **G** (> 32 m).
- DIAMETER CODES: **2** (10-20 cm); **3** (20-40 cm); **4** (40-80 cm); **5** (80-160 cm); **6** (160-320 cm).

The purpose of this modification was to convert stem densities directly into size classes relevant to instream large wood storage, and to maximize sampling efficiency. Visual estimates were periodically calibrated with measurements. Tree height was estimated as the length of the stem that exceeded 10 cm in diameter, rather than to the actual top of the tree, because smaller treetops do not meet the minimum size criteria to qualify as large wood. Branches were ignored, but it must be acknowledged that they contribute some additional amount of small pieces. Accordingly values for small diameter and length classes presented underestimate the true PWL by an unknown amount.

In one patch type at the project site – the open water wetland – PWL was not estimated with PCQ methods because it was impractical. Instead, the laser rangefinder was used to identify all trees within 100 m of a fixed sampling point. All trees within a 155-degree semicircle were tallied and visually classified (Fig. 1). The area of the survey was calculated and findings were converted to a PWL estimate for that patch type. Downed logs in this area were mapped at 1:1,000 from 2010 CIR (leaf-off) orthophotos in ArcMap. Virtually all of these downed trees are cottonwood boles. Bole length was calculated in GIS. It was assumed that bole diameters of the downed logs ranged from class three to five and were present in the same ratios as in tall, dense patches (42.4, 40.4, and 17.3%, respectively). It was also assumed that none were diameter class 2 because pieces of that size are difficult to see reliably in orthophotos.

Figure 1. Potential wood loading plot locations in the upstream source area[1].



Upstream Source Area Plots

Project Site Plots

[1] Five additional plots were located in the Douglas-fir dominated stands behind the Transcanada levee (in the upstream source area); these are not shown.

OBJECTIVE 2 METHOD: Total lateral wood recruitment (L_i) from channel migration in upstream source area

In the upstream source area, total lateral wood recruitment from channel migration was estimated as the product of the area of each patch type eroded from 2005-2010 and the PWL for that patch type. This time interval was selected because the airphotos taken during this period were the highest quality, meaning that stands and logjams could be seen and their dimensions could be reliably measured. Eroded areas were quantified by mapping forests in 2005 orthophotos (1:5,000 scale) and overlaying these boundaries on the 2010 orthophotos. Forested areas from 2005 that were no longer present (i.e., had been converted to unvegetated channel) were mapped by subdividing the initial forested polygons along the new forest margins (at 1:2,000 scale). This analysis produced a map consisting of numerous polygons illustrating where forest erosion had taken place (2005-2010). Photo interpretation was used to subdivide each eroded area into distinct patch types. Lateral wood recruitment from each patch was simply calculated by multiplying the eroded area by the corresponding mean PWL. To estimate total lateral wood recruitment to the upstream source area, large wood recruitment from each eroded patch (between 2005-2010) was summed and divided by five (years) to make it an annual rate. That quantity was divided by the length of the upstream source area in meters (23,000 m or 14.3 miles). The end result was a recruitment rate in units (pieces or m^3) of wood ($L_i\ m^{-1}\ yr^{-1}$). Each eroded patch was assigned to a corresponding river kilometer, indicating the distance upstream from the A-Street Bridge (i.e., $L_i\ km^{-1}\ yr^{-1}$) to plot downstream-to-upstream variation in wood recruitment rates.

- ASSUMPTION 3: Total lateral recruitment rates measured during 2005-2010 intervals are representative of a period of relatively high wood recruitment; the three highest flows (USGS Gage 12099200; White River above Boise Creek at Buckley) on record (since 2003) occurred during this interval; 10,400 cfs on 11 January 2006, 14,700 cfs on 8 November 2006, and 11,800 on 8 January 2009. Periods of high wood recruitment may be expected during cool, wet periods of ENSO (i.e., La Nina) (Naiman et al. 2002) and perhaps from the anticipated effects of climate change on the hydrology of rivers in the Pacific Northwest (Lettenmaier et al. 1999).

OBJECTIVE 3 METHOD: Fluvial transport output from the upstream source area to the project site

Wood flux from upstream source areas to the project site was estimated according to methods proposed by Benda and Sias (2003). Average fluvial transport output rate (over the long term) is approximated as a function (Eq. 2) of the input rate (L_i), the proportion of large wood pieces with lengths less than the active channel width (Φ) and therefore mobile, and the distance an individual piece of wood can travel before disintegrating (ξ; lifetime transport distance).

$$Q_o = L_i * \Phi * \xi \qquad \text{(EQUATION 2[2])}$$

- ASSUMPTION 4: Benda and Sias (2003) assume that piece stability is approximated by the ratio of piece length to channel width. In the White River, all pieces are assumed to be potentially mobile (Φ = 1.0) because active channel width in the White River exceeds the height of all measured trees. Some older trees may in fact be stable owing to their large caliber and rootwads, which are known to increase stability (Abbe and Montgomery 1996). This means wood mobility is likely overestimated in this study, which would exaggerate the fluvial transport output rate.

If Φ is 1.0, wood flux reduces to a function of lateral inputs and lifetime transport distances (Eq. 3). Lateral inputs are estimated as previously mentioned. Model parameters were estimated with direct measurements of the study area where possible.

- ASSUMPTION 5: Benda and Sias (2003) assume that the lifetime transport distance (ξ) of a piece of large wood is a function of the average distance between jams (J), the relative longevity of wood pieces (ζ) and logjams (α), and the average proportion of the channel width blocked by logjams (β). In this study, median values were used instead of average values because the parameters were not normally distributed.

$$\xi = [J * (\zeta / \alpha)] / \beta \qquad \textit{(EQUATION 3}^{2}\textit{)}$$

The value of *J* was estimated by tracing the low-flow channel centerline from 2010 orthophotos (1:2,000 scale), and splitting the line at every transport-impeding jam, defined as any obvious accumulation of wood that appeared to have the potential to trap floating wood (e.g., typically occupied at least 5% of the channel width). The length of each segment (inter-jam distance) was calculated in ArcMap and the median value was used for *J.*

The value of β was estimated by digitizing a line perpendicular to the active channel axis at the site of each channel impeding jam (1:2,000 scale), so that the length of the line approximated the portion of the channel that could be blocked by the jam. A similar, parallel line was digitized at each of these locations to represent the active channel width. The ratio of these values – derived for all jams – provided median estimates of the proportion of the channel blocked by jams.

Piece longevity (ζ) was estimated by using the same decay model as Benda and Sias (2003), which is a negative exponential, where *k* equals 0.03 or 3% (Harmon et al. 1986). Average piece longevity was taken to be the weighted average time required for pieces to decay to 10 cm or less in diameter. Weights corresponded to the estimated relative frequency of each diameter class (i.e., 2-5) reaching the channel through lateral wood recruitment. Decay time was approximated as the time required for decay to reduce the diameter of a piece to decay to 10 cm or less, based on the midpoint diameter in each bin. Breakage (i.e., resulting in shorter pieces) was not estimated, so all pieces are assumed to be transported with their initial length intact (though unrealistic, there is not a simple way to quantify the rate and consequence of breakage).

Logjam longevity (α) was estimated from literature values for key piece retention in the Queets River, Washington (Latterell and Naiman 2007)and validated with direct observation of logjam retention from 2005-2010 in the White River. Latterell and Naiman (2007) find that 50% of functioning key pieces in the active channel were displaced by the river within five years of deposition. To confirm that these values were at least somewhat representative of the White River, the location and fates of two cohorts (2005 and 2007) of logjams in the unvegetated channel was mapped. Newly-deposited jams were mapped and compared to subsequent photos to determine the proportion of each cohort remaining stable after some elapsed time. These values were plotted and fitted with a power function (Latterell and Naiman 2007) to determine how many years typically pass before half of the jams are displaced.

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[2] Equations 2 and 3 are considered to apply only where transport is limited by jams and are not sufficient for rivers where wood may be stored on the floodplain and in off-channel areas (Benda and Sias 2003). They were used anyway because the results are still informative – if incomplete – and no suitable alternative exists. This means the amount of wood being transported to the project site may be overestimated, because some portion would actually be removed from transport and stored in the floodplain and off-channel areas.

Fluvial transport output of large wood from the upstream source area was assumed to be entirely driven by the total lateral recruitment of new wood to the channel. Following the example of Benda and Sias (2003), it was assumed that a balance exists between the quantities of wood leaving the channel as lateral wood outputs (L_o; wood lost to channel abandonment or overbank deposition) and lateral wood inputs from the recapture of remnant fluvial deposits of wood (I_e). This is a simplifying assumption that is likely incorrect over short time scales; Benda and Sias (2003) believed it to hold over century-long time scales. The only empirical data known to this author comes from studies of key piece-sized logs in the Queets River, where floodplain wood stockpiles may compose 28% of the total lateral recruitment of key-piece sized logs (Latterell 2005, Latterell and Naiman 2007). The same study (Latterell 2005) concludes that for every four key pieces that enter the channel, three were standing trees, and one was a remnant of an historic logjam recaptured by the river. For every four pieces entering the channel, two pieces left and were stockpiled in the floodplain. In other words, twice as many key pieces enter the channel each year as leave it through overbank deposition or abandonment. Also, the ratio of lateral wood output to recapture of stockpiled wood was roughly two to one. If this holds for pieces of all sizes, and is representative of the White River, the present study may overestimate total lateral recruitment and fluvial transport output to the project site by around 25%.

OBJECTIVE 4 METHOD: Wood Budget for Project Site

A single wood budget was developed for the project site; a full channel avulsion scenario[3] in which the channel completely relocates in a single year and assumes the dimensions and location proposed by Herrera (i.e., 130 m average width).

The change in instream wood storage (by wood volume) was simulated at the project site (per year, site, and channel width) for the first decade after the project is completed (see Eq. 1). Note that lateral outputs were assumed to be zero and that fluvial transport inputs are the same as fluvial transport outputs from the upstream source area.

- *ASSUMPTION 6*: For the purpose of this analysis, the channel is assumed to completely avulse into the project site in the first year, but the channel could avulse in any of the years, or not at all. The simulation simply illustrates the potential effect of a complete avulsion.

Lateral recruitment will come from three sources: (1) standing forests in the footprint of the planned (post-restoration) new channel via channel widening; (2) downed wood in that footprint; and (3) gradual erosion of standing forests outside the footprint of the planned channel. Lateral wood recruitment to the channel was estimated by overlaying the anticipated boundaries of the planned channel on the existing forests and maps of downed trees. The intersected areas were classified and, as before, the area was simply multiplied by the patch-specific estimates of PWL to generate wood recruitment estimates. Recruitment from gradual channel migration was estimated by assuming the forests remaining after channel relocation will erode according to an exponential decay rate similar to

[3] A split-channel scenario is also possible and could be evaluated in the future. For example, if the channel splits into equal parts, it could simply be assumed that, regardless of stage, half the flow enters each channel. However, the channel will not simply decrease by 50% from current dimensions. According to, Charlton et al. (1978); w = 2.4 Qb0.41 s-0.10), so halving the bankfull discharge should reduce channel width by 25%, assuming slope remains the same. Bankfull discharge (where recurrence interval is one to two years) at Station 12099200 is approximately 7,000 cfs (RI = 1.5). Slope near the project site is 0.002 m/m. At this discharge, the channel is predicted to be 39 meters wide, which very similar to the active channel width at present. According to this relationship, splitting the channel into equal parts should produce two 30-m wide channels.

or faster than floodplain patch types upstream and in similar rivers (i.e., $S_{riparian}$*e$^{-0.03*t}$; Latterell et al. 2006). Thereafter, PWL at the project site was reduced annually by the estimated eroded area.

Fluvial transport outputs were estimated for the project site using the same model as in the upstream source area, but with different parameters. Instead of estimating long-term average output from the site – as in the upstream source area – the magnitude of the output was estimated over the first ten water years following project completion. All parameters except decay rates were measured and estimated separately for the project site, to account for differences in PWL and jam characteristics. Estimates of lifetime transport distance used different values for *J*, *α* and *β*, depending on the year, to better represent the changes expected to occur at the project site. Also, piece lifetime ζ was based on weighted averages to account for size differences in wood originating from differing sources.

- *ASSUMPTION 7*: The new channel, after an avulsion, is assumed to develop natural jams at spacing intervals similar to the upstream source area.

The same decay model and rate coefficient was used as before. Decay was assumed to occur simultaneously on lateral wood recruitment and fluvial transport inputs, and that decay occurred in the same year the wood entered the project reach. The cumulative change in storage was adjusted for decay of previously stored wood by using the same decay model to reduce the previous year's storage before adding it to the next year's inputs.

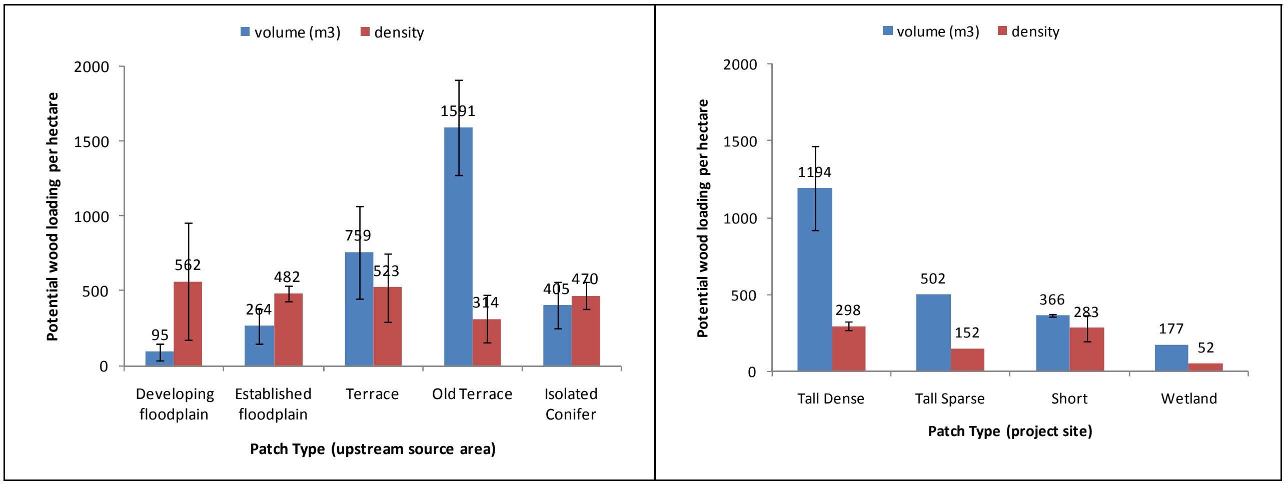
III. RESULTS

OBJECTIVE 1 RESULTS: Potential wood loading

A total of 37 plots was surveyed to estimate potential wood loading (PWL) in nine patch types; five at the upstream source area and four at the project site. A total of 1,480 trees was surveyed in the study over a total of 5.9 km of transect length; a single 100 m transect was used at 15 plots and two were used at the remainder. Sample sizes within patch types were not equal because extra sampling was devoted to highly variable patch types. Sequential sampling charts were used to evaluate whether sufficient plots were surveyed to accurately estimate mean values.

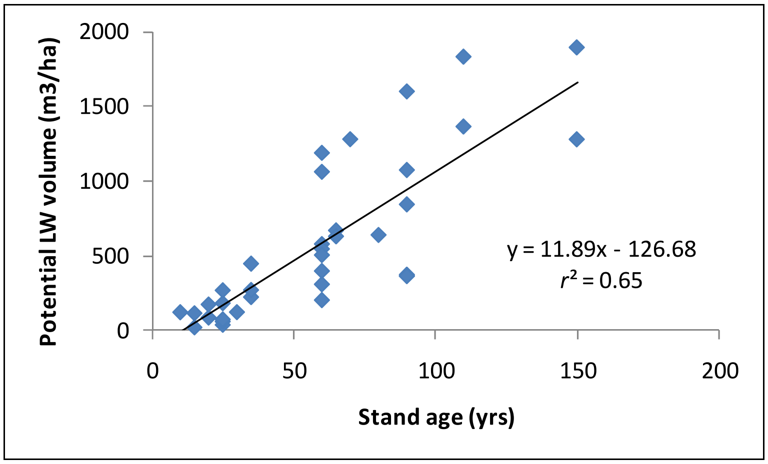
The PWL for each patch type was first estimated by averaging estimated volume and density across plots within a patch type (Fig 2, Table 2). Wood volume differed among patch types but was highly variable within younger patch types; CVs ranged from 20-60% of the mean (Table 2). In the upstream source area, average PWL ranged from 95 to 1,591 $m^3 ha^{-1}$ among patch types. Wood volume generally increased with stand successional stage and age (Fig. 3). Old terraces contained 17 times more wood volume than developing floodplains (the youngest patch type containing abundant supplies of trees at least 10 cm in diameter). At the project site, average PWL ranged from 177 to 1,194 $m^3 ha^{-1}$. Tall dense patches at the project site contained similar volumes of large wood as the old terraces in the upstream source area, and two to three times more wood than tall sparse and short patches.

Figure 2. Potential wood loading by volume and density for patch types in the upstream source area (left panel) and at the project site (right panel).



Estimates of stem density were more similar among patches, compared to volume, but average densities did decline with increasing stand age. In the upstream source area, average stem density was highest in developing floodplain and lowest in the old terraces. Density varied by a factor of nearly two among these patch types. Stem density was highly variable within patch types, with CVs ranging from 10-70% of the mean (Table 2). At the project site, the highest stem density was observed in the tall dense patches, but these values were essentially the same as observed in the short patches. Tall sparse patches were half as dense. Stem densities were less variable within patch types at the project site, with the maximum CV being 30% of the mean.

Figure 3. Relationship between potential large wood volume and estimated stand age, including plots from both the upstream source area and the project site.



The precision of PWL estimates varied among patch types (Table 2). Volume-based estimates of average PWL are highly precise (0 < CV < 20) in old terrace and short patches. Estimates are moderately precise (20 < CV < 40) for isolated conifer and tall dense patches. Estimates for developing floodplains are imprecise, even though nine patches (more than any other) were sampled. Fortunately, this low precision is of little consequence to the wood budget; these patches contain the least amount of wood.

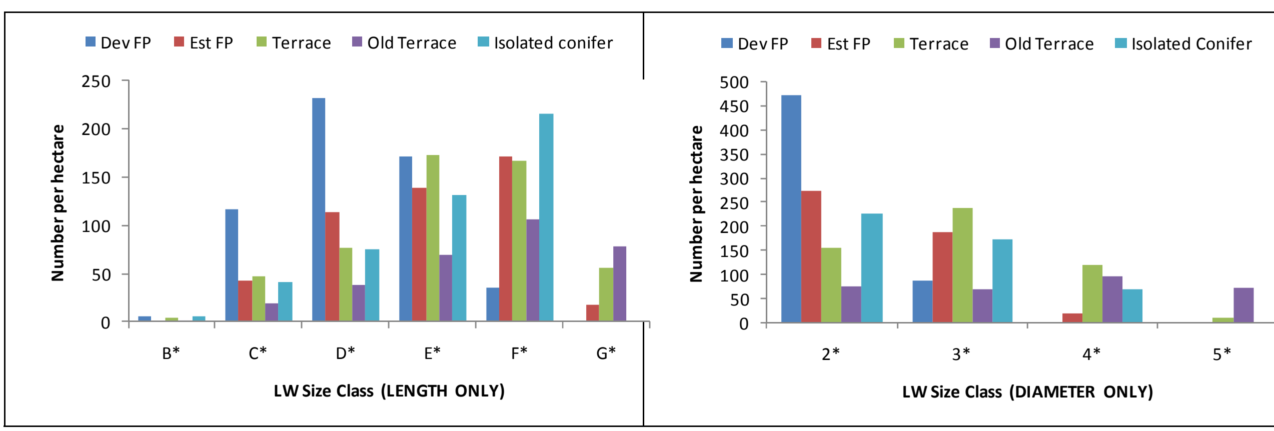
Density estimates are highly precise in established floodplain, isolated conifer, and tall dense patches. Moderate precision was achieved in density estimates for short patches. Density estimates for developing floodplain, terrace, and old terrace plots are imprecise.

Table 2. Potential wood loading by patch type; *n* is the number of plots, SD is standard deviation of the sample , CV is coefficient of variation of the sample.

Reach	Type	*n*	Density (λ; LW/hectare)			Volume (m^3/hectare)		
			Mean	*SD*	*CV*	*Mean*	*SD*	*CV*
Upstream source area	Developing floodplain	9	562	392	0.70	95	57	0.60
	Established floodplain	5	482	50	0.10	264	117	0.44
	Terrace	6	523	230	0.44	759	309	0.41
	Old Terrace	4	314	157	0.50	1591	316	0.20
	Isolated conifer	5	470	87	0.18	405	158	0.39
Project site	Tall Dense	4	298	29	0.10	1194	271	0.23
	Tall Sparse	1	152			502		
	Short	2	283	83	0.30	366	6	0.02
	Wetland	1	52			177		

The caliber and length of large wood heavily depends on what patch type was eroded (Table 3). For example, in the upstream source area, the largest and longest pieces (e.g., G5) originate from terraces and old terraces (Fig. 4), which is consistent with the literature (Latterell and Naiman 2007). In contrast, the erosion of developing floodplains primarily contributes pieces in the D length class and diameter class 2 (Fig. 4). Established floodplains primarily contribute pieces in the F length class and diameter class 2 (Fig. 4). However, pieces in the diameter class 2 may originate from any and all patch types.

Figure 4. Potential wood loading by size class (length and diameter) for patch types in the upstream source area.



The project site differs in that all patch types contain pieces of wood in length classes C through G, so that these pieces may originate from the erosion of any patch type (Fig. 5). Similarly, all diameter classes occur in each patch type, though the relative amounts vary greatly. For example, the erosion of tall dense patches primarily contributes G-class and 3-class pieces. In contrast, the erosion of short patches contributes E-class and 3-class pieces. These differences in potential wood loading have important implications for wood recruitment, as discussed later.

Figure 5. Potential wood loading by size class (length and diameter) for patch types at the project site.

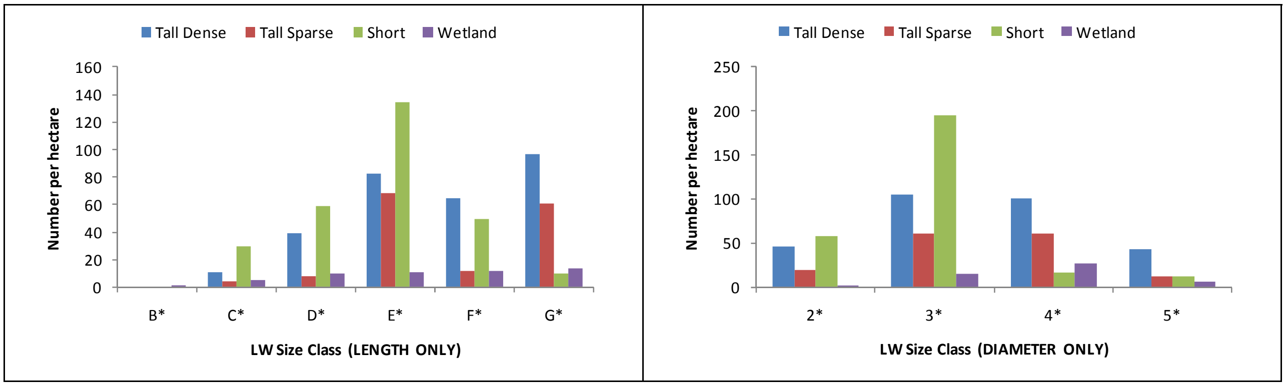


Table 3. Potential (average) wood loading (number of pieces) by patch type and size class (Montgomery 2008); L is length in meters; D is diameter in meters. Zero values removed for clarity.

Class	L (m)	D (m)	Upstream source area					Project Site			
			Dev. floodplain	Estab. floodplain	Terrace	Old Terrace	Isolated Conifer	Tall Dense	Tall Sparse	Short	Wetland
B2	1-2	0.1-0.2	6		4	1	6				1
B3	1-2	0.2-0.4									
B4	1-2	0.4-0.8									
B5	1-2	0.8-1.2									
C2	2-4	0.1-0.2	114	38	45	13	42	6	4	20	1
C3	2-4	0.2-0.4	2	5	2	3		2		10	1
C4	2-4	0.4-0.8				4		4			2
C5	2-4	0.8-1.2									1
D2	4-8	0.1-0.2	214	107	64	38	70	21	4	28	1
D3	4-8	0.2-0.4	18	7	11		6	15	4	31	5
D4	4-8	0.4-0.8			2			2			3
D5	4-8	0.8-1.2						2			1
E2	8-16	0.1-0.2	121	90	42	16	90	19	11	10	
E3	8-16	0.2-0.4	48	48	112	38	38	59	53	116	5
E4	8-16	0.4-0.8	2		19	10	4	5	4	9	5
E5	8-16	0.8-1.2				6					1
F2	16-32	0.1-0.2	15	39		7	19				
F3	16-32	0.2-0.4	21	118	106	29	130	30	4	38	4
F4	16-32	0.4-0.8		13	53	57	66	31	8	9	7
F5	16-32	0.8-1.2			8	13		4		3	1

Class	L (m)	D (m)	Upstream source area					Project Site			
			Dev. floodplain	Estab. floodplain	Terrace	Old Terrace	Isolated Conifer	Tall Dense	Tall Sparse	Short	Wetland
G2	>32	0.1-0.2									
G3	>32	0.2-0.4		10	9						
G4	>32	0.4-0.8		7	45	25		59	49		10
G5	>32	0.8-1.2			2	54		37	11	10	4

Sharp differences in the relative density of tree species were also observed between patch types (Table 4). Developing floodplains were dominated by cottonwood and red alder; fewer than 3% of trees were conifers. Established floodplains were also dominated by cottonwood but nearly 10% were conifers. The most common species on terraces was cottonwood; Douglas-fir and redcedar each represented just over 1/5 of the trees. Old terraces were dominated by redcedar and bigleaf maple. Remnant cottonwood pioneers persisted in many patches and others had colonized forest gaps. Notably, Douglas-fir was missing from old terraces in spite of its prevalence in terrace plots. This may be evidence of a legacy of selective logging, substantiated by obvious stumps.

Table 4. Relative (average) density of species in each patch. Units are percent of all sampled stems in a given patch type. Zero values removed for clarity.

Type	Species	Upstream Source area					Project Site			
		Dev. floodplain	Estab. floodplain	Terrace	Old Terrace	Isolated Conifer	Tall Dense	Tall Sparse	Short	Wetland
Broadleaf	*Acer macrophyllum*		1.5	10.0	30.6	1.5	11.9	5.0	1.3	1.4
	Alnus rubra	25.3	18.0	4.6	10.0		30.6	35.0	92.5	17.1
	Populus balsamifera trichocarpa	72.5	71.5	31.3	11.3	11.5	51.9	47.5	5.0	75.7
	Prunus emarginata			0.4	0.6	0.5	3.1	10.0		
Conifer	*Abies grandis*	0.8								
	Picea sitchensis				1.3					
	Pseudotsuga menziesii	0.8	3.5	24.2		84.5	1.9	2.5		
	Thuja plicata		2.5	21.3	41.3	2.0				
	Tsuga heterophylla	0.6	3.0	8.3	3.1					

At the project site, tall dense patches were dominated by cottonwoods and alders, with <2% conifers. Tall sparse patches were similar in composition. Short patches were vastly dominated by red alder. The open water wetland patches were almost exclusively cottonwood, with some red alder present.

OBJECTIVE 2 RESULTS: Total lateral wood recruitment in upstream source area

From 2005-2010, 60 hectares of forest present in 2005 (4.3% of 1,358 hectares) was eroded by the migrating channel (or 12 hectares per year and 0.09% of the forested valley eroded on an annualized basis). Several large floods occurred in the intervening period (i.e., annual peak discharge at Gage 12099200 exceeded 10,000 cfs in three of five years; WY 2005-2010), so estimates of wood recruitment from this time interval should be considered conservative (or above average) from the standpoint of ELJ design implications.

Total annual wood recruitment (L_i) to the upstream source area was estimated to be 5,819 m^3 or 5,854 pieces (exceeding one meter in length and 10 cm in diameter) (Table 5). Old terraces are disproportionately important to wood recruitment, contributing nearly half (47%) of the total volume despite composing only 17% of the total eroded area. These patches also contribute 86% of all 5-class and 44% of the G-class logs, which have the best chance of acting as key pieces and initiating new logjams. Developing floodplains contribute 40% of pieces but only compose 25% of the total eroded area, making this patch type disproportionately important to how many pieces of wood (regardless of size) enter the channel each year. These patches fringe most of the active channel and are eroded at a high rate (Latterell et al. 2006). The vast majority of wood recruitment to the upstream source area comes from 'natural' forest patches, but 4% – by volume – originates from the isolated conifer patches previously protected from the river by training levees near the Transcanada project site; this site primarily contribute Douglas-fir (Table 4).

Table 5. Summary of annual lateral wood recruitment rates in the upstream source area by size class and landform. Values in rows with alphanumeric codes represent counts of large wood pieces; units are numbers of pieces per year.

Metric	ANNUALIZED TOTAL	Developing floodplain	Established floodplain	Terrace	Old Terrace	Isolated conifer
Eroded area (hectares)	12	4	3	2	2	1
Pieces	5854	2363	1578	1093	539	281
Volume (m^3)	5819	397	865	1585	2730	242
B*	40	27		8	2	3
C*	785	490	140	97	33	25
D*	1618	976	371	160	65	45
E*	1733	720	452	362	120	79
F*	1367	149	559	348	183	128
G*	309		56	118	135	
2*	3460	1980	894	322	129	136
3*	1713	371	618	500	120	103
4*	534	10	67	250	164	42
5*	146			21	125	

A majority (66%) of the pieces enters the river as diameter class 2 (Fig. 6). The most common size class of wood recruited to the channel each year is D2, followed in order by E2 and C2 (Table 6). A relatively small but important number of pieces occur in the largest classes; only 1.6% of all pieces are in the G5-class. Some size class combinations simply do not occur (as whole trees).

Figure 6. Annual lateral wood recruitment to upstream source area by code.

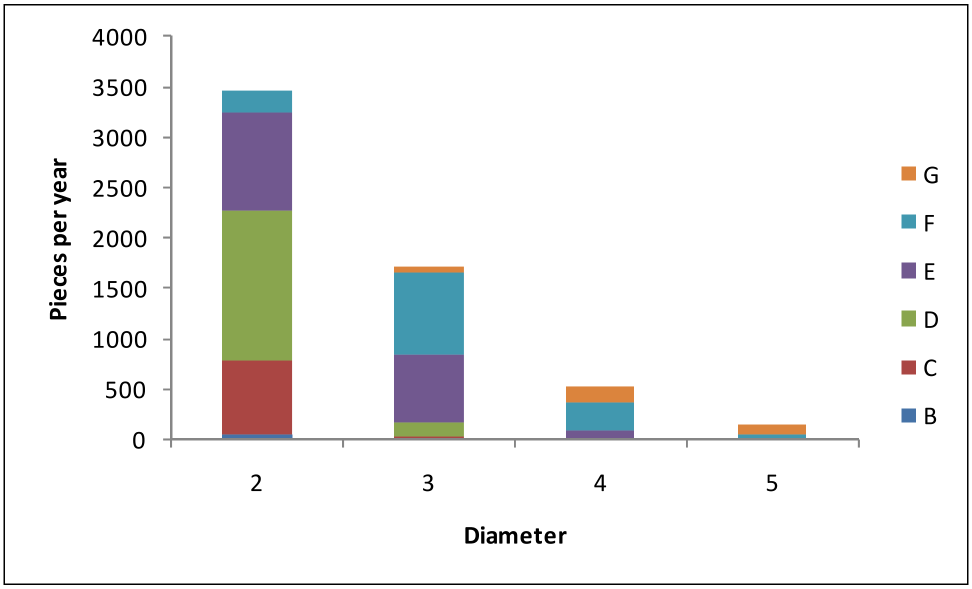
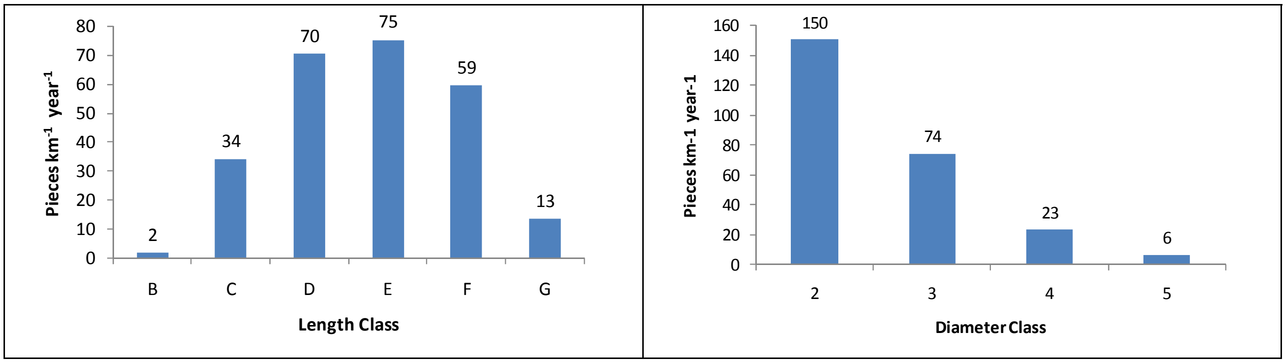


Table 6. Annual lateral wood recruitment to upstream source area by size class. Values represent numbers of large wood pieces in the corresponding length-diameter class; units are numbers of pieces per year.

Length Class	Diameter Class			
	2	**3**	**4**	**5**
B	40			
C	745	33	6	
D	1489	124	4	
E	972	680	70	10
F	213	823	293	39
G		51	160	97

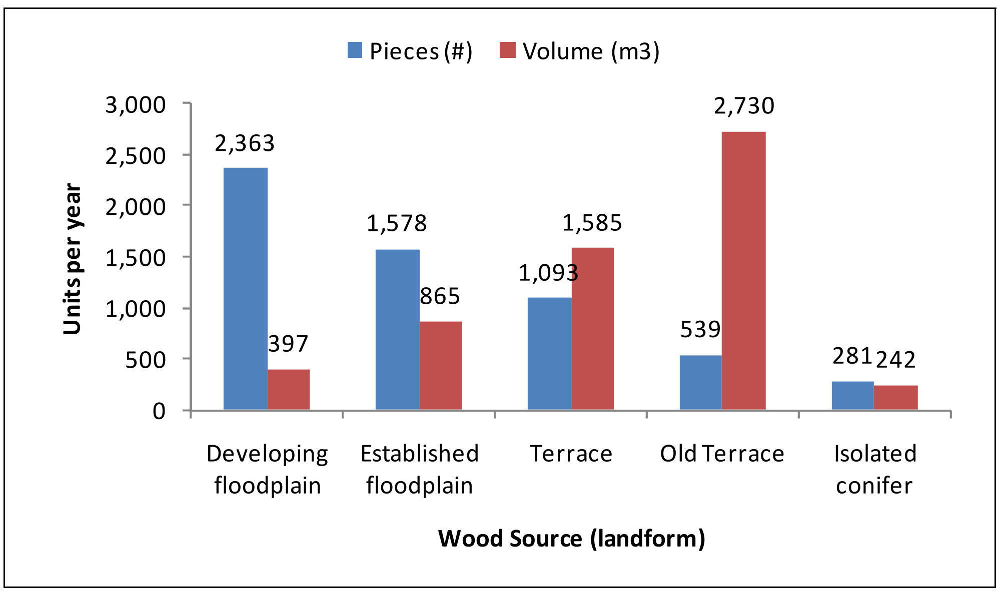
Wood recruitment from the forest to the channel in the upstream source area follows a unimodal normal distribution around E-class pieces (Fig. 7). In contrast, piece frequency declines exponentially across increasing diameter classes. Annual recruitment rates vary from two to 75 pieces km^{-1} across length classes, and from six to 150 pieces km^{-1} across diameter classes.

Figure 7. Length and diameter of large wood pieces annually recruitedby channel migration (on average) from the forest to the channel in the upstream source area. Values represent total recruitment divided by 23 km, as measured along the 2010 channel centerline.



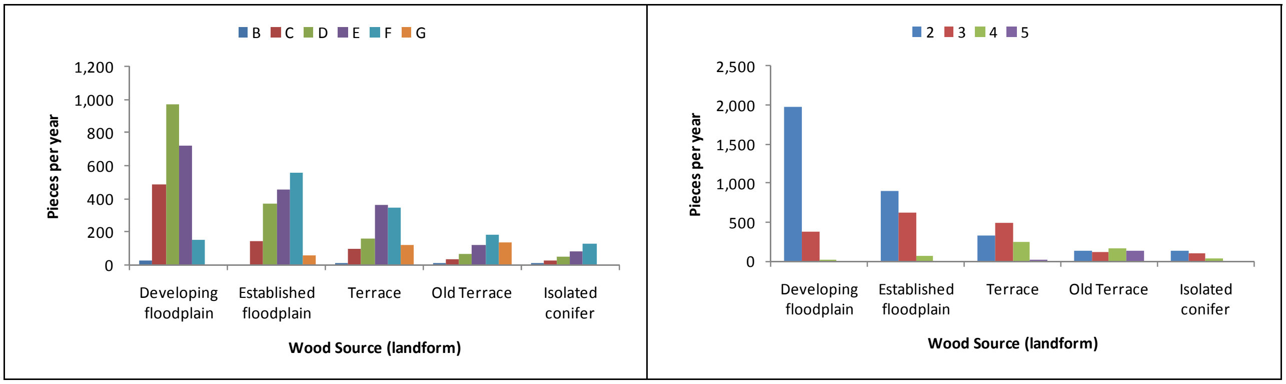
Mirroring patterns in observed PWL, patches contribute unevenly to actual wood recruitment (Fig. 8). The number of pieces recruited is inversely related to the total volume contributed, among patches. One exception is the isolated conifer landform. PWL in this patch type is relatively high (Table 2), but this patch type is restricted to a single location and therefore the contribution to overall wood recruitment in the source area is limited.

Figure 8. Annual lateral wood recruitment to the channel in the upstream source area, by landform.



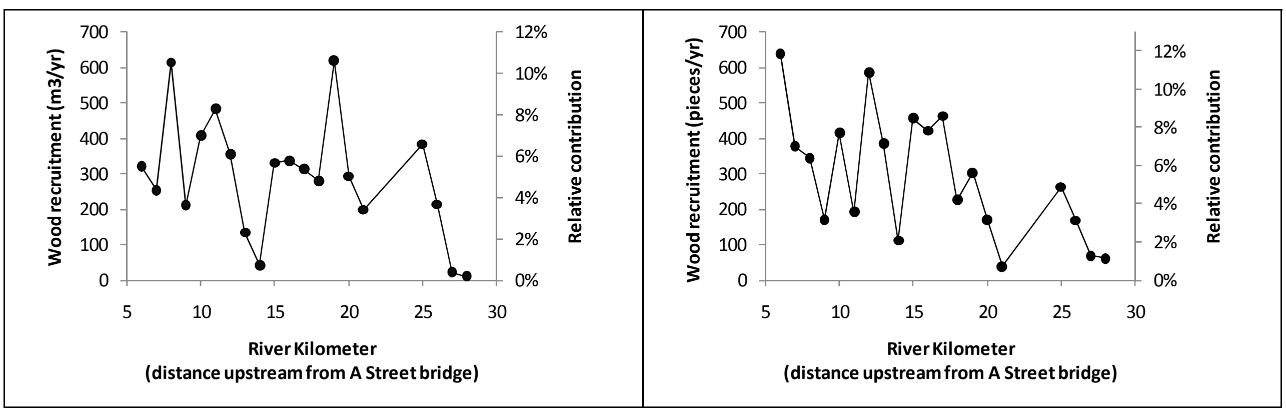
Estimates of wood recruitment also indicate the relative contribution of each landform type to overall wood recruitment to the source area as a function of length and diameter (Figure 9). Size class C and D primarily originated from the erosion of developing and established floodplains. Size class F primarily originated from established floodplains and terraces. Size class G mainly came from terraces and old terraces. Diameter class 2 pieces primarily came from developing floodplains. Diameter class three mostly came from established floodplains and terraces. Diameter class 4 came from terraces and old terraces, and class 5 came from old terraces, as would be predicted on the basis of PWL alone.

Figure 9. Annual lateral wood recruitment to the upstream source area by length (left panel) and diameter (right panel) from each landform type.



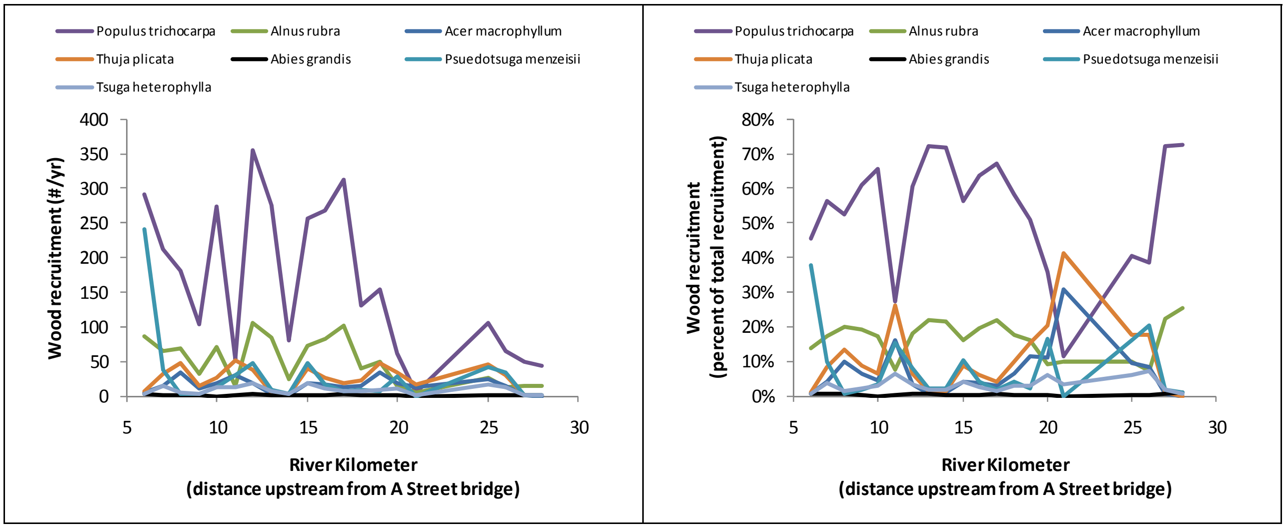
Understanding the upstream-downstream (longitudinal) variation in wood recruitment helps to identify critical source areas in terms of quantity, species, or size. Accordingly, the lateral recruitment estimates (based on observed erosion patterns) were plotted against the distance upstream from the A-Street bridge (taken to be the upstream limit of the project site). Note that this is not equivalent to USGS or King County river miles.

Figure 10. Annual lateral wood recruitment rate by river kilometer (RK) above A-Street Bridge. Left panel illustrates volume and right panel illustrates density. Refer to Vicinity Map for River Kilometers.



Recruitment, by volume, generally ranged from 200-600 m^3 km^{-1} throughout the upstream source area, but was substantially lower around RK 13 and 14 (a straight reach flanking the northeast valley wall), as well as RK 25-28 (immediately downstream from the Lake Tapps diversion). Locations with the highest recruitment rates were RK 8, 12, and 19. At all three locations, the river is actively meandering through an old terrace on the outside bend (wood hotspot). Cottonwood dominated recruitment by volume throughout virtually the entire valley, though Douglas-fir was locally important at RK 6 (as explained below).

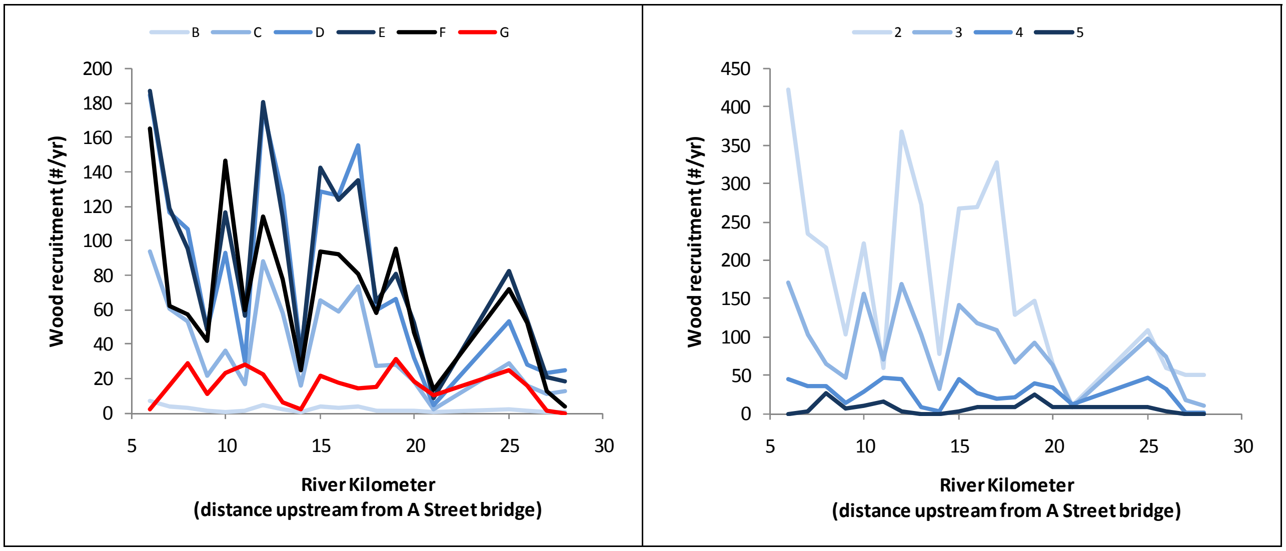
Figure 11. Lateral wood recruitment rate to the upstream source area by tree species and river kilometer, as measured by the distance along the channel centerline from A-Street Bridge.



Recruitment, by number of pieces, generally declined with increasing distance upstream (Fig. 10). This pattern is likely the result of a transition from expansive broadleaf riparian forests in the lower valley, transitioning to conifer dominated riparian forests in the narrower valley below the diversion (Fig. 11). Longitudinal differences in channel migration rates may also contribute to this observation. Whatever the reason, the highest recruitment rate in the entire source area is at RK 6. At this location, the river is meandering through a failing training levee and encroaching on dense fir stands previously isolated from the river (Fig. 11). Cottonwood dominated recruitment by number in almost every location except RK 21-22, where inputs of redcedar and bigleaf maple were more frequent.

Longitudinal patterns were evident in the diameter and length of recruited wood (Fig. 12). For example, the supply of small-diameter pieces was much greater than that of large diameters in the lower valley, but the supply rate generally converged with other diameters farther upstream. Peaks in the recruitment of large diameter (e.g., Class 5) logs coincided with RKs 8, 12, and 19, which were previously identified as wood hotspots. Recruitment of tall trees in the G-class occurred at similar rates throughout much of the valley, but there was substantial overlap in the remainder of the size classes.

Figure 12. Lateral wood recruitment rate to the upstream source area by size class and river kilometer, as measured by the distance along the channel centerline from A-Street Bridge.



OBJECTIVE 3 RESULTS. Fluvial transport inputs from upstream source area to the project site

Total fluvial transport of large wood from the upstream source area (Q_o) to the project site is estimated to average 640 m^3 yr^{-1} or 644 pieces yr^{-1} (over the long term), representing 11% of the total lateral recruitment between Transcanada and the Lake Tapps Diversion (Fig. 13). This value is equivalent to Q_i for the project site (representing fluvial inputs from upstream source area). Most (83%) of the pieces are predicted to be in diameter classes 2 and 3 (<30 cm in diameter). Five percent, or 25 pieces, are expected to be in diameter class 5. Approximately eight percent, or 44 pieces, are expected to attain length class G.

Figure 13. Fluvial transport outputs from upstream source area to the project site by diameter (x-axis) and length class (stacked bar color).

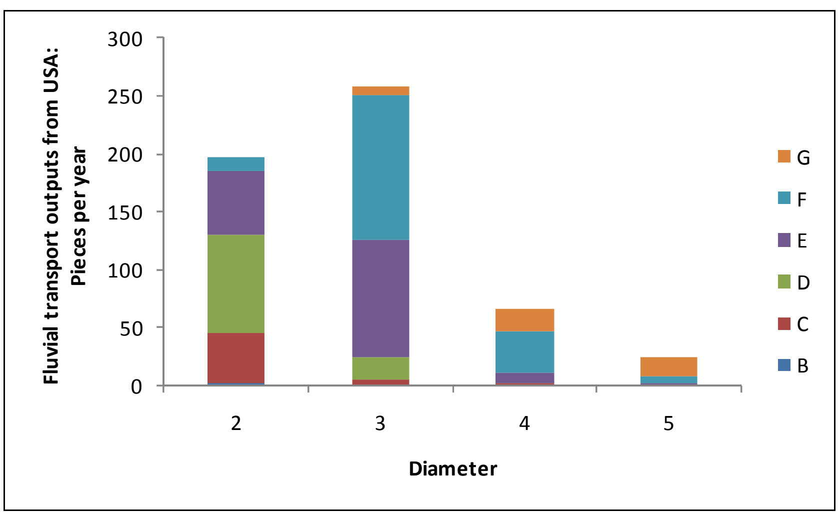


Table 7. Predicted long-term average annual fluvial transport outputs from upstream source area to the project site by size class. Units are large wood pieces per year.

Length	Diameter				Proportion
	2	3	4	5	
B	2	0	0	0	0.00
C	43	5	2	0	0.09
D	85	19	1	0	0.19
E	55	103	9	2	0.31
F	12	124	36	7	0.33
G	0	8	20	16	0.08
Proportion	0.36	0.47	0.12	0.05	

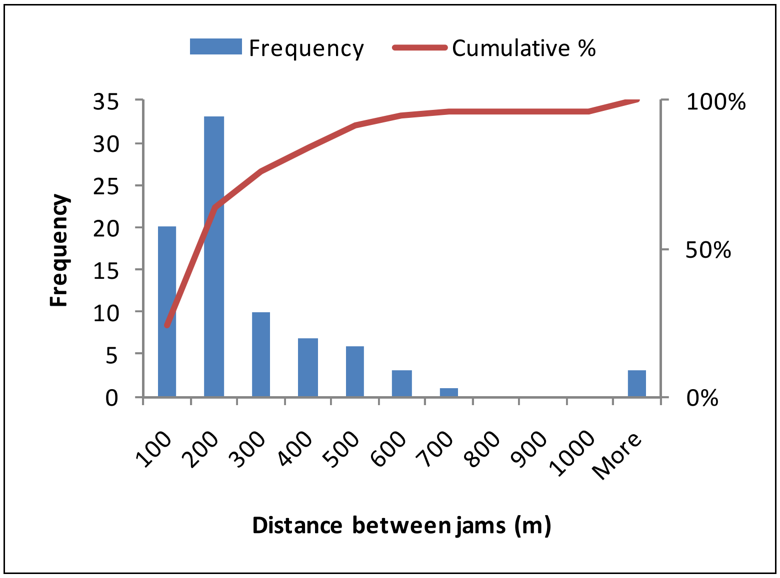
Fluvial transport output calculations were based on a combination of empirical measurements, literature values, and assumptions (Table 8). Estimates for L_i were measured as described in Sections 1.1 and 1.2. A value of 1.0 was assumed for Φ, for all pieces, holding to Benda and Sias (2003); the average width of the active (unvegetated) channel in the upstream source area is 103 m (±36 SD), exceeding the height of all trees in the riparian forest. This likely overestimates the true mobile fraction of wood recruitment because larger trees may have diameters and root wads sufficient to stabilize them in the channel. This means flux estimates presented here are likely higher than the true value.

Table 8. Critical parameters in wood flux calculations for the upstream source area.

Parameter	Value	Units	Source	Description
L_i	0.253 (0.255)	volume m^{-1} (pieces)	Measured	Average annual lateral input rate (2005-2010 over 23 km)
Φ	1.0		Measured	Proportion of pieces < bankfull width (*u/w*)
ξ	2,530	m	Calculated	Average lifetime transport distance
J	164	m	Measured	Median distance between impeding jams in 2010 (n = 83)
ζ	27	years	Literature	Average piece lifetime
α	5	years	Literature	Median jam longevity (site-validated)
β	0.35	proportion	Measured	Average proportion of channel spanned by jam in 2010 (in plan)

The median distance between transport-impeding jams (J) was 164 m, but observed values ranged nearly two orders of magnitude, from 40 to 3500 m (Fig. 14). Accordingly, the median value was used instead of the average (Benda and Sias 2003).

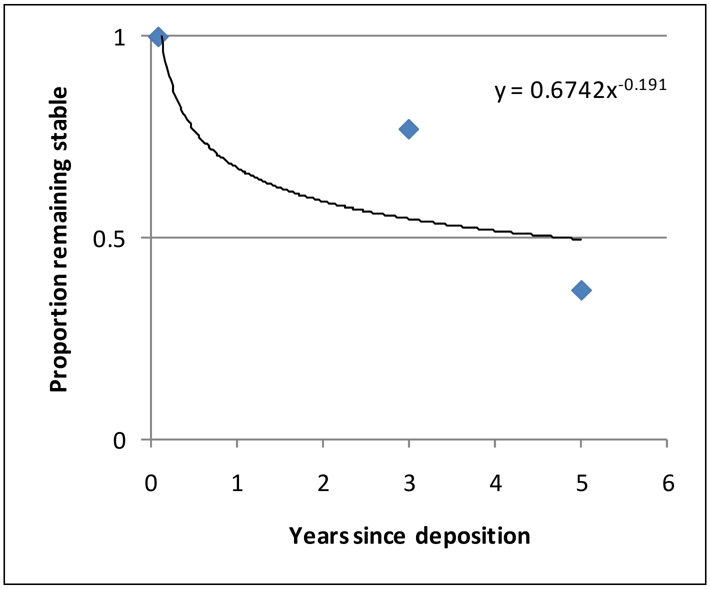
Figure 14. Distance between transport-impeding jams in 2010. Median value is 164 m.



The weighted average piece lifetime (ζ) was 27 years, which was assumed to be the time required for recruited wood to decay to a point where it was smaller than 10 cm in diameter. Using the midpoint diameters for classes 2, 3, 4, and 5, average piece lifetime was estimated to be 14, 37, 60, and 83 years, respectively.

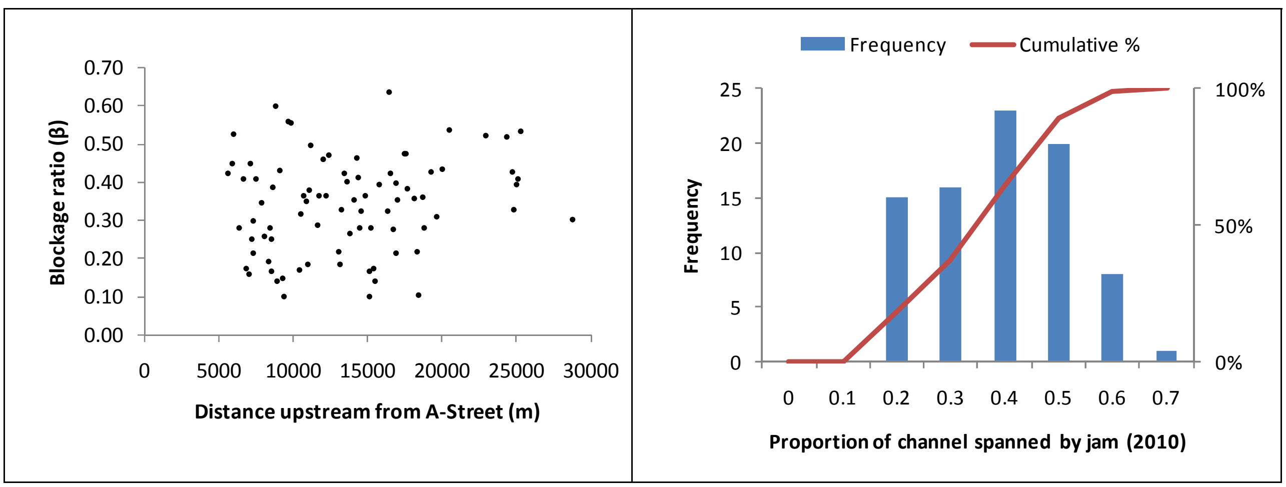
Median jam longevity (α) was estimated at five years, based on two corroborating sources. In the Queets River, half of the logjams formed in year *t* were observed to be displaced by year *t+5* (Latterell and Naiman 2007). The Queets River differs from the White River in significant ways like peak flow magnitude and forest stand structure. However, this value was considered to be a reasonable approximation. To validate this estimate, logjams present in 2005 and 2007 were mapped and treated as cohorts, as in Latterell and Naiman (2007). Maps were compared to subsequent orthophotos to quantify the proportion of the initial cohort that remained stable as a (power) function with time as the independent variable (Figure 15). The results were not sufficient to define a precise retention rate, but did suggest that the assumptions were plausible.

Figure 15. Logjam retention curve for the White River source area, based on logjam cohorts from 2005 and 2007.



The observed median value for jam blockage ratio (*β*) was 0.35 in 2010. The blockage ratio was quite variable among jams, however, ranging from one to over six-tenths of the channel (in plan view). The actual trapping effectiveness of the jam is more complicated than can be captured by this simple statistic, but it should provide a reasonable approximation.

Figure 16. Measurements of jam blockage ratio from 2010 orthophotos.



OBJECTIVE 4 RESULTS: Wood budget for Project site

Natural avulsion of the mainstem channel – based on active channel area boundaries provided by Herrera – is estimated to erode 6.1 hectares of forest and consequently deliver a one-time pulse of wood from standing forests, measuring 2,733 m^3 in total volume and containing 1,144 pieces (Fig. 17). This represents a conservative assumption of a single-event full avulsion. The 6.1 hectares is composed of 0.91 ha of tall dense patches, 0.97 ha of tall sparse patches, 2.20 ha of short patches, and 2.02 ha of open water wetland. The tall dense patches are estimated to contribute 40% of the volume but only compose 15% of the eroded area. Red alder are likely to compose the majority of the pulse (64%), followed by cottonwood (28%). The majority of the pieces are estimated to be E-class and shorter and 3-class and smaller (Table 9).

Figure 17. Sources of wood delivered to the channel at the project site.

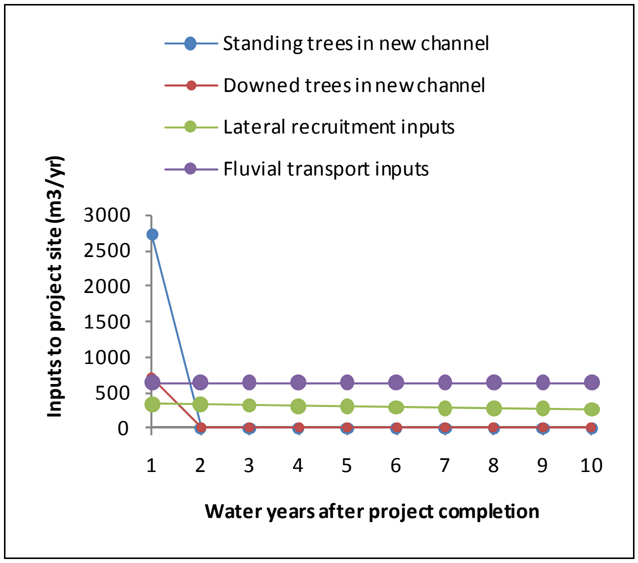
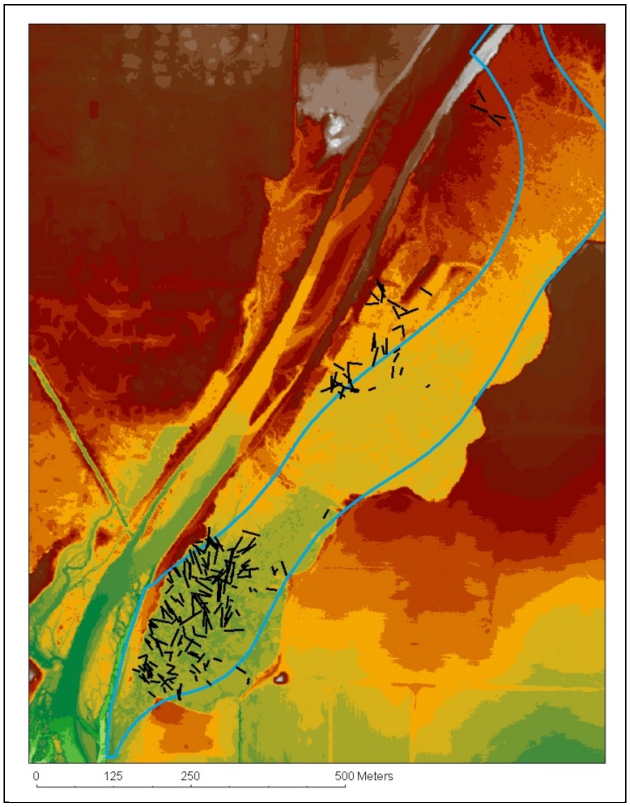


Table 9. Pulse inputs from channel re-location into standing forests at the project site.

	Diameter Class				
Length Class	2	3	4	5	*Proportion*
B	1				*0.00*
C	54	26	8	1	*0.08*
D	86	96	7	3	*0.17*
E	50	371	37	1	*0.40*
F		122	69	11	*0.18*
G			121	74	*0.17*
Proportion	*0.17*	*0.54*	*0.21*	*0.08*	

In addition to recruiting standing wood, a full channel avulsion would also capture 201 downed trees (725 m^3). Most (57%) of these are in the F-length class and diameter classes 3 and 4 (82%, combined) (Table 10). Virtually all of the downed logs that were mapped in photos were located within the footprint of the new channel (Fig. 18).

Figure 18. Downed trees at the project site, represented by black lines on a background indicating topographic relief of the ground surface. The boundaries of the relocated channel are show in blue.



In addition to the initial pulse of wood from channel avulsion, additional wood could be recruited to the channel from ongoing channel migration and adjustment at the project site. In 2010, the project site contained 8.3 hectares of tall dense patches, 4.12 hectares of tall sparse patches, 5.51 hectares of short patches, and 2.02 hectares of open water wetland patches. This means the whole site has an initial PWL of 4,760 stems and 14,357 m^3. Channel avulsion could potentially reduce this amount by 1,144 stems and 2,733 m^3. After this initial pulse enters the channel, the remaining PWL available for recruitment by more gradual channel migration is 3,616 stems and 11,624 m^3. The channel is assumed to completely avulse in the first water year (for the purpose of simulation), and further channel migration would recruit additional wood from remaining forests as an exponential decay function of time, where *k* is 0.03 (i.e., $L_i = S - (S * e^{-kt})$, based on observed rates of forest erosion in an unconfined alluvial river (Latterell et al. 2006).

Table 10. Pulse inputs from channel avulsion into downed wood at the project site.

	Diameter Class				
Length Class	2	3	4	5	*Proportion*
B					*0.00*
C					*0.00*
D		2	2	1	*0.02*
E		26	25	11	*0.30*
F		48	46	20	*0.57*
G		9	8	4	*0.10*
Proportion	*0.00*	*0.42*	*0.40*	*0.17*	

Parameters for estimating export rates (Q_o) of wood from the project site (local origin only) were estimated from design drawings and specifications and from literature values as in the upstream source area (Table 11). In this scenario, a value of 1.0 was assumed for Φ, for all pieces, holding to Benda and Sias (2003); the average width of the active (unvegetated) channel at the project site is expected to be 130 m, exceeding the height of all trees in the riparian forest.

The median distance between transport-impeding jams (J) was assumed to be 275 m in the first year , corresponding to the average distance between the six planned ELJs. Natural jams are expected to form therafter; seven additional jams were assumed to form naturally between the ELJ clusters at the upstream and downstream ends of the sites, at densities that match the upstream source area: one jam every 164 m. This brought the total number of jams to 14 jams over a reach length of 1,415 m, which means J is 109 m. This conforms to the expectation that the project site will likely have more jams than the upstream source area, at least during the design life of the ELJS; they are likely to persist longer, on average, than natural jams.

The weighted average piece lifetime (ζ) was 34 years in the first year, which was assumed to be the time required for recruited wood to decay to a point where it was smaller than 10 cm in diameter. Piece lifetime declines to 29 years after the first year; inputs are dominated by fluvial transport from the upstream source area, which have an average piece lifetime of 28 years.

Jam longevity (α) was estimated at 50 years for the first year, based on design specifications for the ELJs (or 10 times the longevity of naturally occurring jams in the upstream source area). The actual longevity of these structures over multiple decades remains untested. Jam blockage ratio (β) is 0.21 (or 27.4 m/130 m) in the first year after project completion, then increases to 0.35 (or 45.5 m/130 m) in the second year as new wood accumulates on ELJs; this value matches β in the upstream source area and is based on the assumption that jams will develop similar characteristics at the project site.

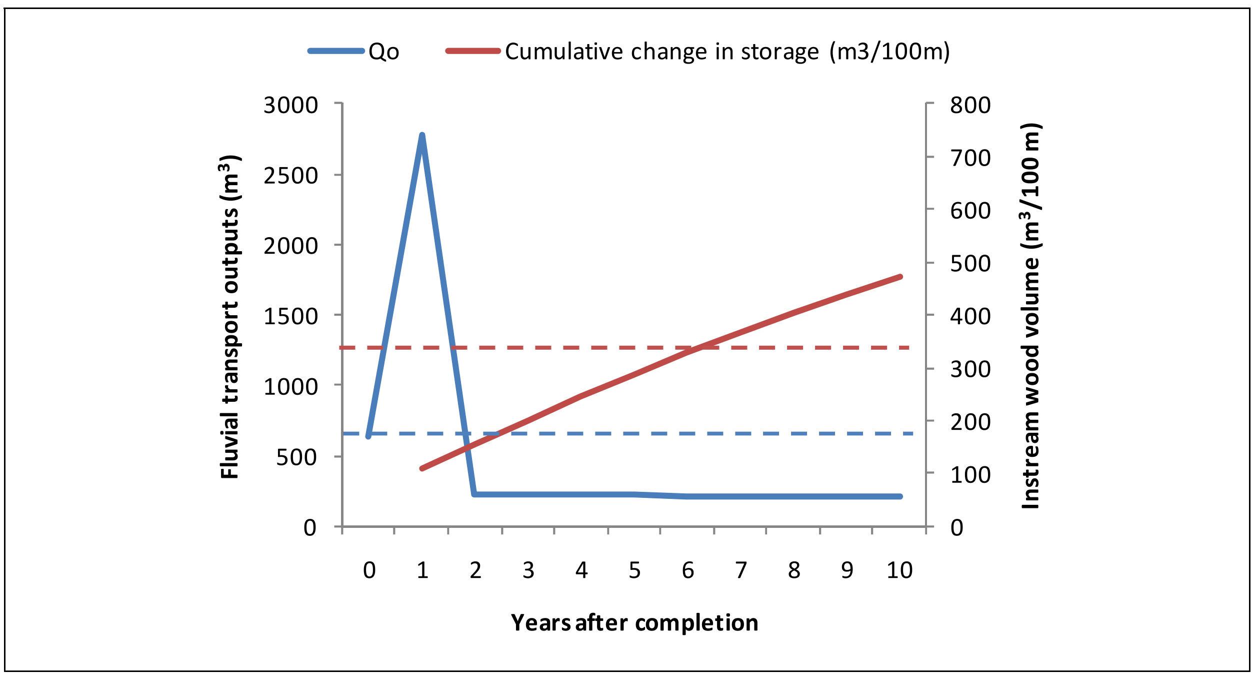
In year 1, jam longevity α was assumed to be 50 years, as per design specifications. After year 1, 7 of 13 jams are assumed to be naturally formed and so exhibit similar longevity to those in the upstream source area (where α is 5 years). Accordingly, in year 2 and thereafter, the average jam longevity is simply the average of 50 and 5, or 28 years.

Table 11. Critical parameters in fluvial wood transport calculations for the project site, assuming a full avulsion scenario.

Parameter	Value	Units	Source	Description
L_i	2.69-0.19 (1.03-0.06)	Volume in m^3 (pieces)	Measured	Average annual lateral input rate (2005-2010 over 1.415 km)
Φ	1.0		Measured	Proportion of pieces < bankfull width (*u/w*)
ξ	886-328	m	Calculated	Average lifetime transport distance
J	275-196	m	Measured	Median distance between impeding jams
ζ	34-29	years	Literature	Average piece lifetime
α	50-28	years	Literature	Median jam longevity
β	0.21-0.35	proportion	Measured	Average proportion of channel spanned by jam

Fluvial transport output from the project site is conservatively estimated to be up to 2,780 m^3 (1,312 pieces) for a full avulsion in the first year (Fig. 17). Wood export is expected to decline after the initial pulse. For example, the annual export rates (attributable to wood recruitment from channel migration) are predicted to decline from 226 m^3 (173 pieces) in the second year to 209 m^3 (168 pieces) per year within a decade (Fig. 19).

Figure 19. Estimated (simulated) fluvial transport output rate from project site and changes in instream wood volume over time. The dashed red line indicates levels of wood loading that would achieve a "good" habitat quality rating. The dashed blue line indicates the background level of fluvial transport outputs.



The proposed wood budget suggests that the project site will accumulate about 1,530 m^3 (or 108 m^3 per channel width in the first year), and approximately 700 m^3 in each of the subsequent nine years (Fig. 19). Consequently, the project site is projected to accumulate roughly 7,000 m^3 of wood (or a total of 473 m^3 per channel width) over the first decade after the project is completed. The project site is predicted to retain between 34 to 74% of the total wood delivery to the reach from local and upstream sources, depending on the year. In year one, these estimates predict wood transport from the project site could nearly quadruple the net export of wood to downstream reaches (2,140 m^3 above background levels). However, the project could potentially reduce the amount of wood reaching downstream reaches to <35% of pre-project levels, on average, by the second year after completion.

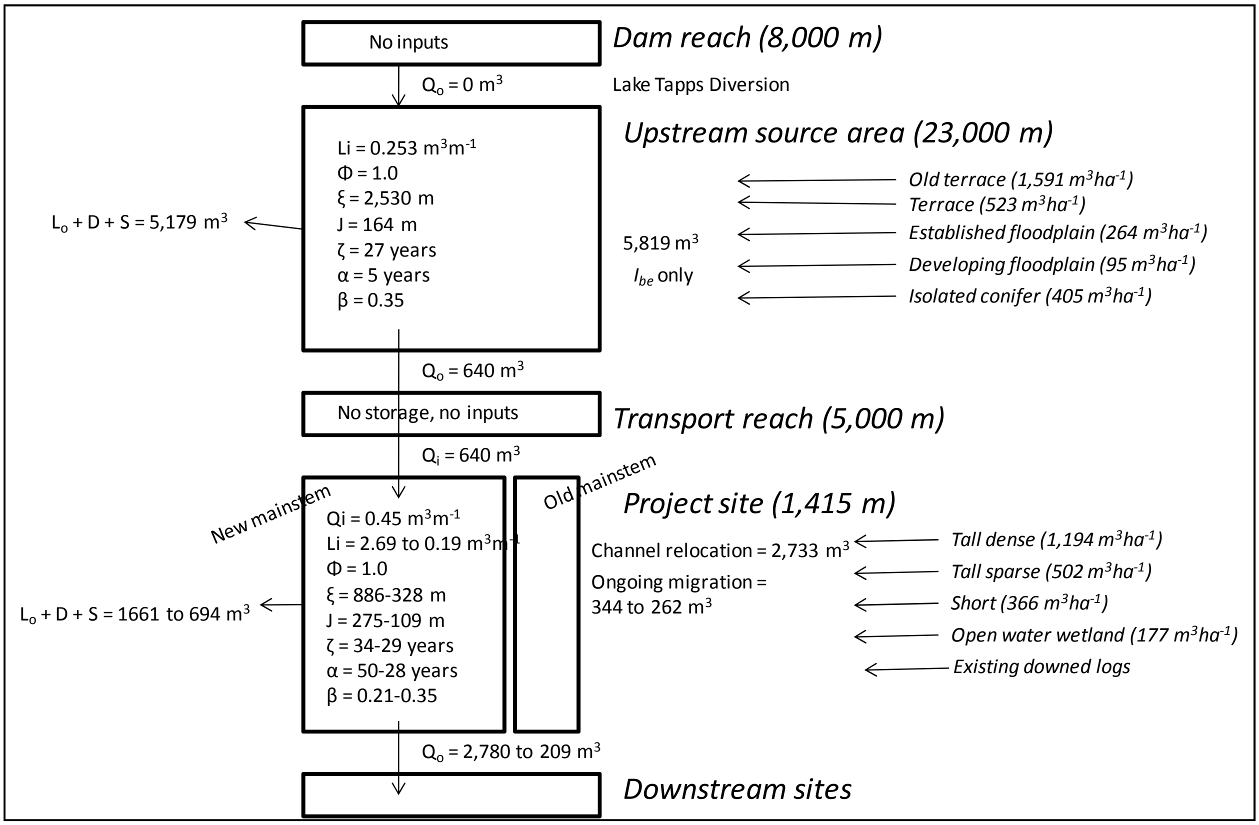
The key findings of this study are synthesized in Figure 20, where boxes represent places where large wood is stored and generated and arrows indicate the direction of large wood movement. The upper box represents the 8 km-long dam reach; the portion of the White River mainstem between Mud Mountain Dam and the Lake Tapps diversion. Little or no wood is estimated to move from the dam reach into the upstream source area, so Q_o is zero.

The 2nd box from the top represents the 23 km-long upstream source area. Each riparian forest patch type is listed on the right; parenthetical numbers indicate the potential wood loading for each patch type. These sources combine to deliver a total of nearly 6,000 m^3 of large wood to the channel per year, on average. Parameters used for calculating fluvial transport outputs of large wood – from the upstream source area to the project site – are listed inside the box. The total amount of large wood leaving the upstream source area is estimated to average 640 m^3 annually; the rest is stored or lost to overbank deposition and decay.

The third box from the top represents the transport reach; the 5 km-long reach between the TransCanada levee site and A-Street, near the project site. No parameter are listed because it has been assumed that, for the purpose of this study, virtually all the wood entering the reach passes through and reaches the project site; accordingly, Q_o is 640 m^3 , which is equivalent to Q_i, the fluvial transport input rate to the project site.

The fourth box from the top represents the 1.4 km-long project site, which begins at the A-Street crossing. Two boxes are shown. The small box on the right represents the old channel, which for simplicity, is assumed to be completely abandoned after a full channel avulsion of the White River into the new channel; the box on the left. As in the 2nd box from the top, the riparian forest patch types are listed, and their potential wood loading is listed in parentheses. The arrows pointing to the channel indicate the total amount of wood they collectively are estimated to contribute to the channel via the processes of full avulsion and gradual migration. As before, the parameters use in wood transport calculations and budgeting are listed inside the box. In this case, the fluvial transport output estimate – indicated by the arrow and quantity leaving the project site – vary to indicate that the rate will vary greatly, depending on when and if a full-scale channel avulsion occurs.

Figure 20. Estimated wood budget for upstream source area and project site.



IV. CONCLUSIONS

1. This study indicates the White River will likely deliver a substantial quantity of wood to the project site. The quantity will vary between years – perhaps by an order of magnitude – but the long-term average is estimated to be 600 $m^3 yr^{-1}$, or roughly 600 pieces, or less[4]. Of course, this assumes that the flow conditions of the last five years accurately represent future conditions. It would be valuable to monitor the actual input rate to validate the accuracy of this prediction, and the utility of this wood budgeting approach. If large and frequent flooding does not persist into the future, the long-term average will likely be smaller than reported here. The simulation results should be interpreted in this context; it is not possible to predict fluvial transport input rates of large wood for a single year with confidence. Rather, the simulation presented in this study characterizes a scenario that likely reflects average conditions during a multi-year spate of relatively high flows.

A full channel avulsion may or may not occur; if it does, substantial quantities of wood will likely enter the project site because the forests upstream are actively eroding from natural channel migration. A partial avulsion may occur instead, in which the existing mainstem persists; this study does not explore the consequences of such an event. In any case, even more large wood could reach the project site if not for an abundance of large natural logjams upstream, which trap some of the floating wood. Most of the trees entering the river are small enough to be transported some distance downstream; <5% are

[4] But see qualifications in following sections; these figures likely overestimate actual fluvial transport inputs.

likely to be large enough to function as key members of stable natural logjams (Fig. 7, Table 7). Large pieces primarily come from old terraces, which are scattered throughout the source areas (Fig. 12); these terraces supply nearly half of the wood volume to the river (Fig. 8). However, younger, broadleaf-dominated stands are more pervasive (Fig. 11) and produce the majority of wood pieces (Fig. 8). So, in a typical year, several hundred large trees (i.e., potentially key members) fall into the source area, along with thousands of small trees (Table 6). This leads to the formation of abundant and large natural logjams; they are spaced about one-and-a-half channel widths apart and typically block about one-third of the active channel (Fig. 16). The close spacing and large size of the natural logjams in the upstream source area prevents about 90% of the large wood inputs from reaching the project site (Fig. 20).

This study indicates that the design of engineered logjams should consider that this study estimates roughly 80% of the pieces entering the project site from upstream will be <30 cm in diameter; only 5% are likely to exceed 80 cm. There is reasonable confidence in the length of the pieces of wood when they enter the channel, but breakage could not be reliably addressed. For example, this analysis suggests about one-third of the large wood inputs will be one to eight meters, one-third will be eight to 16 meters, and another third will be 16 to 31 meters long. But the river will inevitably snap and shorten many pieces. Accordingly, the observed length distribution could be more heavily skewed toward short pieces than what is reported here; relatively few trees are expected to arrive at the project site fully intact.

2. This study indicates that the project site is likely to initially increase the amount of wood reaching downstream areas. But eventually, as the site evolves, the project site may reduce the amount of wood reaching downstream areas, at least until large wood loading at the site approaches reference conditions. *To be clear, this study does not provide the basis for predicting that the channel will entirely avulse in the first year after the project is completed.* Instead, it provides a scenario to consider the potential consequences of channel avulsion into the project site to inform design team's decisions as they balance risk, benefits, and costs. The scenario evaluated here assumes the channel relocates entirely and in a single year because this likely represents an extreme and conservative scenario in which large wood inputs reach their highest possible rate.

The channel avulsion scenario is plausible, but no one can accurately predict the timing or extent of the event. Fortunately, the wood budget at the project site is not very sensitive to the timing of the channel avulsion. However, the budget – at the project site – would be invalidated if the channel simply braids, or switches gradually, producing several small, long-lived channels. These channels will have very different transport capacity for wood than the channel used in the simulation. If the channel braids or splits, the project reach would be expected to trap even more wood. So more would be trapped on site, and less would reach downstream locations. A key question remains: Is there a point at which the project reach will 'saturate' with large wood, after which the amount of wood passing to downstream sites climbs back to (or surpasses) pre-project levels? This could happen at some point in the first decade after the project is finished – probably after wood loading approaches 300-400 m^3 per channel width.

3. This study required many simplifying assumptions[5]; accordingly, several qualifications limit the reliability and scope of the findings. In general, it must be acknowledged that wood budgeting is a new analytical approach, relative to other methods in stream ecology. Though few field studies have validated the approach, it is the state of the art for predictive quantitative theory in the study of wood in

[5] Key assumptions and qualifications are plainly stated in the body of this report; refer to these, as well, because they are not restated here.

streams (Benda and Sias 2003). Most importantly, in my view, it is based on sound logic and fairly conservative assumptions. The framework is “useful for defining the field measurements that are necessary to construct empirical mass budgets of LWD [large woody debris] in streams over large temporal and spatial scales” (p. 14, Benda and Sias 2003). However, this study focuses on a small area and short period of time, which means the near-term wood budget may not resemble the long-term average. This is a major limitation, but there seems to be no alternative method with greater short-term accuracy. Nor am I aware of any previous applications of Benda and Sias (2003) technique to a project site, for comparison. Most of the assumptions made in this report tend to overestimate fluvial wood transport rates, so this should be considered in use of these findings. Actual fluvial wood transport is likely to be somewhat lower than estimated here.

V. ACKNOWLEDGEMENTS

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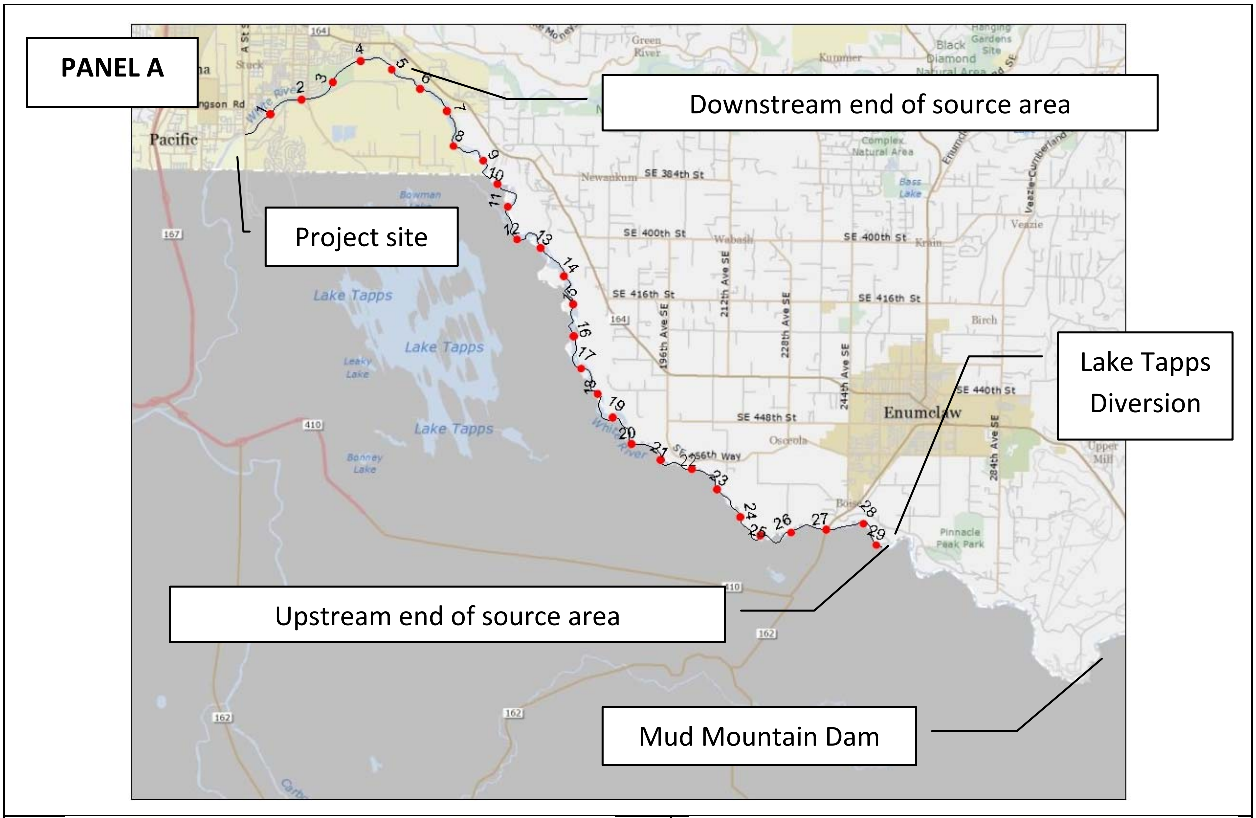
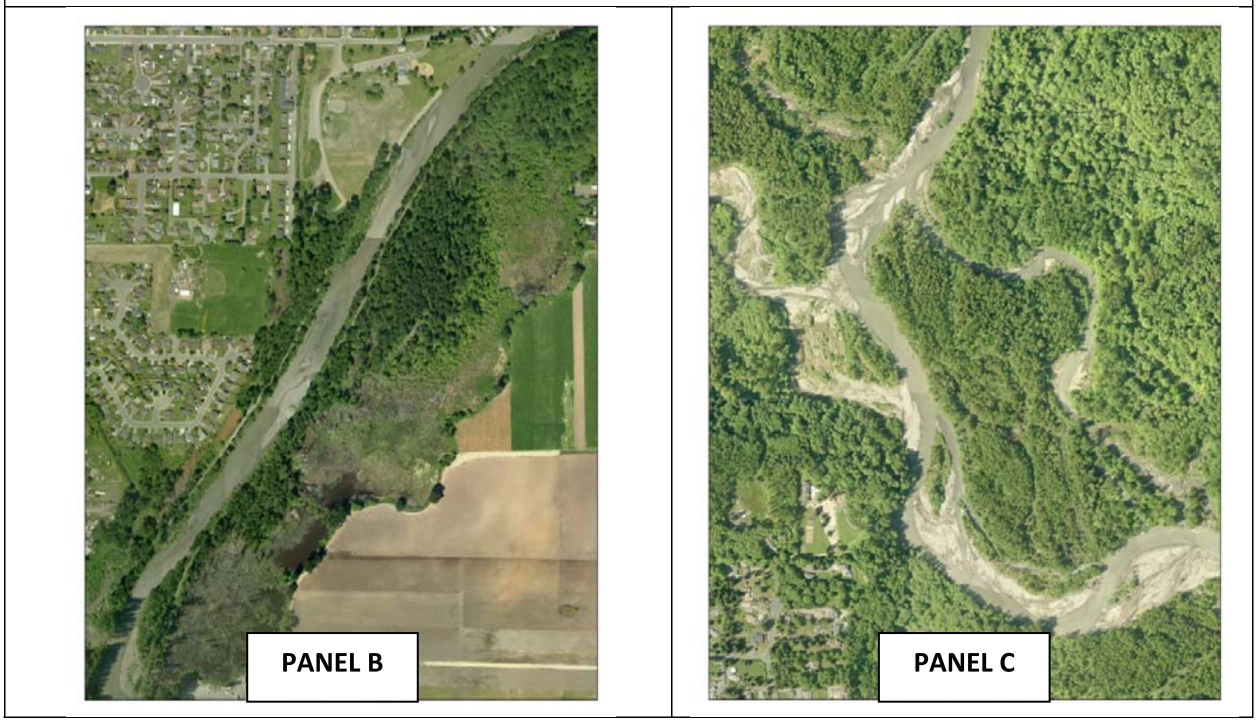
VII. APPENDICES:
VICINITY MAP AND SITE PHOTOS

Vicinity Map

Panel A indicates key locations and the distance above A-Street, in kilometers. Panel B shows the current condition of the project site. Panel C shows the condition of the upstream source area, for comparison. Each aerial photo is shown at 1:5,000 scale.





Site Photos

ID	AGE	TYPE	SITE PHOTO
Plot 15	10	Developing floodplain	No photo
Plot 6	15	Developing floodplain	
Plot 24	15	Developing floodplain	

Plot 14	20	Developing floodplain	
Plot 23	20	Developing floodplain	

Plot 3	25	Developing floodplain	
Plot 4	25	Developing floodplain	

Plot 8	25	Developing floodplain	
Plot 13	25	Developing floodplain	

Plot 16	25	Established floodplain	
Plot 5	30	Established floodplain	

Plot 7	35	Established floodplain	
Plot 11	35	Established floodplain	

Plot 22	35	Established floodplain	
Plot 17	60	Terrace	

Plot 9	65	Terrace	
Plot 10	65	Terrace	No photo
Plot 12	80	Terrace	

Plot 2	90	Terrace	
Plot 20	90	Terrace	

Plot 18	110	Old terrace		
Plot 21	110	Old terrace		

Plot 1	150	Old terrace		
Plot 19	150	Old terrace		

Plot 34	60	Isolated conifer	
Plot 35	60	Isolated conifer	

Plot 36	60	Isolated conifer		
Plot 37	60	Isolated conifer		

Plot 38	60	Isolated conifer	
Plot 25	90	Short	

Plot 29	90	Short	
Plot 31	60	Tall Dense	

Plot 30	60	Tall Sparse	
Plot 27	70	Tall Dense	

Plot 26	90	Tall Dense	
Plot 28	90	Tall Dense	

Plot 32	60	Wetland