

## Water Resources Research

### RESEARCH ARTICLE

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#### Key Points:

- Wood flux is strongly influenced by the shape and patterns of water discharge at varying time scales
- Flow history is the most important variable for prediction of the magnitude of wood flux
- Repeat monitoring of temporary storage with new or historic imagery is a very useful tool for constraining wood flux histories

#### Supporting Information:

- Supporting Information S1
- Data Set S1
- Movie S1

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## The pulse of driftwood export from a very large forested river basin over multiple time scales, Slave River, Canada

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**Abstract** This study presents a case study of large wood transport on the great Slave River in northern Canada with the objective to better understand the processes of and variability in pulsed wood fluxes from large forested catchments. We use a varied approach, integrating field characterization of wood, historical anecdotes, repeat aerial imagery of stored wood, and time-lapse imagery of moving wood, for a robust analysis and synthesis of processes behind pulsed wood flux, from yearly uncongested export to rare congested wood floods. Repeat monitoring of known sites of temporary storage with new or historic imagery proved to be a very useful tool for constraining wood flux histories. Pulsed wood export on the Slave River is not an artifact of episodic recruitment from major up-basin disturbances, but rather reflects decadal- to half-century-scale discharge patterns that redistribute wood recruited from channel migration and bank slumping. We suggest that the multiyear flow history is of paramount importance for estimating wood flux magnitude, followed in declining importance by the yearly sequence of peaks and the magnitude and characteristics of the rising limb of individual floods.

**Plain Language Summary** Driftwood is an important element of landscapes and ecosystems because it provides essential nutrients and habitat in many water environments. This work describes how driftwood is transported through really big rivers at multiple time scales from days to decades to a half century. We characterize large driftwood floods, which are events of massive floating mats of driftwood, as well as transport of wood within ice from a relatively pristine forested river basin. Describing driftwood transport in a mostly unaltered basin, such as the Slave River, helps scientists understand the impact of driftwood depletion on river, lake, and ocean ecosystems from human land use practices, such as dams and deforestation.

### 1. Introduction

Wood transport processes have arguably received the least attention by river scientists compared to recruitment and storage of wood [Ruiz-Villanueva *et al.*, 2016a; Kramer and Wohl, 2016]. Furthermore, most large wood studies focus on headwater rather than lowland rivers [Wohl, 2016; Seo *et al.*, 2010]. In the recent wood literature, some of the largest rivers are the Queets River, Washington [Collins *et al.*, 2012], Sacramento River, California [MacVicar *et al.*, 2009], Aïn River, France [MacVicar and Piégar, 2012], Tagliamento River, Italy [Ravazzolo *et al.*, 2015], Saint-Jean River, Gaspé Peninsula, Québec [Boivin *et al.*, 2015, 2016], and Lower Roanoke River, South Carolina [Schenk *et al.*, 2014]. For perspective, the Slave River in northern Canada described in this paper has a drainage area 10–100 times larger, is 10–100 times wider, and has maximum and average flows 10–100 times greater than these rivers. Thus, this case study on the Slave River expands our understanding of how large wood processes aggregate in great rivers with large forested basins. Export estimates and descriptions of wood dynamics based on field data from the mouths of the largest rivers can be used to test the validity of (future) landscape models because outputs from network-scale models that integrate wood budgets [Benda and Sias, 2003] from headwaters to oceans should match field observations at these locales.

We focus on describing the temporal variability of driftwood pulses from the Slave River to the Great Slave Lake. Because we discuss the transfer of drifting wood from a very wide river to a lake, we use the terms *driftwood*, *large wood (LW)*, or most simply *wood* rather than the more widely used *instream wood* because *instream wood* is not universally applicable to both rivers and lakes. We center our paper on understanding

a wood flood (atypical massive, congested, downstream transport of floating wood) that we witnessed in 2011. Congested wood transport occurs when input rates of wood exceed some threshold [Braudrick *et al.*, 1997; Bertoldi *et al.*, 2014] and is often related to wood recruitment from local remobilization of wood jams [Bertoldi *et al.*, 2014; Nakamura *et al.*, 2000], upslope landslides and debris flows [West *et al.*, 2011; Nakamura *et al.*, 2000], and riparian forest disturbance during exceptional flooding [Johnson *et al.*, 2000]. Large rivers can easily transport all sizes of logs because wood is shorter than the width of the channel and thinner than the water depth at a variety of flows. Thus, it is tempting to make the assumption that export patterns of wood in larger rivers will reflect the recruitment processes along the riparian corridors, discrete small events such as bank failures and tree mortality that are separable in space and time.

However, the export regime of the Slave River does not reflect these discrete input processes. Despite wide channels (0.3–2 km) and high discharges ( $>20^3 \text{ m}^3 \text{s}^{-1}$ ), the Slave River has a dominant export regime of large masses of wood transported in short amounts of time related to ice and flow regimes. If viewed from large spatial and temporal scales, the aggregate of the discrete recruitment events along thousands of kilometers of length of a river can be thought of as a continuous input. Thus, the Slave River could be classified as an event-driven export regime, which was recently defined in Jochner *et al.* [2015] as episodic transport with continual recruitment. Although this classification was developed using headwater streams, and bank recruitment processes are not strictly continuous, it remains a useful framework for thinking about wood transport dynamics for large to great rivers.

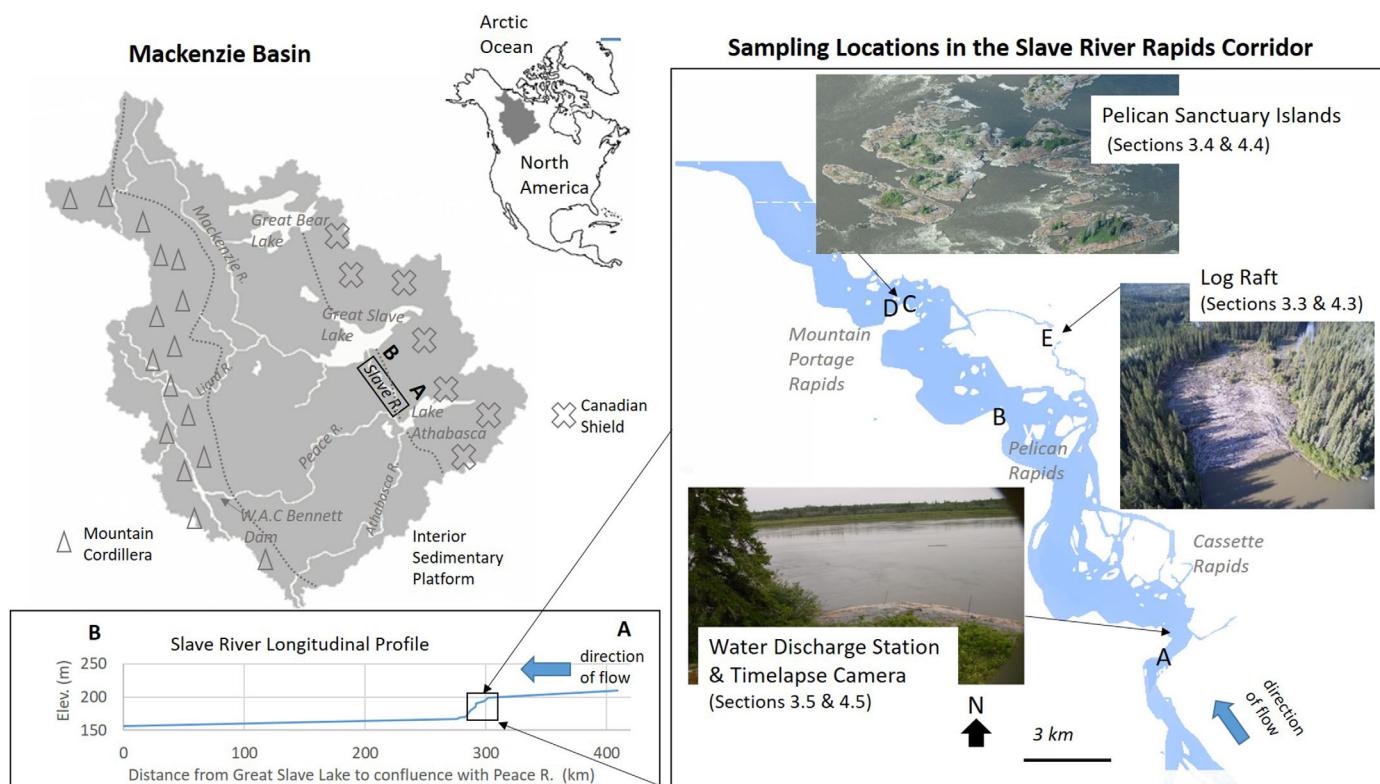
Local-scale congestion resulting from events such as the release of log jams from erosion of bars is discussed in the literature [Bertoldi *et al.*, 2014]. However, discussion about how remobilization of previously recruited, individually stranded wood along banks in large rivers can result in regional-scale congested transport (such as moving log rafts over many days traversing thousands of kilometers) is lacking. In this study, we seek to describe the processes that transform discrete recruitment events into pulsed, episodic export of congested wood in great rivers by exploring evidence of wood export in the Slave River across a variety of time scales. Although several studies allude to the importance of flow history on magnitude of wood mobilization and magnitude of flux [Johnson *et al.*, 2000; Haga *et al.*, 2002; Lassettre *et al.*, 2008; Bertoldi *et al.*, 2013; Jochner *et al.*, 2015; Boivin *et al.*, 2016], this is the first study that we know of to directly address relationships between wood flux and discharge on decadal time scales with yearly to subyearly resolution. We have generally organized our methods and results from long (half-century) to short (daily) time scales.

## 2. Study Site

The Slave River drains approximately  $6 \times 10^5 \text{ km}^2$  and connects the Peace and Athabasca Rivers to the Great Slave Lake in northern Canada (Figure 1). The water from the Great Slave Lake flows into the Mackenzie River and eventually to the Arctic Ocean. Study sites were located within the Slave River Rapids Corridor, which is on the  $60^\circ\text{N}$  parallel on the border between Alberta and the Northwest Territories. The Slave River Rapids Corridor drops 32 m of elevation in 26 km. This is a unique stretch of river characterized by split flow and powerful hydraulic forces around bedrock islands of polished Canadian Shield granite. Within the corridor, there are four main sets of steep rapids split by intervening lower gradient reaches. We had field sites in the three sets of upstream rapids: Mountain Portage, Pelican, and Cassette (Figure 1).

Downstream of the rapids, the river meanders for 276 km through incised Great Slave Lake deltaic deposits that date from 8000 B.P. at Fort Smith (downstream end of the rapids) to 1000 B.P. at the start of the modern delta [Vanderburgh and Smith, 1988]. Upstream of the rapids, the river is fairly straight from the confluence of the Peace and Athabasca Rivers, flowing north along the contact between the Canadian Shield to the east and Interior Platform sedimentary rocks to the west (Figure 1). Channel margins are erodible, composed of Glacial Lake McConnell lacustrine deposits [Craig, 1965] and mudstones and dolomites of the Keg River Formation [Okulitch and Fallas, 2007]. Channel widths upstream and downstream from the rapids are about 0.5 km, whereas widths in the rapids sections increase to as much as 2 km. Channel gradients are distinct for the three sections. The gradient is 0.1 m/km upstream of the rapids, 1.3 m/km for the rapids corridor, and 0.04 m/km downstream of the rapids (Figure 1).

Just upstream of Cassette rapids, Water Survey Canada has operated the *Slave River at Fitzgerald* gauging station, 7NB001, from 1921 to present (see Figure 1 for location). Base flows are approximately  $2000 \text{ m}^3 \text{s}^{-1}$  and summer flows commonly reach  $6000 \text{ m}^3 \text{s}^{-1}$ . The Slave River freezes every winter (November) and

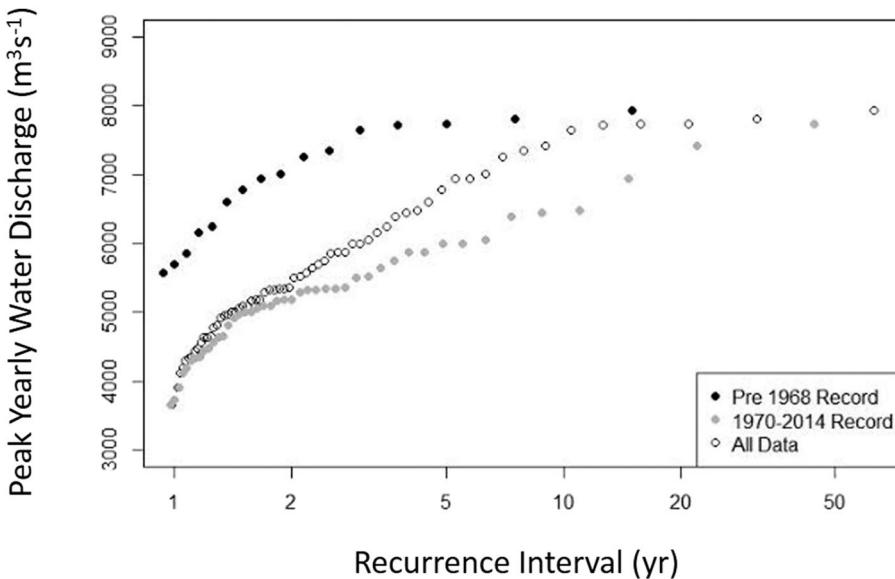


**Figure 1.** Study sites in the Slave River Rapids Corridor, Canada. Letters A-E correspond to location of photos in Figure 3.

there are generally two hydrograph peaks: the first corresponds to ice breakup (May) and the second is a freshet peak (June–July) related to runoff from snowpack and glacier melt from the southern Canadian Rockies. The highest recorded flow of  $11,200 \text{ m}^3 \text{ s}^{-1}$  was associated with a mechanical ice breakup event in May 1974. Mechanical ice breakup events do not occur in all years because they are dependent on river flows and the formation and location of ice jams. In recent years, ice breakup events appear to be less common [Beltaos *et al.*, 2006]. Although ice breakup return periods are unknown, during our 5 years of monitoring from 2012 to 2016, there were three ice jams. As the climate warms and glaciers recede, we expect that the Slave River will start to experience more mid to late summer hydrograph peaks from large rainstorms and earlier spring melt.

In the mid-1960s, the large, earthen W.A.C. Bennet Dam was built on the Peace River approximately 1000 km upstream from the Slave River Rapids Corridor (Figure 1). Flow regulation from operation of the dam has greatly altered river hydrology, ice processes, and flooding on the Peace River and the Peace-Athabasca delta [Beltaos *et al.*, 2006]. Impacts of flow regulation on the Slave River are buffered by discharge from the unregulated Athabasca River, but an analysis of gauge records indicates that the Slave River, since construction of the dam, has had higher base flow, lower magnitudes for 1–20 year recurrence intervals (Figure 2), decreases in breakup and freshet peak magnitudes, and increases in the number of late summer secondary peaks due to releases. Several large-capacity hydropower projects are currently under negotiation for the Peace, Athabasca, and Slave Rivers. At the time of this study, less than 10% of the Slave River drainage is upstream of dams. Thus, our data provide a baseline for wood dynamics in a great river prior to extensive development of the river corridor because wood is not halted by reservoirs from greater than 90% of the basin area.

Most of the wood transported through the Slave River is sourced from the banks of the Peace River and deposited along the shores of Great Slave Lake [Kindle, 1919], where the wood interacts with sediments and vegetation to create complex shoreline morphologies [Kramer and Wohl, 2015]. In a write-up of a field excursion in 1917, Kindle [1919] writes “there is probably no lake in North America which receives anything



**Figure 2.** Recurrence interval at Fort Fitzgerald gauge, 7NB001, before and after construction of the W.A.C. Bennett Dam.

like the amount of driftwood which is poured into the Great Slave Lake, chiefly through the Slave River" (p. 358). Kindle noted large amounts of wood sourced from banks that become caught up in vast driftwood piles on mid-river, small, bedrock knobs upstream of the rapids section. If flows do not redistribute these piles before vegetation establishes, then the piles form the nuclei for stable mid-channel islands and commonly grow to become interconnected [Kindle, 1919]. Wood-initiated, mid-river, vegetated islands and log rafts are not unique to the Slave River. This process and resulting landforms have been well documented elsewhere on other large rivers draining forested catchments in North America, Europe, and Africa [Hickin, 1984; Triska, 1984; Jacobson *et al.*, 1999; Gurnell and Petts, 2002; Collins *et al.*, 2012; Boivin *et al.*, 2015].

Wood dynamics on the Slave River reflect the aggregate of up-basin recruitment of wood by bank failures, riparian ice gouging [Uunila and Church, 2015], and lateral migration into riparian forests along meander bends in the boreal plains, rather than episodic loading from landslides in mountainous regions because the wood from the Canadian Rocky Mountains is mostly trapped behind the W.A.C. Bennett Dam before reaching the lowlands. Based on our observations, there is active slumping of banks that regularly recruit wood to the river. Newly recruited wood and fluvially stranded wood along the lower banks in the late summer appear to be routinely transported by ice each spring. Locally sourced trees in the riparian forests along the banks of the Slave River are fairly small (<30 cm diameter) aspens, poplars (*Populus* spp.), birch (*Betula* spp.), alders (*Alnus* spp.), willows (*Salix* spp.), and white spruce (*Picea glauca*). Riparian vegetation becomes larger farther south along the Peace River. A short video about driftwood in the Slave River and Great Slave Lake is provided as a supporting information (*ms01\_WoodResearchVideo.mp4*) and is particularly useful for gaining an appreciation for the great scale of the place, system, and processes described in this paper.

### 3. Methods

A variety of methods were employed to relate wood export to flow at multitemporal time scales. We used (i) wood characterization (section 3.1) to glean information about transport processes based on the size, type, and condition of wood (section 4.1); (ii) historical imagery and field anecdotes (section 3.2) to constrain recurrence intervals and to estimate the magnitude of rare, massive, wood flux events (section 4.2); (iii) repeat aerial and satellite imagery of a permanent log raft (section 3.3) to constrain wood flood recurrence intervals (section 4.3); (iv) repeat aerial imagery of mid-channel islands that temporarily store wood (section 3.4) to assess decadal patterns of change in storage in relation to yearly peak freshets and ice jams (section 4.4); and (v) time-lapse imagery to capture wood in transport for multiple years (section 3.5) with the goal of assessing variability and defining thresholds between wood flux and discharge (section 4.5). A

basic summary of methods is provided in the following section. Further detail, especially regarding wood metrics and analysis of repeat photography, is supplied in the supporting information.

### 3.1. Wood Metrics

Because wood characteristics are not the focus of this paper, we focused only on basic metrics of wood size and condition for ease of comparison with other studies and to provide anecdotal insight into provenance and transport history, as done in other studies [e.g., Piégay *et al.*, 2016; Moulin and Piégay, 2004]. The size distribution and condition of wood transported by the 2011 wood flood were characterized by conducting line intersect transects laid across two flood deposited point jams, one raft, one racked piece accumulation, and two bay accumulations (see Figure 3). Along most line intersects, large wood pieces (LW) ( $>10$  cm in diameter on the largest end and  $>1$  m in length) that intersected the line were measured and characterized. For a smaller subset of transects, all pieces were measured, regardless of size. Length was measured from the intersection of the root with the bole to the tip, and diameter was measured at both the small and large ends with a standard tape measure. Mean log diameters were calculated as the average of the two ends. Additional characteristics noted were: condition (index for amount of decay, abrasion and bark), log type (coniferous or deciduous), and rootwad presence and size. The wood accumulations measured were chosen based on accessibility.

### 3.2. 2011 Wood Flood Description

We describe field observations of the 2011 wood flood and combine these observations with discharge records to obtain a rough estimate of wood flux during the wood flood. Although no formal field measurements were made, one of the authors was on the river almost every day for a month preceding and following the 2011 wood flood. Historical photographs as well as anecdotes from local people are used to assess the uniqueness of the event.

### 3.3. Log Raft—Recurrence of Wood Floods in a Half Century

A permanent log raft clogs a side channel in the Slave River Rapids Corridor (located at  $59.95530^{\circ}\text{N}$ – $111.65456^{\circ}\text{W}$ , annotated on Figure 1). This same log raft is mentioned in Alexander Mackenzie's journals circa 1789 during his quest to find a route to the Western Ocean through Canada [Mackenzie, 1793]. We hypothesized that the position of the front of the raft was migrating upstream with episodic forward growth due to additions from wood floods such as the one in 2011. To test this hypothesis, we gathered as many historic aerial photographs and satellite images of the raft as possible and mapped the progression of the jam front upstream through time.

Each photo was georectified in ArcGIS (v 10.3.1) to a 2004 Google Earth screen capture with first-order polynomial transformations. Residual error for tie points was  $<7$  m. The average residual error was about 2% of the total length under study and is smaller than distance gained from episodic large additions to the front of the raft (45–143 m). The distance between jam fronts in two adjacent photos was measured along the center of the channel. A negative distance is recession of the log front downstream and a positive distance is advancement of the log front upstream. In 1930, the log raft split into a primary raft and a secondary smaller raft further upstream. Therefore for 1930, we measured from the front of the primary, downstream raft.

### 3.4. Island Repeat Photography—Decadal to Season Patterns of Wood Flux

Changes in storage of wood on mid-channel islands were graphically compared to patterns of flow and discharge magnitudes on decadal and seasonal timeframes in order to relate wood flux to flow history. Thirty years of repeat photographs of the Pelican Sanctuary islands ( $59.97116^{\circ}\text{N}$ ,  $111.74853^{\circ}\text{W}$ ) and records from the Fort Fitzgerald gauge (7NB001, Water Survey Canada,  $59.868923^{\circ}\text{N}$ ,  $111.582301^{\circ}\text{W}$ ) were used to compare change in wood storage to highest recorded discharge between photos. We hypothesized that higher peak discharges would relate to greater changes in wood storage on the islands. Figure 1 indicates the general location of the islands and gauge.

The historical aerial photo record of the islands was obtained from the Fort Smith Pelican Advisory Circle, which has monitored the nesting pelican colony on the islands since 1975. Photos were captured by obliquely pointing a camera outside a window of a fixed wing aircraft 2–4 times each summer. Flights were, and still are, funded by Environment Natural Resources, Government of Canada. Due to a lack of overview photos that cover the entire set of islands prior to 1983, we only used photos from 1983 to 2014. Prior to 2005, photos were stored on slides, whereas from 2005 to 2014 photos were stored digitally. Thus, we were



**Figure 3.** Wood accumulations in the Slave River Rapids Corridor resulting from the 2011 wood flood. Arrows denote general direction of flow. (a) Photo of congested wood transport during the wood flood taken with a wide angle lens at Fort Fitzgerald; discharge =  $7200 \text{ m}^3 \text{s}^{-1}$ , channel width = 500 m. (b) This point jam was one of the largest jams that was deposited during the 3 day wood flood. By 2013, the point jam was mostly gone, scraped clean by ice breakups. Typically, bays collect very large rootwads and numerous small wood pieces, such as bark and small branches, whereas point jams collect more mid-size pieces. (c) Photo of racked pieces shows split flow around bedrock islands typical of the river (upstream flow width = 60 m) which, at this location, is just a fraction of the 1000 m wide river. (d) The dashed yellow line on the raft indicates new wood delivered in 2011 to a small side channel, east of Pelican Rapids, channel width = 50 m. Locations of photos are marked by letter on Figure 1.

only able to obtain low-resolution scans of the pre-2005 slides (<800 pixels per side), whereas we were able to obtain high-resolution copies of the digital images (>3000 pixels per side).

The photographs were georectified using spline transformations with greater than 50 tie points per image. High-resolution images were then brought into object identification software eCognition and segmented, wood was semimanually classified, and wood polygons were exported as shapefiles. Low-resolution images

did not segment well and so were brought straight into ArcGIS where polygons were drawn around wood manually using the ArcEditor toolset. Shapefiles of wood areas in ArcGIS were analyzed in two different ways; (i) change within the same common area between all the photos from 1983 to 2014 (data set 1, *ds05\_D1areas.csv*) and (ii) change between adjacent photos in time from 1988 to 2014 (data set 2, *ds06\_D2change.csv*).

Data set 2 was subset to start in 1988 rather than 1983 due to many missing adjacent timeframes from inadequate coverage of the islands prior to 1988. For data set 1, we simply summed the total area of wood within the common area of interest for all photos. For data set 2, we estimated areas of wood that overlapped in adjacent photos ("stayed"), that were present in the second photo but not the first ("came"), and that were present in the first photo but not the second ("went"). Fractions were then calculated for each time period as each category divided by the total amount of wood that passed through storage in the interval (came + went + stayed). For example, fraction of wood that stayed equals stayed/(came + went + stayed). The highest peak discharge within the time period under scrutiny was extracted from the discharge records for comparison.

It is important to note that the derived data contain noise because it was impossible to line up wood polygons exactly between years due to the obliquity and variability in the source photographs. For example, a piece that should be 100% stationary based on visual inspection of location on photographs will always have some portion of its area that came or went due to slight misalignments and slightly different shapes. The error is greatest only for years with little to no change.

We used data set 1 to graphically assess the absolute change in total area of wood through time, which enabled us to identify timeframes when wood was accumulating on the islands versus when it was being removed. We used data set 2 to investigate inter- and intra-annual variability in wood imports versus exports and to identify patterns and thresholds for wood change in relation to discharge. Because of the unique, high temporal resolution of these repeat photographs (two to four photos per summer for 30 years), we were also able to assess the relative influence of ice jam flooding compared to freshet flooding on wood storage.

### 3.5. Time-Lapse Photography—Yearly to Daily Patterns of Wood Flux

A Brinno TLC200 camera was installed next to the Slave River at Fitzgerald gauge 7NB001 (located at 59.868923°N, 111.582301°W and annotated on Figure 1). Following methods from Kramer and Wohl [2014], images were collected of the river every 10 min from April to August in 2013 and 2014 from which estimates of wood flux as  $\hat{p}$  per day were calculated. The variable  $\hat{p}$  represents the proportion of frames within a time interval that wood floats past the camera. Thus,  $\hat{p}=1$  means that there was wood floating past the camera 100% of the day, whereas as  $\hat{p}=0$  means that no wood passed the camera that day. There are several advantages to using  $\hat{p}$  to characterize wood flux. It is quick to obtain, avoids uncertainty from wood volume estimates due to flotation depth and estimating sizes at variable distances in the frame of view, and allows an estimate of wood flux to incorporate data periods with missing samples, such as night. Missing photos due to darkness are minimized for the Slave River during the summer because of its location on the sixtieth N parallel where it never becomes fully dark in the middle of the summer. Although we did not estimate flux volumes, estimates of  $\hat{p}$  proved useful for comparing basic shapes and patterns of wood flux to daily discharge and yearly hydrographs.

In addition to  $\hat{p}$  estimates, images were categorized as congested transport, clumped transport, or sparse transport. Sparse transport was defined as one to several pieces of wood that could be counted at a glance. Clumped transport was defined to be more than a few pieces, commonly with groupings of two or more pieces touching. Congested transport was large amounts of wood jumbled together such that it would be very difficult to count all the pieces.

The 2013 and 2014 images were stored as video files and frames were extracted for periods when wood was present. The camera was placed on the outside of a bend and most wood was carried within 100 m of the camera. The extracted images had resolution of 96 dpi (1268 × 760 pixels). Raw time-lapse data can be accessed at <https://dspace.library.colostate.edu/handle/10217/100436>. We also included in our analysis, 13 July 2012 to 13 August 2012 data from Kramer and Wohl [2014] as well as estimates of  $\hat{p}=1$  for 16–18 July 2011, which correspond to our visual observations of the wood flood (sections 3.2 and 4.2).

## 4. Results

We present here a summary of results relevant to understanding the main points of the paper. Data sets used to derive results are supplied as supporting information data files *ds01\_Largewood.csv*, *ds02\_Smallwood.csv*, *ds03\_Rootwads.csv*, *ds4\_lograftposition.csv*, *ds05\_D1areas.csv*, *ds06\_D2change.csv*, and *ds07\_FFWoodphyatQ.csv*. A detailed description of these data sets as well as expanded analyses using these data are supplied in the supporting information. In particular, the supporting information contains additional imagery as well as further analysis of wood metrics and Pelican Island repeat photography beyond what is presented here, which are useful for a deeper understanding of the processes described in this paper.

### 4.1. Wood Metrics

A summary of basic wood metrics is provided in Table 1. Large wood measured from line intersect surveys ( $n = 187$ ) had a mean length of 6.1 m with a standard deviation of 4.4 m, a median of 4.7 m and a maximum of 19.4 m. Representative diameters (average of end diameters) had a mean of 0.21 m with a standard deviation of 0.11 m, a median of 0.18 m, and a maximum of 0.7 m. We found that point accumulations were enriched in shorter pieces and had a significantly different size distribution than all other accumulation sites. We attribute this to preferential trapping of smaller pieces on point jams. Thus, data from log rafts, bays, and racked accumulations are likely more representative of the size of wood in transport than wood in point accumulations. When point jam data are extracted from the data set, mean and median lengths increase by about 1 m and mean and median diameters by about 2 cm. Without the point jam data, mean wood length is 7.4 m with a standard deviation of 5 m and a median wood length of 6.1 m; mean diameter is 0.23 m with a standard deviation of 0.12 m and median diameter of 0.21 m. Based on proportions of wood as bark, small wood (length  $< 1$  m or diam.  $< 10$  cm), medium LW, and large LW (length  $\geq 3$  m and diam.  $\geq 0.23$ ) measured along a complete line intersect survey in a bay, we estimate that the Slave River carries 2680 pieces of bark per 407 pieces of small wood per six pieces of medium LW per 1 piece of large LW.

The bulk of LW pieces on the Slave River are smooth boles with no bark and sound wood. Overall, 84% of wood is sound compared to 16% decayed; 19% of wood contains bark versus 81% with no bark; and 6% of wood shows limited abrasion whereas 94% of pieces are abraded. This indicates that wood in transport has traveled long distances (highly abraded with smooth boles), has spent time in the water (no bark), but has not spent a long time rotting in place on floodplains (sound wood rather than decayed). A high percentage (35%) of wood contained rootwads, confirming that recruitment is likely dominated by bank erosion. About 5% of LW wood from line intersect surveys is beaver chew. There were no large differences in wood condition between coniferous and deciduous trees. We also found that deciduous trees enrich size distributions with smaller lengths of wood, most likely because they contribute greater quantities of larger snapped off branches than coniferous trees. When all the data are considered, 58% of LW is deciduous and 42% is coniferous. However, if we select the data to include only trunks with rootwads, the percentages reverse to 42% deciduous and 58% coniferous.

**Table 1.** Site and Wood Characteristics Summary<sup>a</sup>

Site Characteristics	
Latitude	60°N
Elevation	~200 m asl
Drainage area	$6 \times 10^5$ km <sup>2</sup>
Channel width	0.3–2 km
Gradient	0.04–1.3 m km <sup>-1</sup>
Discharge	2000–11,200 m <sup>3</sup> s <sup>-1</sup>
Magnitude RI <sub>1.2years</sub> <sup>b</sup>	~4200 m <sup>3</sup> s <sup>-1</sup>
Large Wood Size	
Length (m)	Mean, sd, med, max
Mean diameter (m)	7.4, 5, 6.1, 19.4 (n = 100)
Coniferous root volume* (m <sup>3</sup> ) <sup>c</sup>	0.23, 0.12, 0.21, 0.7 (n = 100)
Deciduous root volume* (m <sup>3</sup> ) <sup>c</sup>	1.2, 1.3, 0.8, 7 (n = 52)
Large Wood Type and Condition	
Coniferous:deciduous	58:42 (all pieces, n = 169)
Coniferous:deciduous <sup>d</sup>	42:58 (only with rootwads, n = 60)
Sound:decayed	84:16 (n = 185)
No bark:bark present	81:19 (n = 185)
Abraded:limited abrasion	94:6 (n = 184)
Beaver chew	5 (n = 145)
Rootwads	32 (n = 187)

<sup>a</sup>See supporting information for additional explanation and descriptions.

<sup>b</sup>Ri is recurrence interval. This value reflects yearly recurrence interval postdam. See Figure 2.

<sup>c</sup>This is the air-wood rootwad volume which is the volume of a box that completely encloses the rootwad [Thevenet *et al.*, 1998].

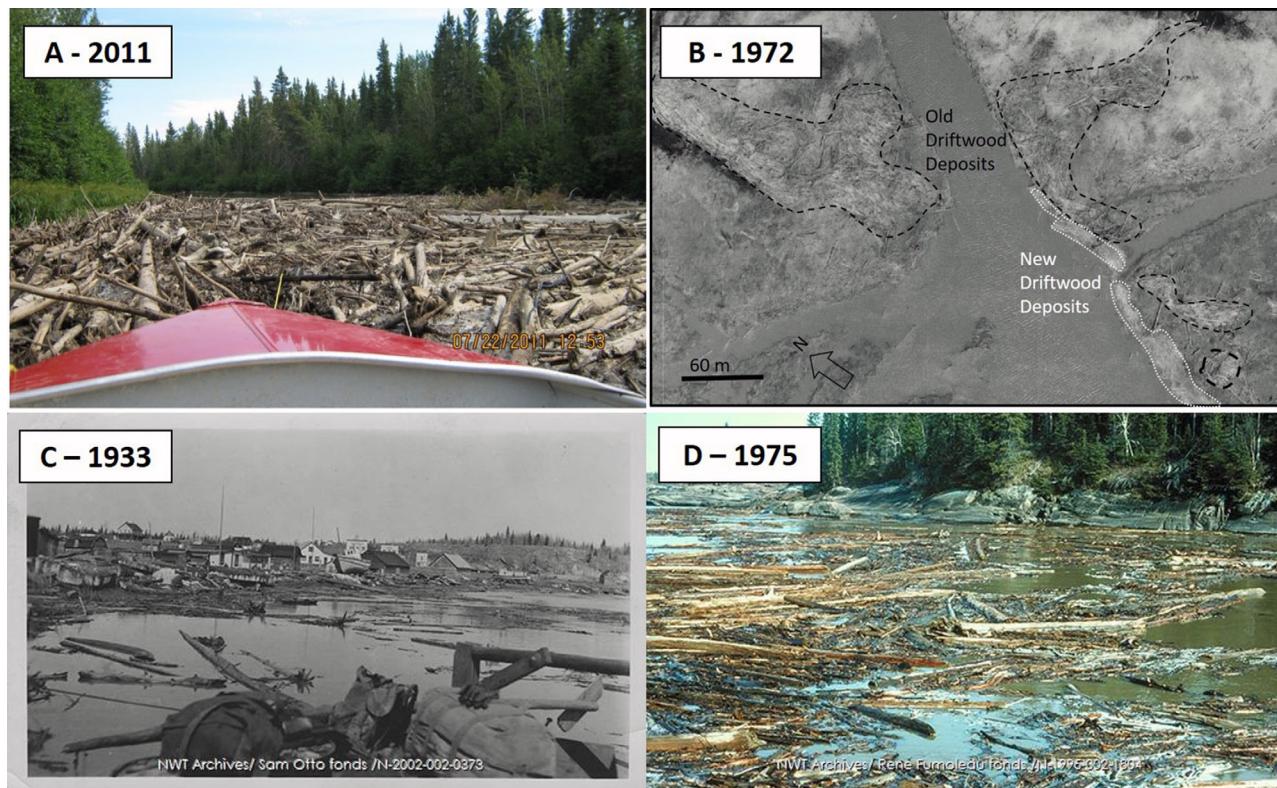
<sup>d</sup>Proportions based on only pieces with rootwads and may more accurately represent recruitment because deciduous are more likely to break and contribute more large pieces per tree to overall wood loads.

#### 4.2. 2011 Wood Flood Description

The wood flood we witnessed on the Slave River in 2011 was a swath of congested wood transport about 20–100 m wide that lasted 3 days. It looked like one long, continuous snake of driftwood moving down river. Uncongested transport continued for weeks afterward. The 2011 wood flood completely reorganized wood and deposited fresh wood accumulations in the Slave River Rapids Corridor. Figure 3 shows type deposition sites including point jam, bay, raft and racked piece accumulations. In the winter of 2013, fluvially deposited wood piles from 2011 were again reorganized, this time by ice push during breakup. Ice-pushed jams were usually deposited on the lee side of islands and appeared to be more densely packed and randomly oriented than fluvially deposited jams.

The water discharge during the 2011 wood flood was about  $7200 \text{ m}^3 \text{ s}^{-1}$  (return period  $\sim 17$  years post dam,  $\sim 7$  years predam—Figure 2). Flow depths at the Fort Fitzgerald gauge (Figure 1) range from 8 to 12 m and channel width is close to 400 m. Using an estimate for cross-sectional area of  $4000 \text{ m}^2$ , the mean velocity during the flood was about 1.8 m/s. This matches well with surveyed ranges of surface velocities at lower discharges at the gauging station from 0.2 m/s at the banks to about 2 m/s in the thalweg (G. Lennie, Water Survey Canada, personal communication, 2013). If we assume complete congestion of a 50 m swath of logs 0.15 m thick (median diameter of all large wood measured in this study) moving at 1.8 m/s, then the wood discharge rate was  $20 \text{ m}^3/\text{s}^{-1}$ . This amounts to  $5 \times 10^6 \text{ m}^3$  of wood transported by the river over the 3 days and  $2 \times 10^6 \text{ m}^3$  over 1 day. After conducting an uncertainty analysis by adjusting the width, thickness, and velocity, we consistently estimate 3 day flux volumes over  $10^6 \text{ m}^3$ . In addition to this volume, there was also sparse transport of wood for weeks after the main body had passed. The flux volumes of the main body is  $\sim 10^4$  times the  $492 \pm 120 \text{ m}^3$  total seasonal background flux volume estimated for the same location between 13 July and 13 August in 2012 [Kramer and Wohl, 2014].

When delivered to the Slave River Delta, the wood from the 2011 event completely clogged the Nagle distributary channel and boat launch (Figure 4a). Residents of Fort Resolution who regularly use this channel



**Figure 4.** Historic photos of wood transport and deposition. (a) Wood deposition clogging the Nagle Distributary channel of the Slave River Delta from the 2011 flood. Photo by Eric Beck. (b) Driftwood deposits in the Slave River Delta, 29 May 1972. National Air Photo Library (NAPL) Roll #A22708, photo #20, 61.203831°N-113.708468°W. Photos c and d are from the NWT archives <http://www.nwtarchives.ca/>. (c) The 1933 photo of river driftwood at Fort Fitzgerald upstream of the rapids, photo by Sam Otto Fonds, accession number N-2002-002, item number 0373. (d) River driftwood at the bottom of Mountain Portage rapids, photo by Rene Fumoleau Fonds, accession number N-1995-002-1804.

for travel spent several days clearing the wood. Failure to clear this channel would have likely caused avulsion and repositioning of the channel. Much of the wood in 2011 was delivered to the delta front in massive mats and large driftwood berms. Historic air photos of the Slave River Delta in 1972 show distinct new and old wood deposits on the delta front (Figure 4b).

Many residents noted that the event in 2011 was unique in their experience. Some residents who frequent the river mentioned that driftwood is common every year, especially near ice breakup, but the magnitude and late summer timing of the event in 2011 were unusual. After a search of the NWT Archives (<http://www.nwtarchives.ca/>), we found photographs of congested wood transport in 1933 (Figure 4c) and in 1975 (Figure 4d).

#### 4.3. Log Raft—Recurrence of Wood Floods in a Half Century

Between 1930 and 2015, the log front progressed a total of  $260 \pm 5$  m upstream (Figure 5). This progression upriver is not uniform in time. Three large advances of 98, 143, and 45 m occurred between 1930 and 1950, 1950 and 1966, and 2004 and 2013, respectively. One minor advance of 19 m occurred between 1982 and 1991. The advance of the log raft between 2004 and 2013 was due to the 2011 wood flood. Although we do not have the temporal resolution to constrain exactly when jam advances occurred between 1930 and 1950 and between 1950 and 1966, jam progression upstream was probably episodic, as in 2011, rather than continuous. If the three largest raft advance events within the 82 year study period are directly a result of wood floods, then the recurrence interval of wood floods is about  $\sim 27$  years.

Large raft advances are usually followed by smaller raft recessions. Between 1950 and 1966, the raft grew the most, but by 1970, just 4 years later, the raft front had receded downstream by 41 m. Wood at the back of the jam is very stable. It is buried in silt and is vegetated with shrubs and even  $\sim 50$  year old white spruce trees. We saw no evidence for export of pieces out of the back of the jam, but we did see widening of the channel and bank collapse following large forward progressions. Thus, the pattern of large advance followed by smaller-scale recession is related to bank erosion expanding the width of the channel as well as compaction of the raft in years following wood delivery.

We have depicted a stepped progression for the jam in Figure 5 that is representative of the episodic process of infrequent wood events causing sudden raft progression upstream. We have placed inferred wood

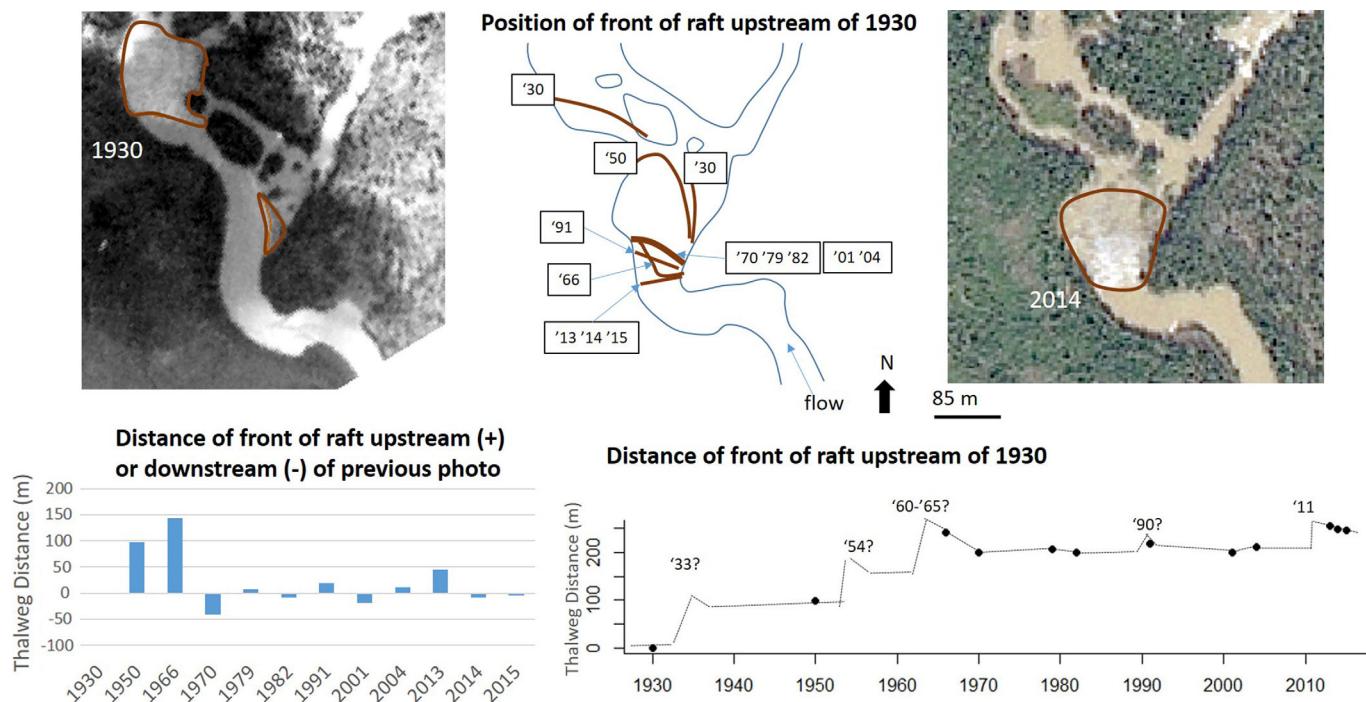


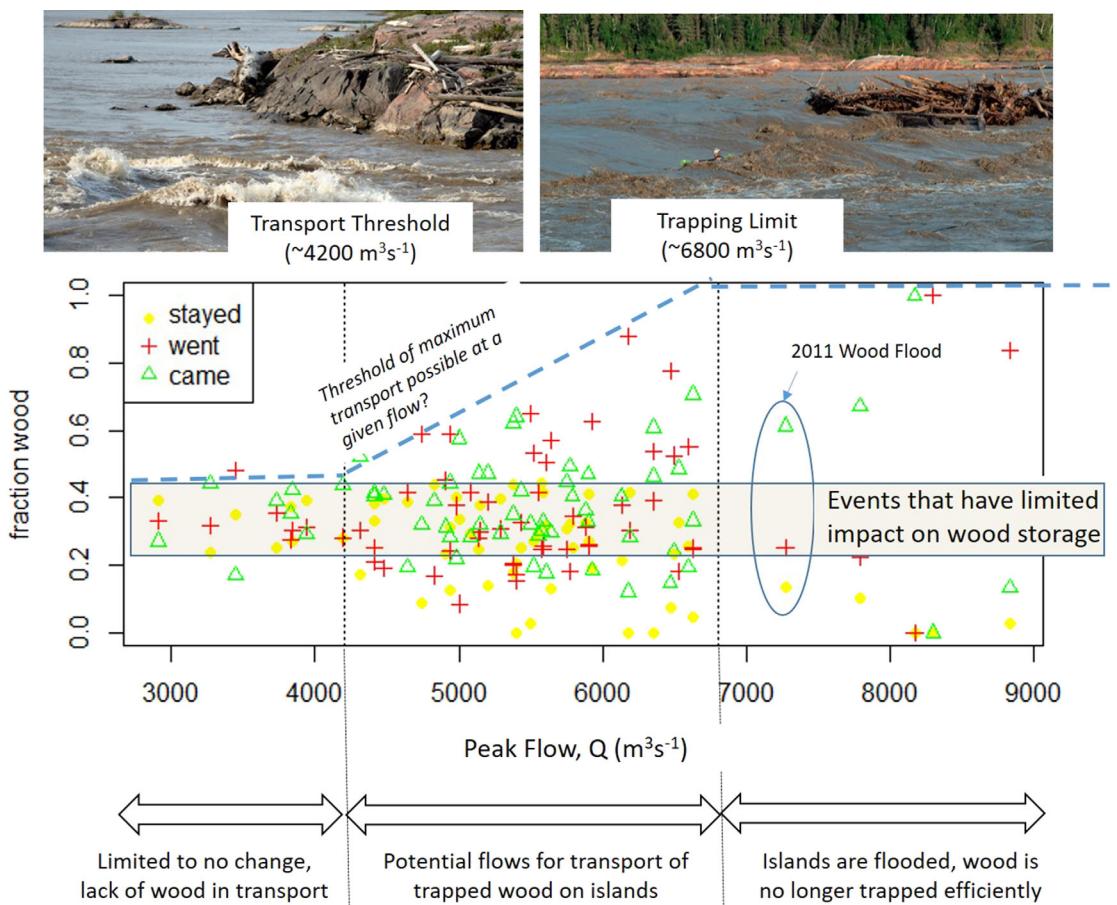
Figure 5. Log raft evolution from 1930 to 2015.

events at 1933, 1954, 1960, and 1990 and a known wood event in 2011. We placed a wood event at 1933 because a historic photo shows wood in transport during this date. We chose 1954 because this was a high water year, coupled with evidence from the Great Slave Lake that large amounts of drift piles germinated in the early 1950s [Kramer and Wohl, 2015]. We chose 1960 because this was the first year of high flows after 5 years of a decreasing pattern of flows similar to the pattern preceding 2011 (see section 4.4). The minor jam advance in 1991 was likely caused by a wood event in 1990, which was a year with a flashy breakup preceded by lower water years.

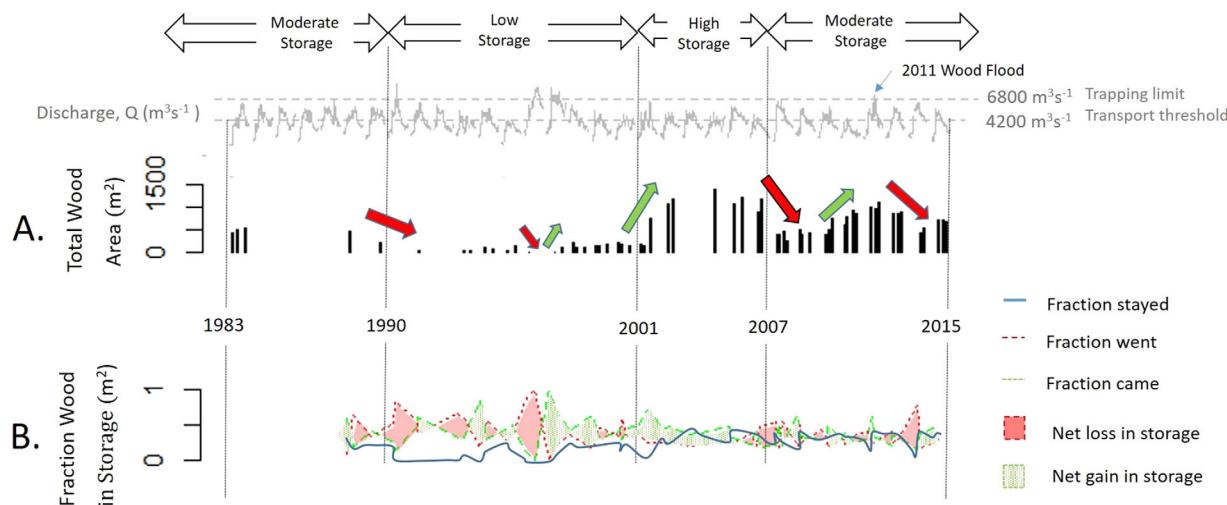
#### 4.4. Repeat Photography—Decadal to Season Patterns of Wood Flux

To test our hypothesis that the amount of change in storage increases with increasing discharge, we plotted the fractions of wood that came, went, or stayed from wood within a small common area (data set 1) against discharge. On Figure 6, an upper threshold for maximum possible change at a given discharge (annotated with a dashed line) is apparent. Less than 50% of wood changes position below  $4200 \text{ m}^3 \text{s}^{-1}$ . For discharge above this transport threshold, there is a linearly increasing threshold for maximum amount of change up to around  $6800 \text{ m}^3 \text{s}^{-1}$ , when a trapping limit is reached as the islands become flooded.

However, underneath the stepped upper threshold for amount of change possible (dashed line on Figure 6), there is great variability and higher discharges do not always equate with greater amounts of change. There are many events that experience high flows, but wood is not changing position very much. There is also evenly dispersed scatter in the amount of wood that either went or came. The lack of pattern between discharge and type of change indicates that import and export of stored wood are equally likely at all flows. To constrain noise in the data related to misalignment (see section 3.4), we have interpreted Figure 6 to include a band to indicate events that have limited impact on wood storage. The band was defined from



**Figure 6.** Flow thresholds for change in storage on the Pelican Islands. High values of wood that stayed indicate little to no change on the islands.



**Figure 7.** Decadal patterns in wood storage. Only summer flows (April–September) are shown. (a) Plots of volume of total wood stored within a common area (data set 1) from 1983 to 2014. Bars are located at photo date. All photos had wood in them except for 1996, when no wood was present. Arrows indicate general periods of wood loading or deloading. (b) Lines represent the fraction of wood in storage (data set 2) that came (green small dashed line), went (red long dashed line), or stayed (solid blue line). Regions that are shaded with stippled green indicate periods when more wood was recruited than exported, whereas regions shaded solid red indicate periods when more wood was exported than recruited. Sharp downward spikes in fraction stayed indicate time periods with large changes in storage. There were large proportions of change between 1990 and 2001 due to the extremely low wood loads, making it possible for a few pieces to greatly impact the fractions that went, stayed, or came.

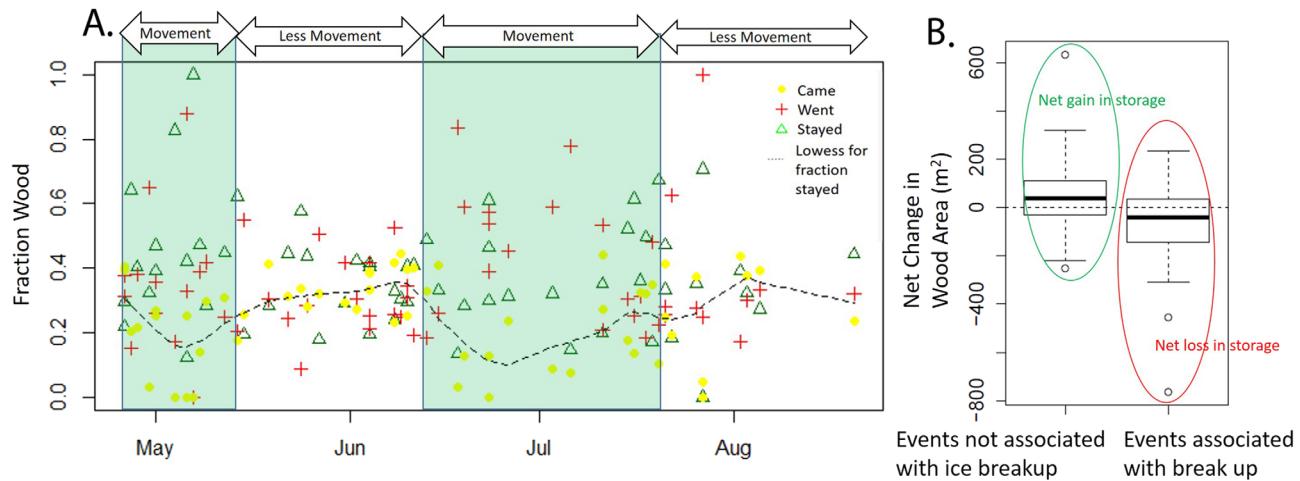
0.2 to 0.4, based on a consistent upper threshold for highest fractions stayed, the lower data limit for fractions less than the transport threshold, and visual inspections of photographs.

The supporting information (*ms02\_Planimation\_2fps.avi*) is an animation of the changes in wood position from 1983 to 2014 extracted from the aerial photographs. In order to assess how patterns in yearly and decadal hydrograph regimes might impact storage, we plotted the summer (April–September) hydrographs against total wood in storage through time (data set 1) and fractions of change in storage between adjacent time periods (data set 2; Figure 7). The islands fluctuate between low, moderate, and high wood loads on a decadal time scale (6–12) years (Figure 7a).

Flows between 1983 and 1990 were consistently between the transport threshold and trapping limit. Thus, despite some data gaps, we think that wood in storage was likely in equilibrium at the moderate levels, as bracketed by the 1983 and 1988 data. In 1990, water levels spiked well above the  $6800 \text{ m}^3 \text{ s}^{-1}$  trapping limit, which resulted in clearing the islands of wood (Figure 7b). Wood levels remained in a low equilibrium for about one decade until 2001, when late summer freshets peaked just below the trapping limit and reloaded the islands. Flows then again hovered at or under the transport threshold for the next 5 years and wood slowly accumulated until 2007, when ice breakup flows rose to just below the trapping limit and flushed wood from the islands, setting wood loads back to moderate levels. Rather than staying in equilibrium, wood loads from 2007 to 2014 have fluctuated.

A 4 year hydrograph sequence with each year peaking just below the year before occurred from 2007 to 2010. Wood loads responded by increasing each year as new wood was deposited at lower elevations than the prior year (Figure 7a). River levels during 2010 were record setting lows. In 2011, the year of the wood flood, the levels spiked in a late summer freshet to above the trapping limit for the first time in 14 years. Despite high volumes of wood moving down the river, there was only a slight increase in total wood storage after the flood (Figure 7a). However, there were large changes in the positioning of wood, with overall net gain of new pieces in new places (Figure 7b). In the 2 years following the wood flood, ice jamming flushed wood from the islands and decreased wood loads (a field observation supported by Figure 7). This pattern can also be viewed toward the end of supplemental animation *ms02\_Planimation\_2fps.avi*.

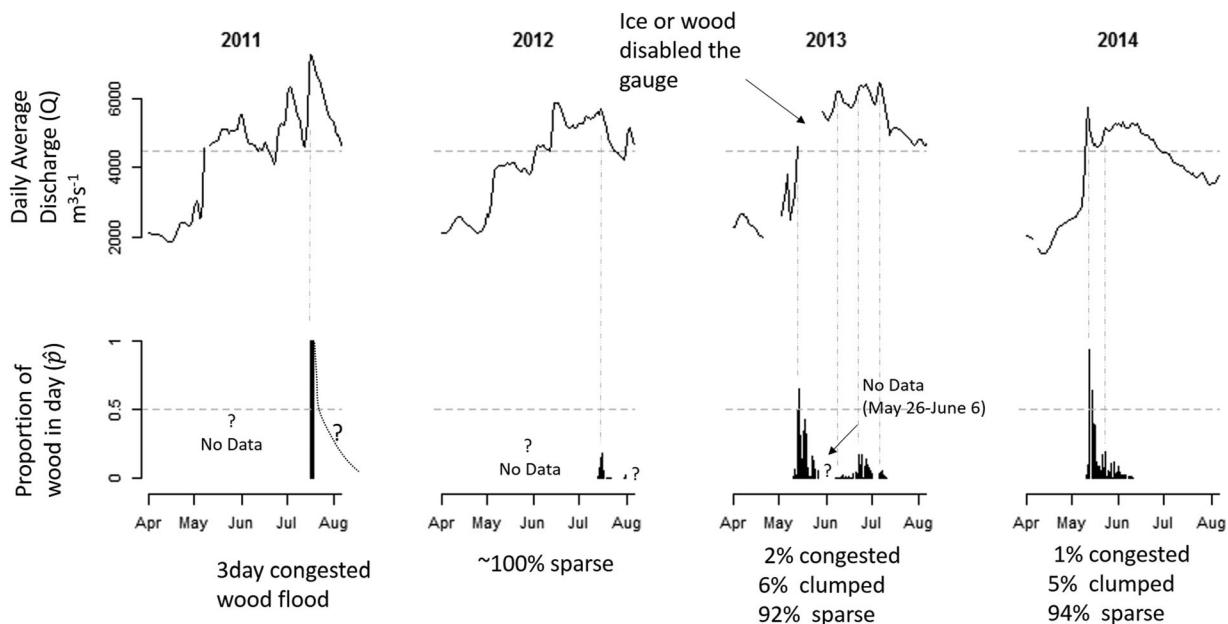
Patterns of change by month (Figure 8, left) show that change in storage on the islands occurs either in late April to mid-May in association with ice breakup, or mid-June to early July in association with spring freshet. Although there is some variability, on average, flashier ice breakup events tend to flush wood, resulting in loss of wood in storage, whereas later summer freshets tend to build wood in storage (Figure 8, right).



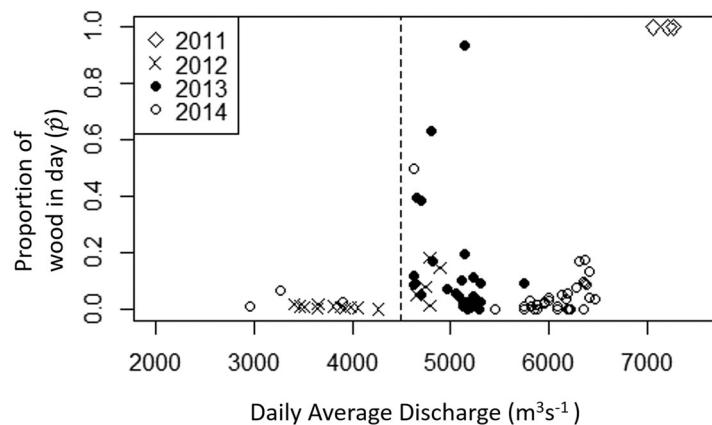
**Figure 8.** Seasonal patterns in wood storage. (a) Low values of fraction stayed and separation between fraction stayed and the rest of the data indicate timeframes of greater change. (b) Flushing versus storage for ice breakup and freshet events. Using a one sided  $t$  test with  $\alpha = 0.1$ , the mean change in storage is  $< 0$  for ice breakup ( $n = 18$ ,  $p_{\text{val}} = 0.10$ ) and  $> 0$  for freshet peaks ( $n = 35$ ,  $p_{\text{val}} = 0.04$ ).

#### 4.5. Time-Lapse Photography—Yearly to Daily Patterns of Wood Flux

We compared wood flux ( $\hat{p}$ ) to water discharge for 2011–2014 (Figure 9). Although we did not take any photos for 2011, we marked  $\hat{p}=1$  for the 3 day wood flood (16–18 July) based on field observations during that time period. Within a year, wood peaks generally correspond with hydrograph peaks. Wood flux only reaches above  $\hat{p}=0.5$  for rapid and large changes in discharge (increases of about  $2000 \text{ m}^3 \text{ s}^{-1}$  within a few days). Although these larger events usually occur in May due to ice jamming, as in 2013 and 2014, they can also happen later in the summer due to rapid melt of snowpack, torrential up-basin rainstorms, or large releases from the W.A.C. Bennett Dam, as in 1996. We also noted that on the rising limb of wood-transporting floods, wood transport increases rapidly, peaks with water discharge (on a day-averaged time scale) and then decays more slowly as flows recede, resulting in a skewed distribution with a heavy positive, or right tail (Figure 9).



**Figure 9.** Wood discharge compared to water discharge 2011–2014. Horizontal guidelines drawn at  $\hat{p}=0.5$  (wood in 50% of photos for the day) and at  $Q = 4500 \text{ m}^3 \text{ s}^{-1}$ , a transport threshold identified in Figure 10. Vertical guidelines are drawn to connect hydrograph peaks with wood graphs. The 2012 data are from Kramer and Wohl [2014].



**Figure 10.** Identification of a wood transport threshold.

In 2012, there was no ice jamming. Instead, there was a stepped ice-off. Although there are no data at the beginning of the summer, wood movement from the second freshet was minimal, peaking around  $\hat{p}=0.2$ , with most photos containing only a single log. Within the rapids corridor, the wood deposited in 2011 remained essentially undisturbed. The wood that was being transported appeared to be the wood that was stranded at the end of the 2011 event.

In 2013 and 2014, ice jamming was captured by the camera. The supporting information movie file, *ms03\_FF2013051314\_10min5fps\_breakup.avi*, is a video time lapse of breakup and wood transport over 2 days in 2013. The river first thermally melts and is largely ice free. Then, quite suddenly, an ice jam moves through the site for about 2 h. Wood is jumbled within the ice jam, and large clumped mats of driftwood follow in its wake. About half a day to a day after the major ice jam, there is increased semi to congested wood transport. Wood accumulations within the rapids corridor were repositioned from ice push (field observation). These patterns are also seen in 2014, but the ice jamming was smaller and less dramatic.

The magnitude of wood flux is not directly related to the magnitude of water discharge (Figure 10). For any given discharge, we found that there could be either high or low wood flux. However, there is a transport threshold at  $\sim 4500$  ( $m^3 s^{-1}$ ). Below this threshold there is minimal wood transport, whereas above this discharge there is the potential for appreciable wood flux. Further evidence for this threshold effect is the shape of the wood flux curves. Generally, wood flux (on the time scale of a day) does not gradually increase but jumps quickly to maximal flux and then has a longer trailing tail (Figure 9). This pattern appears to be true for both the larger steeply rising events as well as smaller later summer events, although more data are needed to rigorously test this idea.

## 5. Discussion

### 5.1. Provenance and Transport Processes

Useful information can be gained about transport processes and wood provenance by characterizing wood size and condition [Moulin and Piégay, 2004; Piégay *et al.*, 2016]. Although we did not directly evaluate fluctuations in up-basin recruitment, the characteristics of wood temporarily stored in the Slave River Rapids Corridor indicate that wood mostly originates from banks and travels long distances, moving from one temporary storage site to another.

The high amount of abrasion and lack of bark suggest nonlocally sourced wood, whereas the lack of appreciable decay suggests that wood in active transport does not remain long enough in one place to become decomposed by organisms or spend long amounts of time submerged or buried. At high latitudes, more wood from up-basin may cumulatively travel longer distances in good condition because the wood decays more slowly [Dahlström *et al.*, 2005]. In an Alaska stream at similar latitude, Murphy and Koski [1989] found that the mean age for trees with bark and limbs attached was 4.5 years and that residence time for wood with solid centers but with extensive surface rot was 125 years. Because the majority of the wood on the Slave River was solid, yet lacked limbs and bark (Table 1), residence times are likely greater than 4.5 years

The 2011 hydrograph is distinct due to the double-humped, late summer, steeply rising freshet peaks. The wood flood occurred during the second, not the first, peak. Although there was some wood transport during the first peak (field observation), it was not nearly the quantity of the second peak. The steeply rising second peak likely crossed some threshold above  $6000 m^3 s^{-1}$  that enabled access to large amounts of stored wood at higher elevations in a short enough time to initiate congested transport.

and less than 100. The large proportions of trees with rootwads and the up-basin meandering stream morphology of the Slave and Peace Rivers suggest that the bulk of the wood originates from banks, rather than hillslope failures. In support of our findings, Piégay *et al.* [2016] found that wood is primarily sourced from banks and deposits of wood are not generally close to recruitment sites for a large river in France. We suggest that wood studies should subsample the complete size distribution of wood, rather than just measuring the large wood. If this is done, it becomes possible to better understand how fluvial processes alter size distributions by comparing instream wood size distributions to riparian tree distributions, as suggested by Turowski *et al.* [2013].

### 5.2. Threshold Response

Over time for a given flow regime, consistent thresholds can be identified below which wood transport is close to negligible [Ruiz-Villanueva *et al.*, 2016b]. MacVicar and Piégay [2012] found that a transport threshold is reached at 3/4 bankfull depth. Ravazzolo *et al.* [2015] found that wood was transported when flow was above a 10–20% exceedance probability. Ruiz-Villanueva *et al.* [2015] found different threshold responses in wood transport between multithread and single thread channels mountain rivers related to bankfull discharge.

In this study, using multiple methods, we found a consistent Slave River threshold for transport between 4200 and 4500 m<sup>3</sup>/s<sup>2</sup>, which is between a 1 and 2 year recurrence interval. Interestingly, there is a sharp inflection in postdam discharges at  $\sim$ 4200 m<sup>3</sup> s<sup>-1</sup> and recurrence interval of  $\sim$ 1.2 years (Figure 2). The occurrence of this inflection close to thresholds identified in this study suggests that wood transport thresholds are set by peak flow histories. Prior to the construction of the WAC Bennet dam 1000 km upstream, events with less than a 10 year recurrence were 1.5 times higher in magnitude (Figure 2). Thus, wood transport thresholds could have been higher predam when the flow regime had higher peak magnitudes and more frequent ice jamming [Beltaos *et al.*, 2006].

Although we have shown the remobilization of wood occurs as a threshold response to discharge of common rather than rare floods, it is important to recognize that this is a time averaged threshold below which wood transport is typically negligible, rather than a threshold above which wood transport always occurs. In Figures 6 and 10, we have shown that not all years or events that exceed the identified threshold result in wood transport. Thus, crossing the discharge threshold does not imply that there will be wood transport, only that transport is possible. Whether transport happens and the magnitude of the wood flux depends on the flow history.

### 5.3. Multiple Modes of Wood Flux

Wood on the Slave River is transported episodically over varying time scales and at varying magnitude, and is generally not reflective of recruitment patterns. Although recruitment processes govern the total amount of wood available for transport, the flow regime governs the timing and volume of wood flux as wood is transported through the fluvial system. Across diverse drainage basins, events such as massive hurricanes [Phillips and Park, 2009] or afforestation [Lassettre *et al.*, 2008] will increase the amount of recruited wood, which will increase overall wood loads and fluxes. But, depending on the location and type of wood recruitment, there may be some lag time or dissipation of volumes between input and export response [Lassettre *et al.*, 2008; Boivin *et al.*, 2016; Piégay *et al.*, 2016].

For example, the average rate of the raft progression upstream was much faster prior to construction of the W.A.C Bennett Dam (7 m/yr compared to 1 m/yr). Also, the stasis of the jam from 1970 to 1990 corresponds with the period of lower wood storage noted on the Pelican Islands from 1983 to 1990 (see section 4.4). Thus, there was less wood in transport during this time period, which may reflect blockage of wood from the mountainous regions of the catchment by the dam, or could be part of the natural variability in wood fluxes on time scales longer than those covered by our data.

Flashier hydrographs which exceed a transport threshold are known to mobilize and transport more wood over longer distances than slowly rising hydrographs [Ruiz-Villanueva *et al.*, 2016b]. Our time-lapse camera observations suggest that large changes of discharge in short amounts of time (steep rising limbs) associated with ice jamming or flashier freshet peaks create larger magnitude wood fluxes that are more likely to have clumped transport. This finding is supported by flume experiments which indicated that the rate at

which dowels were introduced is the dominant explanatory variable behind whether the dowels were transported as congested, semicongested, or uncongested [Braudrick *et al.*, 1997].

Although we have mainly focused on wood floods because they are the mechanism by which the largest volumes of wood are exported, we identify three types of export occurring on the Slave River: sparse wood flux, ice wood flux and congested wood flux.

### 5.3.1. Sparse Wood Flux

We see evidence for scattered or sparse export of individual logs occurring almost every year near the peak of the highest flow(s) for the year. This yearly sparse transport of wood can be thought of as a background flux. The Pelican Island data show that there is some movement almost every year whether or not there is a massive flux event like a wood flood. The time-lapse data support existing research indicating that sparse export rapidly increases as flood waters rise and begin to access wood stranded on the banks from preceding high flows and then more slowly decreases [MacVicar and Piégay, 2012; Kramer and Wohl, 2014]. Thus, it is likely that wood transported during smaller nonwood flood events is deposited along decreasing channel margin elevations as flows recede. Although much smaller in magnitude than infrequent wood floods, sparse wood flux plays a large role in organizing positions of re-recruitable wood along channel margins.

### 5.3.2. Ice Wood Flux

Wood flux from ice is an extremely important part of the wood dynamics on the Slave River. Our time-lapse imagery shows that wood is interspersed and transported within ice jams progressing downstream and that congested wood transport follows the ice jam by a lag of about 1 day (watch *ms03\_FF2013051314\_10min5fps\_breakup.avi*). Furthermore, the data from the Pelican Sanctuary show that ice movement in the early summer is an important process for reorganizing and redistributing fluvially deposited from the prior year. Ice will commonly compact wood and push wood to higher elevations, making wood harder to access by summer flows. *Uunila and Church* [2015] showed that, along the Peace River, ice can deposit wood 7 m above water level. Thus, perhaps the Slave River is particularly prone to episodic massive wood floods because ice regularly pushes wood from lower elevations to a narrow band of bank where wood is too high to be redistributed by regular flows. Ice gouging controls the community structure of riparian vegetation [*Uunila and Church*, 2015] and is likely a main variable controlling the yearly flux of wood from the banks to the river. Wood-ice transport processes are also highlighted as an important part of wood dynamics for the St. Jean River in Québec *Boivin et al.* [2016]. We posit that, when present, ice is a dominant variable controlling wood fluxes. However, almost no detailed studies have looked explicitly at the relationship between wood flux and ice and we recommend it as an avenue of further research.

### 5.3.3. Congested Wood Flux

Congested wood floods are not unique to the Slave River. The wood flood we witnessed on the Slave in 2011 was strikingly similar (albeit smaller) to a 1919 wood flood described by *Kindle* [1921, p. 53] on the Mackenzie River:

The immense volume of this floating mass of travel-scarred tree trunks and forest debris greatly exceeded anything seen or imagined. In general, it formed a nearly continuous mass of a mile or more in width...Walking over this driftwood was often more feasible than canoeing through it... The closely packed phase of this particular exodus occupied about four days in passing a given point.

Wood floods are not just associated with high magnitude flows, but are highly dependent on the magnitude of wood in storage preceding the event. The potential for wood reorganization and transport downstream depends on the sequence of peaks as well as multiyear fluctuations in elevations and availability of stored wood for transport. The Pelican Sanctuary data show that prior to 2011 it was the combination of 4 years of decreasing flows that loaded banks and islands with wood, along with the highest peak flows in 14 years, that likely precipitated the wood flood. Peak discharges were higher in 1996 and 1997, but they occurred in years with low wood storage, and we found no evidence for wood floods during these years in historical documents, the log raft, or the memory of local people.

What is interesting is that in 2011, despite high volumes of wood moving down the river, there was only a slight increase in total wood storage after the flood (Figure 7a). This is probably because high amounts of wood were already in storage on the island before the flood and the wood that was there may have simply been replaced, resulting in little net change. The sharp downward spike in wood that stayed (Figure 7b) in

2011 supports the idea that, while there was little net change in total stored area (Figure 7a), there were large changes in the positioning of wood, with overall net gain of new pieces in new places (Figure 7b).

Correspondence between different lines of evidence for “return interval” of wood floods on the Slave River suggests that periodicity in wood flux is real and not an artifact of a particular data set or method of analysis. Succession of driftwood deposits from large wood floods like 2011 are a primary driver of outer deltaic morphology and vegetative patterns in the Slave River Delta [Kramer and Wohl, 2015]. Tree core dates on trees growing on drift piles suggest that discrete driftwood berms are deposited every 30–50 years [Kramer and Wohl, 2015], which corresponds fairly closely with the wood flood recurrence interval of ~27 years from the log raft.

Furthermore, vegetated drift piles identified by Kramer and Wohl [2015] were clumped around the 1930s, early 1950s, mid-1960s, late 1970s, and early 1990s. These dates correspond well with evidence from the Pelican Islands, log raft, and historic photos. The two very large advances of the log jam front between 1930 and 1950 and again between 1950 and 1966 (Figure 5) correlate with the early 1950s and mid-1960s vegetated driftwood dates from the lake. And, the vegetated 1990s deposits in the lake relate well to the raft moving forward in 1991, likely from the same high flows that removed wood from the Pelican Islands (Figure 7) during ice breakup.

Although there was no recorded change in the raft position for the mid-1970s, wood transport and delivery to the lake occurred in the early to mid-1970s based on dates of lake driftwood and congested wood transport in the 1975 historic photo (Figure 4). Evidence for a mid-1970s wood flood may be missing from the log raft for several reasons. First, wood during the 1970s did not enter the side channel with the raft because the wood in the photo was sourced from local remobilization in the Rapids Corridor of destabilized wood by ice push and ice jam flooding in 1974 (the highest recorded discharge on record) rather than regional transport of new wood coming from upstream. Second, we only analyzed the log raft in 1970 and again in 1979, so we may have missed changes to the log front in the middle of the decade. Third, it could be that the 1975 photo date is in error.

#### 5.4. Synthesizing Pulsed Export Processes

In Figure 11, we present a conceptual model to explain the processes by which wood is exported downstream in pulsed fluxes of varying magnitude despite conditions imposed by different recruitment regimes. This model works for explaining how wood from episodic massive recruitment events (i.e., landslides) and small discrete recruitment events (i.e., bank erosion) are routed through river systems.

Where and when newly recruited wood is deposited depends upon the interactions among flow, wood characteristics, and channel characteristics [Kramer and Wohl, 2016; Ruiz-Villanueva et al., 2015]: we call this the trapping function. When wood is deposited in locations that are accessible by subsequent flows, it is in temporary storage. If the wood decays or is vegetated before it can move again, then it has become laterally exported from the active channel and is in permanent storage within the geosphere and biosphere.

At some point, wood that is in temporary storage is remobilized when the elevation of flow surpasses the elevation of the wood [Bertoldi et al., 2013], modified by an anchoring effect. We define the anchoring effect to be anything that limits mobilization when flow elevation equals wood elevation. Factors that limit wood mobilization include larger piece sizes, partial burial, rootwad presence, contact with other pieces, bracing against channel boundaries, protection by larger pieces, and channel irregularities [Wohl and Goode, 2008; Merten et al., 2010; Kramer and Wohl, 2016]. Wood is often stranded at a narrow range of elevations from a flood [Bertoldi et al., 2013], therefore the mobilization threshold for one piece of wood is also the mobilization for many, resulting in a rapid increase in wood flux over some reach-scale discharge threshold. After the threshold is crossed, we suggest that the magnitude of the wood flux is mostly a function of three nested processes operating on three different time scales (Figure 11): (i) the characteristics of the rising limb during one flood, (ii) the sequence of flows during run-off season, and (iii) multiyear to multidecadal flow history.

The transport threshold of a specific fluvial recruitment event can vary between floods because it is highly dependent on the elevation at which the preceding flood deposited wood [Haga et al., 2002; Bertoldi et al., 2013]. Over time and on average, this transport threshold appears to be between the 1 and 2 year recurrence interval. If water level does not increase sufficiently to access wood on the banks, no wood will be transported, no matter how steep the rise. Generally, wood pieces found on lower sections of bank are

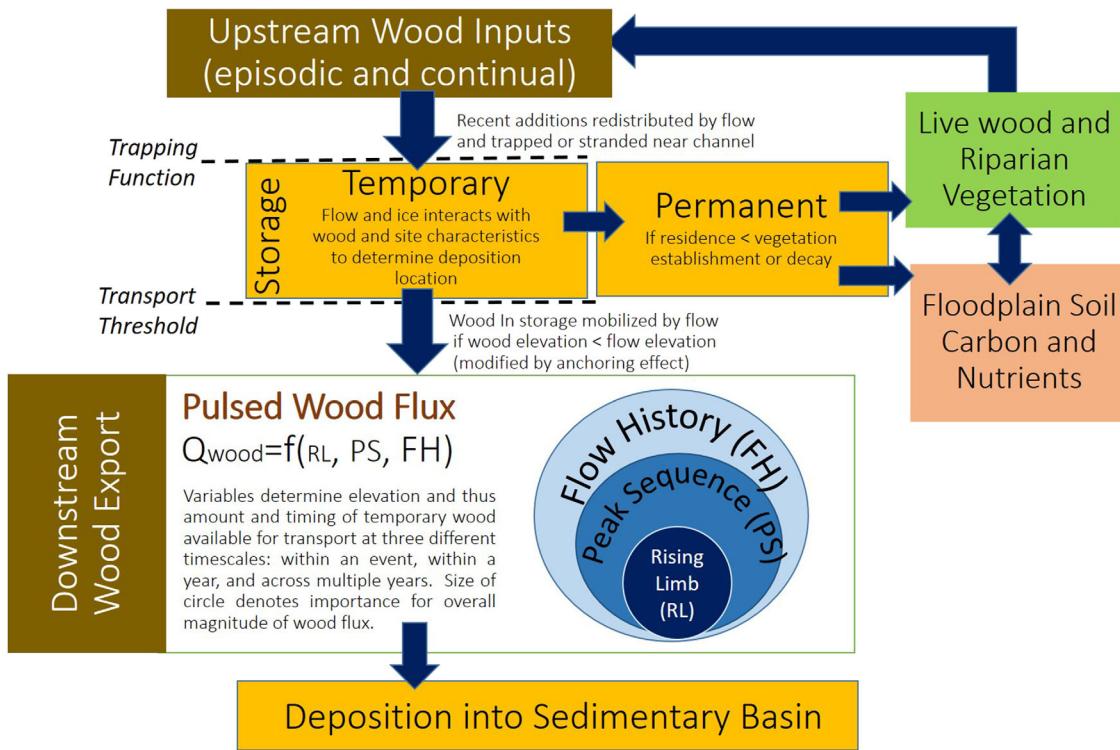


Figure 11. Conceptual model of pulsed wood export from drainage basins.

transported more often for shorter distances and follow a sparse transport style. When a flood is able to access multiple elevations of accumulated wood in a short amount of time along a very long stretch of river bank, congested wood floods can occur.

Thus, the sequence of peaks within a year governs the location and availability of wood, whereas the rate and magnitude of the rising limb dictates whether the wood is accessed. We have shown that the highest wood fluxes occur as infrequent, episodic congested wood floods within the context of flow history. The largest wood floods happen when there are multiple years of decreasing peak discharges that strand wood at successively lower elevations, followed by an exceptional year with a flashy peak that is of sufficient magnitude to quickly recruit wood stranded from multiple years.

Previous studies that have examined change in wood storage have focused on mobilization only from single events or one to a few run-off seasons along a reach [e.g., Young, 1994; Berg *et al.*, 1998; Cadol and Wohl, 2010; Dixon and Sear, 2014; Iroum   *et al.*, 2015]. Generally, all wood is counted and then after a year (or one flood), wood is tagged and counted again. Although this approach provides a general sense for average percentage of wood that moves in 1 year or one flood, it is inherently limited for understanding variability of wood export and transport thresholds as it does not account for change in thresholds due to sequence of flows or flow history.

Known temporary trapping sites that have high turnover of wood, such as channel constrictions, channel spanning jams, and mid-channel bars and islands, are ideal locations to study wood transport through time and can be analyzed with historic imagery or actively monitored with time-lapse cameras. Other ideal locations are sites of continued and permanent deposition such as log rafts [Boivin *et al.*, 2015], lakes and reservoirs [Moulin and Pi  g  y, 2004; Seo and Nakamura, 2009], and delta fronts [Kramer and Wohl, 2015].

## 6. Conclusion

We found that the magnitude of wood flux is strongly influenced by the shape and patterns of water discharge at varying time scales: (i) the rate of rise on the rising limb, (ii) the sequence of peaks within a year, and (iii) flow history that sets decadal patterns of wood storage. Within the framework of recruitment and

wood availability, we argue that flow history is the most important variable for prediction of the magnitude of wood flux, followed by decadal patterns and the rate of change during the rising limb.

We suggest replication of our approach of monitoring known sites of temporary or permanent storage through using repeat imagery or surveys coupled with active monitoring of wood in transport with video or time-lapse photography. This would facilitate further exploration of the relative importance of discharge/transport thresholds, sequences of flows, influence of wood trapping sites, and influence of wood recruitment in natural rivers of differing size and type.

Mapping or surveying relative abundance of wood volumes at varying elevations at chosen monitoring sites could be used as a hazard management tool to understand when banks are becoming loaded with wood versus when they are losing wood [e.g., Lassettre *et al.*, 2008]. Similar to earthquake hazards, risk increases when more time elapses between wood flushing events because banks may become more heavily loaded with wood. Picking monitoring plots through drainage networks could also help to understand how waves of wood from mass recruitments propagate downstream.

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