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Simulated wood budgets in two mountain streams

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ABSTRACT

Large wood (LW) recruitment, transport, and storage were evaluated over a century in Gregory and Riley creeks (Haida Gwaii, British Columbia) by modeling a reach-scale LW budget using two frameworks for output: LW loss through decay and downstream transport, and loss through depletion. At reach and at watershed scales, mass movement and bank erosion dominated inputs, and fluvial transport was an important flux term in several reaches. Large wood recruitment by mortality was relatively minor in comparison. Large proportions of the in-channel LW were stored in jams with a mean age of 40–50 years. Overall, both modeling approaches yielded reasonable stored LW predictions in the study creeks, with the omission/inclusion of transport responsible for the largest differences between models. Modeled storage generally was within 30% of that measured in the field, and our results illustrate the large temporal variation in storage resulting from episodic inputs of LW from hillslopes.

1. Introduction

In forested regions, within-channel large wood (LW) constitutes an important geomorphic, hydraulic, and ecological component of stream systems (Keller and Tally, 1979; Hogan, 1986, 1987; Bilby and Ward, 1989; Gurnell et al., 2002; Abbe and Montgomery, 2003; Phillips, 2012; Wohl, 2013). Large wood is recruited to a stream channel network through a variety of processes including mass movement, bank erosion, and mortality and is transported and redistributed from upstream through fluvial and mass movement processes (Martin and Benda, 2001; Benda and Sias, 2003; May and Gresswell, 2003; Kasprak et al., 2012; King et al., 2013; Benda and Bigelow, 2014, Ruiz-Villanueva et al., 2014; Lucia et al., 2014). Once in the stream, LW can (i) promote sediment storage and regulate bed material sediment transport (Keller and Tally, 1979; Hogan, 1986; Roberts and Church, 1986; Gippel, 1995; Wilcox and Wohl, 2006; Andreoli et al., 2007; Eaton et al., 2012; Davidson and Eaton, 2013); (ii) alter channel morphology and promote pool formation (Bilby and Ward, 1989; Jackson and Sturm, 2002; Bocchiola, 2011; Faustini and Jones, 2003; Wohl and Jaeger, 2009; Thompson, 2012; Davidson and Eaton, 2013); (iii) produce local channel scouring (Smith, 1992); and (iv) modify channel width, gradient and channel-floodplain connectivity by triggering bank erosion and avulsions (Nakamura and Swanson, 1993; Brummer et al., 2006; Sear et al., 2010; Wohl, 2011, 2013; Phillips, 2012; Davidson and Eaton, 2013). Changes to the delivery, storage, and transport of LW therefore lead to changes in sediment storage, stream morphology, and aquatic habitat (McHenry et al., 1998, Gurnell et al., 2002; Benda and Bigelow, 2014).

Timber harvesting operations change the supply and nature of LW entering a stream (e.g., Hogan, 1986, 1987; Hogan et al., 1998a, 1998b; McHenry et al., 1998; Benda and Bigelow, 2014) by removing the standing timber stock, and regulations are widely applied to this industry in order to maintain a supply of LW to streams (e.g., Forest and Range Practices Act, 2004). In addition, many watershed restoration efforts have focused on returning LW to logging-affected channels in order to improve aquatic habitat (e.g., Roni et al., 2002) and to mitigate any logging-related stream channel disturbance (e.g., Faustini and Jones, 2003; Czarnomski et al., 2008). It is therefore of interest to scientists and watershed managers to develop management practices that sustain LW volumes in managed streams while still allowing access to commercial timber resources. This requires a detailed understanding of LW input and flux.

The sources of LW delivered to a given stream will vary with geology, topography, forest type, management and landscape history, floodplain configuration, character of flood events, channel network structure, and the geomorphic coupling between hillslopes and channels (May and Gresswell, 2003; Wohl, 2013; Benda and Bigelow, 2014). Two types of linkages are defined (Brunsden, 1993; Whiting and Bradley, 1993): (i) coupled — in which there is a free transmission of material and energy from hillslope to channel, and (ii) decoupled — in which there is (temporarily) no interaction between hillslope and channel given the presence of barriers such as floodplains. Temporal and spatial variations in hillslope-channel connectivity (coupling) have a significant influence on the evolution of forested landscapes, channel dynamics in mountain streams, habitat diversity and quality, and LW recruitment processes (Montgomery and Foufoula-Georgiou, 1993;

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Montgomery, 1999; Jakob et al., 2005; Savi et al., 2013). Similarly, the character and quantity of stored LW along channels can vary with channel morphometry. A controlling factor of downstream change in LW storage is channel geometry: as channel width and depth increase, flows are more capable of transporting recruited LW material (Hassan et al., 2005; Eaton et al., 2012; Rigon et al., 2012).

Some studies have suggested that, in steep terrain, mass movement can dominate the delivery of LW to channels (Lienkaemper and Swanson, 1987; Nakamura and Swanson, 1993; May and Gresswell, 2003; Benda et al., 2005; Rigon et al., 2012). Other studies, conducted for the most part in relatively low-relief terrain, have suggested that hillslope input plays only a minor role in delivery of LW to streams and that inputs of LW from mortality and bank erosion are most significant (e.g., Murphy and Koski, 1989; Martin and Benda, 2001; Benda et al., 2002; Benda and Bigelow, 2014). Furthermore, most LW budget studies are either purely synoptic in design or are relatively short-term case studies (e.g., Lienkaemper and Swanson, 1987). In summary, there remains a lack of understanding as to the relative importance of different LW recruitment processes within and between basins in steep terrains over timescales sufficient to capture the episodic nature of hillslope input.

Utilizing a unique data set, in this paper we investigate LW dynamics using two approaches to develop reach-scale budgets in paired watersheds over a century-timescale. The specific objectives of the study are: (i) to compare LW recruitment processes between reaches within the same watershed and between watersheds, and (ii) to evaluate and contrast the LW budget using depletion and decay/transport frameworks. A comparison between these two frameworks will help identify the dominant processes controlling reach-scale LW dynamics.

2. Watersheds and study reaches

This study focuses on the Gregory and Riley Creek watersheds in Rennell Sound, on the west coast of Graham Island in the Haida Gwaii (formerly Queen Charlotte Islands) archipelago (Fig. 1). Riley and Gregory Creeks drain an area of 27.6 and 35.0 km^2, respectively, of steep terrain (Table 1). The region is moist and temperate, with mean annual precipitation of 3400 mm (Wang et al., 2012). The most intense storm events typically occur in the fall and the winter with maximum precipitation in October (Hogan and Schwab, 1990). The watersheds have been shaped dramatically by repeated glacial episodes, and valley walls tend to be steep and covered with unstable glacial drift material (Roberts and Church, 1986). The region is composed of weak, highly erodible sedimentary and volcanic rock (Sutherland Brown, 1968; Roberts and Church, 1986). The combination of high precipitation, unstable surficial materials, weak lithology, and steep hillslopes contributes to extensive mass movement in the region (Hogan et al., 1998a, 1998b).

Forest cover in the basins is typical of the Coastal Western Hemlock biogeoclimatic zone (CWHvm) with high forest density (Meidinger and Pojar, 1991; Hassan et al., 2005) and infrequent, localized disturbance that create canopy gaps (e.g., Daniels and Gray, 2006). In 2005, the Province of British Columbia performed an inventory of forest resources on all public lands, collecting data to describe forest composition, age,

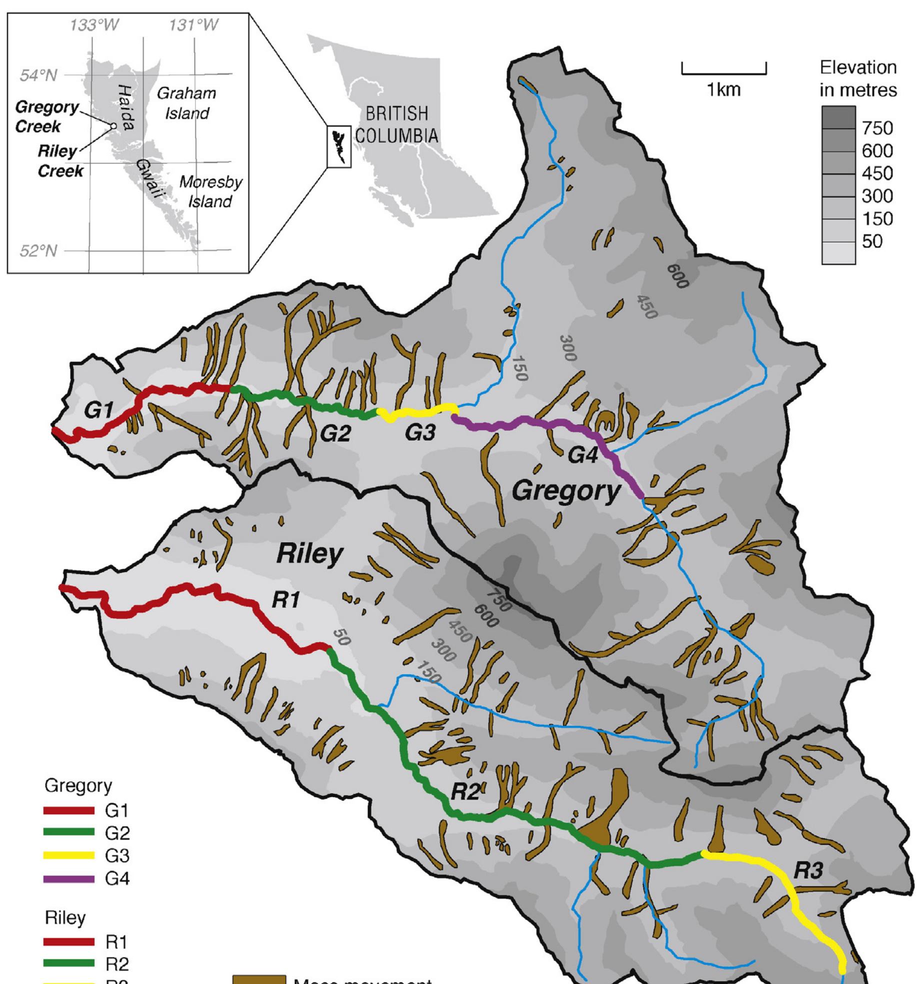

Fig. 1. Location map, watershed, and study reaches of Riley and Gregory creeks.

Table 1
Characteristics of the study reaches in Riley and Gregory creeks.

Reach	Reach length (m)	Bankfull width (m)	Bankfull depth (m)	Channel slope (m/m)	Bank erosion rate (m/y)	Error (%)	Mass movement input to channel
Riley Creek							
R1	3976	24.9	2.0	0.0080	0.089	10.2	No
R2[a]	5926	22.1	1.7	0.0196	0.028[b]	12.3	Yes
R3	2294	13.6	1.2	0.0173	0.091	10.2	No
R1–R3	12,206	21.7	1.7	0.0155	0.069	10.9	Yes
Gregory Creek							
G1	2586	29.1	2.0	0.0108	0.101	7.8	Yes
G2	1990	31.1	1.7	0.0125	0.127	7.8	Yes
G3	1109	32.1	2.2	0.0106	0.118	7.8	Yes
G4	2873	15.9	1.5	0.0200	0.036	7.8	Yes
G1–G4	8558	25.5	1.8	0.0143	0.096	7.8	Yes

[a] The reach was logged between 1973 and 1978.
[b] Pre-logging bank erosion rate.

and stature (http://www.for.gov.bc.ca/hts/vri/) at a map scale of 1:20,000. Variables relevant to this study are summarized in Tables 2 and 3.

In 1988–1989, the British Columbia Ministry of Forests conducted an extensive, continuous survey to characterize channel morphology and geometry, LW (within and suspended above the channel), the influence of debris slides and flows on channel morphology, and bank erosion throughout Haida Gwaii. This included channel surveys carried out along 8.56 km of Gregory Creek and 12.21 km of Riley Creek, beginning in the relatively low-relief estuaries and ending near the coupled headwaters. Each survey was divided into channel reaches based on channel morphology, location of tributary junctions, and land use (i.e., logging) (Table 1, Fig. 1). The reaches help to isolate processes that deliver LW to the channel and allow comparison of reach-scale LW dynamics by position within a drainage basin. Extensive logging occurred in the riparian area and on the adjacent hillslopes of reach R2 in Riley Creek (logging began in 1973 and about 12% of the basin was logged by 1990).

3. Reach-scale LW budget

We have developed a reach-scale budget to study LW dynamics over a period of 100 years. The budget concept has been used in previous studies to quantify sources, storage, transfer, and loss of LW in streams (Martin and Benda, 2001; Benda et al., 2002; Benda and Sias, 2003; King et al., 2013; Benda and Bigelow, 2014). The general reach-scale LW balance can be written as

$$\Delta S = [I\Delta x - L\Delta x + (Q_i - Q_o) - D]\Delta t \quad (1)$$

where ΔS is the change in LW storage in a reach of length Δx over time Δt, I is the rate of LW recruitment, L is the rate of overbank and abandoned loss of LW, Q_i and Q_o are the transport of LW into and out of the reach, respectively, and D is the in situ decay of LW.

Within this framework, Benda et al. (2002) calculated LW recruitment from a variety of sources as

$$I = I_m + I_f + I_{be} + I_{ms} + I_e + I_a \quad (2)$$

where I is the total input or recruitment of LW to the channel; I_m is the input from tree mortality, blowdown, disease, or competition mortality; I_f from disturbance such as fire or windstorm; I_{be} from bank erosion; I_{ms} from mass movement; I_e from entrainment of pieces fallen into the channel and exhumation of LW from the channel bed; and I_a from anthropogenic inputs. Assuming (as within our study area) inputs from disturbances such as fire or windstorm (I_f), entrainment and exhumation of LW (I_e), and anthropogenic inputs (I_a) are negligible, then total input (I) can be simplified as

$$I = I_m + I_{be} + I_{ms}. \quad (3)$$

Generally, the terms in Eq. (3) and the storage term (S) in Eq. (1) can be measured directly or modeled over a range of periods. However, the terms that describe the removal of LW from a reach (L and D) and the transport or flux of LW through a reach (Q) are more difficult to quantify. If the period is short relative to the frequency of LW-moving flows and the decomposition rate so that D and L are negligible and if LW is relatively static given the dimensions of LW pieces relative to the morphometry of the channel (e.g., Braudrick and Grant, 2000; Hassan et al., 2005; Cadol and Wohl, 2010; Eaton et al., 2012), then the removal and flux terms can be reasonably omitted from the analysis (e.g., Martin and Benda, 2001; Benda et al., 2002). However, over relatively long periods (i.e., a century or more) and/or in channels with mobile LW, the removal of LW from a channel must also be accounted for within a budget (as is the focus of this paper).

Murphy and Koski (1989) suggested that the exponential decay model is a realistic description of LW removal from processes described by D and suggested the form

$$V_t = V_o e^{-kt} \quad (4)$$

wherein V_t is the amount of LW at time t, V_o is the amount of LW at initial conditions ($t = 0$), and k is the decay constant ($k = 1/\Delta t$), which is represented either as the inverse of the weighted mean age of LW (Murphy and Koski, 1989; Beechie et al., 2000) or the arithmetic

Table 2
Forest characteristics averaged from VRI map[a] polygons and stratified by source area within each watershed; riparian area data was used to model recruitment of LW from mortality and bank erosion; data were limited to live trees ≥17.5 cm breast height diameter; data from logged areas was omitted.

Site	Volume of tree stems (m^3/ha)	Tree stems per hectare (no./ha)	Tree diameter[b] (mm)	Tree height[c] (m)	Age[d] (y)
Upslope area					
Riley	540	771	384	31	281
Gregory	558	724	398	32	303
Riparian area					
R1	968	441	439	44	270
R2	702	566	391	36	290
R3	886	515	488	42	275
G1	772	416	416	38	305
G2	730	429	429	40	255
G3	766	426	426	40	261
G4	898	473	447	43	319

[a] http://www.for.gov.bc.ca/hts/vri/.
[b] Quadratic mean stand diameter measured at breast height.
[c] Height of the leading tree species.
[d] Age of the leading tree species projected to 1989.

Table 3
Maximum age of tree species found in the riparian area of Gregory and Riley creeks; the reported maximum age range is taken from Waring and Franklin (1979) and Burns and Honkala (1990); the basal area is derived from the VRI map and describes the relative amounts of each species in the respective riparian areas averaged across all polygons that intersected the channels.

Tree species	Basal area (m^2/ha)		Maximum age (y)		P_F ($\times 10^{-3}$)
	Riley	Gregory	Reported range	Value used in model	
Western hemlock (*Tsuga heterophylla*)	36.4	43.5	400 to >500	500	2.0
Sitka spruce (*Picea sitchensis*)	21.4	18.4	>750	750	1.3
Western red cedar (*Thuja plicata*)	14.9	12.1	800 to >1200	1200	0.83
Yellow cedar (*Chamaecyparis nootkatensis*)	2.0	1.0	700 to >3500	1000	1.0
Lodgepole pine (*Pinus contorta*)	0.2	0.2	300 to 400	300	3.3

mean age of LW (Benda and Bigelow, 2014). The decay (D) of LW over time period T is then

$$D = \int^{T} V_o(t) \cdot \left(1 - e^{-kt}\right) \Delta t. \quad (5)$$

Beechie et al. (2000) and Hyatt and Naiman (2001) used a similar model but expanded the definition from decay to depletion (R) and included decay, transport, and loss with other sources in the term. The main difficulty with this approach is in obtaining a reliable estimate of k. Field estimates of LW age are usually obtained through simple tree ring counts of nursed trees growing on LW (e.g., Hogan, 1987) or by more advanced dendrochronological techniques that compare growth patterns of LW to adjacent trees in the riparian forest (e.g., O'Connor et al., 2003). The former technique gives the minimum age of LW (assuming no missing rings) and can often be done in the field, while the latter technique can establish an absolute age but requires laboratory analysis. Annual monitoring of LW in a reach can also be used. However, it is usually not possible to age each LW piece in a reach, so only a portion of LW is used to calculate k. Alternatively, LW can be grouped into age classes based on the physical characteristics of LW in conjunction with tree ring counts where possible (e.g., Benda and Bigelow, 2014).

In this paper, we evaluate two approaches for estimating the removal of LW from the channel over a period of 100 years. First, we estimate k from the mean weighted age of LW stored in the channel, model Q based on Eaton et al. (2012), and omit L from the analysis. Second, we derive k from Eq. (4) and our field measurements of S and I. In the latter approach, we assume equilibrium conditions; and over a period of 100 years, the average rate of LW input (I) equals the average depletion rate (R). If we further assume an exponential depletion model, then R will equal the average rate of change along the appropriate exponential decay curve. Our period of interest is from $t = 0$ to infinity as R describes the average rate of change over the entire function. Given that the residence time ($t = k^{-1}$) of an exponential function describes the average time a given quantity will remain stored in a system, the rate of change at t describes R. The rate of change of any exponential function is given by its first derivative with respect to t giving $-V_o k e^{-kt}$, and because we are considering the rate at t, the product of k and t equals 1. By definition, the volume of LW (V_t) at t equals V_o ($1/e$). Assuming field storage volumes (S) are at equilibrium conditions, then V_t can be approximated by S. If we are at equilibrium conditions with a relatively constant I (and therefore relatively constant R), then the volume of LW stored in the channel should be equivalent to the volume of LW stored in the channel at the residence time. Following this approach, R is given by

$$R = -kSe^{-1} \quad (6)$$

and, after rearranging Eq. (6), k is derived by

$$k = -R/\left(S\,e^{-1}\right). \quad (7)$$

4. Data and budget term determination

4.1. Mortality

Large wood recruitment from mortality can be considered a chronic source of LW (Benda et al., 2002).We use a model developed by Van Sickle and Gregory (1990) to simulate LW recruitment rates from mortality for both creeks. According to the model, the expected volume of LW (V_b) entering a channel from a single tree-fall event because of mortality can be expressed as

$$E(V_b) = \int_{a_s}^{180-a_s} V_b f(a) da \quad (8)$$

where a_s is the angle of fall at which the tree top contacts the nearest channel bank and $f(a)$ is the probability of a tree falling at angle a relative to the channel banks. Calculated using tree height and diameter (Table 2), V_b is derived from VRI map polygons and from field measures of channel width (Table 1). The calculation was performed for each polygon intersecting a reach and then summed to account for differences in forest structure (Table 2 presents the average). The bole was assumed conical in shape and only the length of the bole that enters the channel was considered (i.e. the length of the cone was reduced by the distance from the trunk to the bank). In the case where the entire tree crown enters the channel, the bole volume was truncated below a diameter of 10 cm (i.e. tree tops or small wood pieces were omitted). For each standing tree, a random fall probability was assigned. Eq. (8) was integrated over the limits of 180°-a_s to a_s, representing an arc defined by the tree crown as it intersects the channel banks at angle as and then again at 180°-a_s.

In small streams, fallen wood is often suspended above the channel banks (i.e., bankfull width < tree height), and direct input to the channel may not occur until a log is either broken or reoriented (Nakamura and Swanson, 1993). We assume that the period of observation (100 years) is greater than the period for a fallen log suspended above the channel banks to fragment and decay and that the section of the modeled log is eventually transferred to the channel in its entirety. Approximately 20% of LW by volume was suspended above at least one channel bank at the time of our survey.

The total volume of LW (I_m) entering a channel following tree mortality in a given year was modeled as follows (after Van Sickle and Gregory, 1990):

$$I_m = \Sigma D_s \Delta Z_j \Delta x P_f E(V_b) \quad (9)$$

where D_s is the stand density (m^3/ha), Z_j represents the distance between a tree and the stream banks (measured in 1-m steps), Δx is reach length (m), and P_f is the probability of a tree falling during t_i to t_{i+1}. We assumed that P_f could be modeled by the inverse of the typical age at which mortality occurs for a given tree species (Table 3). The likelyhood of a tree falling (P_f) is thus described by a uniform probability distribution where a mortality event has an equal chance of occurrence throughout the expected life of a given tree.

4.2. Mass movement

Mass movement processes have been studied extensively on Haida Gwaii (e.g., Gimbarzevsky, 1988; Schwab, 1998; Martin et al., 2002), revealing that LW delivery to some stream channels is dominated by mass movement events during major, infrequent rainstorms (Hogan et al., 1998a, 1998b; Schwab, 1998). For the study basins, large storms and associated landslides occurred in 1891, 1917, 1935, 1952, and 1978 (Hogan et al., 1998a, 1998b; Schwab, 1998). Landslides were identified and assessed based on field and air photo measurements undertaken concurrently with our channel survey (described in Schwab, 1998). In a 100-year record, 36 and 24 major landslides entered Gregory Creek and Riley Creek, respectively, although not all landslides delivered LW to the channel.

For a slide on an open slope, modeled LW input (I_{ms}) was defined as

$$I_{ms} = A_{sf}(V_{sd} + V_{CWD}) + I_g \tag{10}$$

where A_{sf} is the area of the slide (ha), V_{sd} is the volume of trees in the forest by slide area (m^3/ha), V_{CWD} is the volume of coarse woody debris (CWD) stored on the forest floor by slide area (m^3/ha), and I_g is input to a slope failure from forested gullies (m^3/ha) (see Oden, 1994). The terms V_{sd} and V_{CWD} were estimated at time of failure from the VRI data and regional values, respectively. We used regional CWD values of 570 m^3/ha for wet forests in the CWH biogeoclimatic zone (reported in Stevens, 1997). Although there was up to a 100-year lag from the occurrence of a landslide event to the compilation of the VRI data, we assumed that old growth forests (defined as >250 years old in coastal British Columbia) within the respective watersheds were relatively stable in biomass during this period, and that V_{sd} values derived from multiple VRI polygons across multiple slides was a fair approximation of past conditions. However, the assumption of old growth conditions was inappropriate on landslides that reoccurred on the same landslide scar. In this situation, values of V_{sd} were based on values for five age classes of regenerating forests on landslide scars for Haida Gwaii reported in Smith et al. (1986) and ranged from 4.3 m^3/ha for forests near 10 years old to 143.1 m^3/ha for forests >60 years old (cf. Table 2). The CWD was assumed negligible. If a landslide occurred on a slope post-logging, V_{sd} was estimated from values for regenerating forests given by Smith et al. (1986), while CWD volumes were based on regional values for logged forests in the CWHvm biogeoclimatic zone of 698.10 m^3/ha (Wells and Trofymow, 1997).

The input of LW from gullies was modeled using gully recharge rates calculated by Oden (1994) for 29 gullies in Rennell Sound, including sites in the Gregory and Riley Creek basins. In the context of LW, gully recharge rate is defined as the rate at which organic debris accumulates in a gully following scouring by a debris torrent (Oden, 1994). The total volume of LW residing in a gully at the time of slope failure (I_g) was defined as

$$I_g = U_g A_{sf}\, \Delta t_g \tag{11}$$

where U_g is LW recharge rate (m^3/y/ha), and Δt_g is the period of time elapsed since the last instance of gully scouring from debris torrent. The gully recharge values were applied to recurring and to first-time slope failures. For slides that were not identified in the inventory as recurring, Δt_g was set equal to the average time between recurring slide failures in the basin.

4.3. Bank erosion

Input of LW because of bank erosion and collapse (I_{be}) results from recruitment of riparian standing trees (I_{bet}) and CWD (I_{beCWD}). The term I_{bet} was modeled as (modified after Benda and Sias, 2003)

$$I_{bet} = \Sigma D_s B \Delta x P_f E(V_b) \tag{12}$$

where B is the lateral rate of bank erosion per year (m/y) averaged over the reach length (Δx); P_f was set at 1.0 so that all standing trees in an eroded area fell to the ground. The range of fall angles was limited to those that intersected the channel, as each log undermined by bank erosion or collapse is assumed to fall towards the channel (Murphy and Koski, 1989; Benda et al., 2002). The term I_{bet} was set to zero if the streambanks were logged. The I_{beCWD} was modeled using regional CWD values of 570 m^3/ha for wet forests in the CWH biogeoclimatic zone (reported in Stevens, 1997) and 700 m^3/ha for logged forests in the CWHvm biogeoclimatic zone (Wells and Trofymow, 1997). Then, the I_{beCWD} was modeled as

$$I_{beCWD} = B \Delta x V_{CWD}. \tag{13}$$

The lateral rates of bank erosion were modeled from the age, spatial extent, and species composition of riparian forest patches growing on each valley bottom. Considered over time, valley bottom deposits closest to the channel are more susceptible to bank erosion than those more distant, often leading to a logarithmic distribution of valley bottom surfaces by area and age (Everitt, 1968; Gottesfeld and

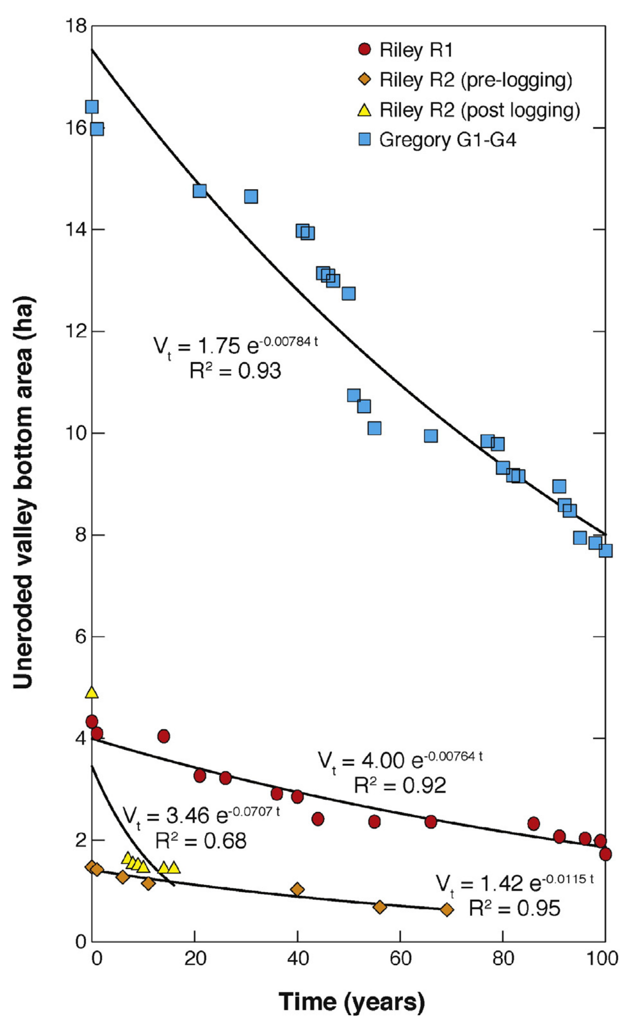

Fig. 2. Area of uneroded valley bottom with time for study reaches in Gregory and Riley creeks. Note for reach R2 we fit separate relations for pre- and post-logging. Uneroded valley bottom area includes the area of the valley bottom not eroded over the period of observation (100 years) based on the age distribution of the riparian forest.

Johnson Gottesfeld, 1990; O'Connor et al., 2003). In Haida Gwaii, red alder (*Alnus rubra*) is a pioneering tree species that quickly colonizes fresh sediments, often within a year following disturbance. We used the area and age of riparian forest patches dominated by red alder as a surrogate for a measure of the magnitude and timing of erosional events generated by lateral channel instability (generally bank erosion and/or channel avulsion around a log jam). Following this approach, the minimum age of the oldest patch of red alder represents the earliest erosional event preserved in the record and the time in years since initial conditions (or no recorded erosion) and is given by $t = 1$. The remaining area of old, coniferous forest (tree species are given in Table 3) then represents the area of stable valley bottom as is plotted against t. The areal decay of the valley bottom through time was derived by fitting an exponential decay function to the plot (Fig. 2). The area of each forest patch was determined by measuring a valley bottom cross section once every fifth channel width along Δx and recording the distance at which a cross section intersected a forest patch of a given age. The age of each forest patch was modeled by tree-ring counts of the oldest tree(s) in each patch using an increment borer. This technique enables an estimate of the long-term rate of bank erosion but does not capture relatively low-magnitude erosion and accretion events that do not leave a record in the structure of the riparian forest.

Validation of this approach is based on a comparison between the modeled residence times of the Gregory and Riley valley bottoms (k^{-1} given in Fig. 2) and the maximum tree ages in the respective riparian forests. Modeled values of k^{-1} along forested sections of Gregory and Riley creeks were 128 and 131 years, respectively, while k^{-1} along the logged valley bottom in Riley Creek was 14 years. In comparison, the VRI map indicates that the ages of the oldest leading tree species in the unlogged, old-growth riparian areas of Riley and Gregory creeks were generally 280 and 290 years, respectively, while Bird (1993) provided an estimate of 400 years based on field data from a portion of Gregory Creek. The lateral rates of bank erosion were then derived by dividing the area of the valley bottom by the length of the channel with an erodible valley bottom present (i.e. relatively short sections of bedrock channel were omitted) and then dividing again by the respective residence times.

4.4. Fluvial transport of LW

The main controls on fluvial transport of LW are the ratios of wood piece length to channel width and LW diameter to channel depth (e.g., Lienkaemper and Swanson, 1987; Braudrick and Grant, 2000; Gurnell et al., 2002; Hassan et al., 2005; Eaton et al., 2012; Gurnell, 2013). We assumed logs stored partially outside the active channel and/or logs stored in log jams remain stable at bankfull flows and may only be mobilized during nonfluvial transport events. The limiting diameter for the remaining logs to resist floatation at bankfull stage was calculated after Braudrick and Grant (2000). The travel distance (X_{travel}) of each mobile piece of LW was modeled as follows (after Eaton et al., 2012):

$$\frac{X_{travel}}{W} = 10e^{-3.8\left(\frac{L_b}{W}\right)} \tag{14}$$

where W is the channel width (m), and L_b is the log length (m). Log jams in the study reaches are likely to affect LW movement. We calculated the probability of LW being trapped in jams (P_{trap}) as

$$P_{trap} = 1 - \left(1 - \frac{X_{travel}}{\Delta x}\right)^{Nj} \tag{15}$$

where Nj is the number of jams in the reach (after Eaton et al., 2012). Given the size of our basins (see Benda and Bigelow, 2014) and the relatively large number of jams, actual LW transport is likely lower than our modeled results. Collectively, transported LW volume (Q) is then described as

$$Q = \sum\left(\left(X_{travel}V_p\right)\left(1 - P_{trap}\right)\right) \tag{16}$$

where V_p is the volume (m^3) of the LW pieces. Large wood transport was calculated for the main channels and also for major tributaries to the study reaches.

Although LW and channel parameter data were not available for calculating nongully tributary input as above, an estimate was developed by relating average transport rate to the contributing area upstream in the main channels (also see Benda and Bigelow, 2014). Results yielded minor contributions from tributaries (<5 $m^3\ y^{-1}$) in Riley and Gregory, and field observations confirm that tributary input is minimal.

4.5. Output

With the decay and LW transport approach, LW losses are described by D and Q_o. Loss because of transport is described in Eqs. (14), (15), and (16). To calculate D for each year in each reach, Eq. (5) was applied, where V_o is the stored volume (m^3) of LW derived from the previous year in the model-run. Decay constants were derived from the mean weighted age of LW stored in log jams, described by Murphy and Koski (1989) as $\Delta T = \Sigma a_i p_i$, where a is the age (y) of LW, and p is the proportion of LW of that age. The modeled k values given in Table 4 generally fall within the range of rates observed in other locations with similar tree species found along the west coast of North America (Murphy and Koski, 1989; Hyatt and Naiman, 2001). The collective annual loss of LW in a reach is then given as the sum of D and Q_o.

With the depletion approach, all losses of LW within a reach are assumed to be represented by a single exponential function, which incorporates decay, transport, and any other losses. To determine depletion rate (R) in the study reaches, the input volume from all sources for each year of the 100-year record was calculated (I_t). However, as our inputs included several extreme events in the form of hillslope input of LW, a simple average value would be biased towards these extreme values. To overcome this bias, values in the distribution of I_t were bootstrap resampled with replacement ($n = 100{,}000$) and a median value for each sample was calculated. The mean value of all samples was then used for our value of R. To calculate R for each year, Eq. (5) is again used (substituting R for D), but k is calculated using Eq. (7). With this method, V_o at $t(0)$ is set to equilibrium storage where $I = R$, and subsequent values of R are based on S at the previous time-step in the model.

4.6. Storage

Channel storage of LW was derived from an inventory surveyed during 1988–1989 in Riley and Gregory creeks (Hogan et al., 1998b) using the method described in Hogan (1986, 1987) and Hogan and Bird (1998). The characteristics of log jams (age, size, function) were classified according to Hogan and Bird (1998). Jam ages were determined from the age of nursed trees (typically red alder) growing on logs or on sediment trapped within the jam (by either cutting a disk or using an increment borer, depending on tree size) and by assigning logs into decay classes.

4.7. Uncertainty in the measured and modeled values

The uncertainty associated with each term in the LW budget is summarized in Appendix A and Table A1.

Table 4
Volumes of LW inputs, rate of decay and LW storage.

Reach	LW input									Storage[a]		Transport[b]	Decay		Depletion	
	Bank erosion				Mortality		Hillslope					Volume	k	Error	k	
							Landslides		Gully			(m^3/y)	Exponent		Exponent	Error
	Standing LW		CWD				CWD	Standing LW								
	Input	Error	Input	Error	Input	Error	Input	Input	Input	Volume	Error					
	(m^3/y)	(%)	(m^3/y)	(%)	(m^3/y)	(%)	(m^3/y)[c]	(m^3/y)[d]	(m^3/y)[e]	(m^3/y)	(%)					
Riley Creek																
R1	28.6	4.9	30.8	31.8	2.0	78.7	0	0	0	5762	10	43	0.01879	0.00399	0.0306	0.0034
R2	16.2	6.8	14.0	32.8	2.2	65.9	4583.5	4645.9	116.9	10,311	7	45	0.02782	0.00457	0.0095	0.0007
R2 logged[f]	111.3	1.9	196.9	57.0	1.0	79.2							0.02037	0.00358	0.0368	0.0042
R3	15.2	5.3	15.0	24.7	0.8	126.9	0	0	0	2384	11	24	0.02346	0.00704	0.0203	
R1–R3	60.0	5.6	59.8	30.3	5.0	47.8	4583.5	4645.9	116.9	18,457	5					
R1–R3 logged	155.1	2.8	242.7	51.8	3.7	63.8										
Gregory Creek																
G1	20.1	12.9	20.4	20.6	0.8	219.2	529.5	346.3	0	3572	7	104	0.02037	0.00358	0.0312	0.0023
G2	20.0	7.0	25.3	20.6	0.9	119.8	2572.3	5631.9	3451.1	3476	7	63	0.02037	0.00358	0.0380	0.0027
G3	7.7	9.9	9.7	20.6	0.4	178.5	1579.8	1380	0	1506	18	17	0.02037	0.00358	0.0511	0.0096
G4	8.9	17.4	9.5	20.6	1.3	118.8	1045.1	1432.2	0	2031	24	8	0.02037	0.00358	0.0331	0.0080
G1–G4	56.5	6.0	64.9	26.5	3.5	79.0	5726.7	8790.4	3451.1	10,585	6		0.02037	0.00716	0.0378	0.0027

Values reflect post-logging riparian inputs; hillslope input not affected.
[a] Based on field survey.
[b] Fluvial transport with an estimated error of 60%.
[c] With an estimated error of 19% in unlogged and 57% in logged areas.
[d] With an estimated error of 10%.
[e] With an estimated error of 32%.
[f] The reach was logged between 1973 and 1978.

5. Results

5.1. Large wood input, storage, and balance

Summary results of LW inputs to the study reaches are presented in Table 4 and Fig. 3. The mortality rates for Riley Creek are <2% of the total LW input (Fig. 3D). The overall input from mortality to Riley Creek was about 1% of the total. Large wood inputs from mortality to Gregory Creek were about the same as those for Riley Creek, ranging from 1 to 3% (Fig. 3I).

Bank erosion input rates for Riley Creek ranged from 31 to 78%, highest in reach R1 and averaged about 36% for all reaches. Similar ranges were obtained for Gregory Creek (Fig. 3A). In addition to triggering numerous slope failures, major rainstorms in 1974 and 1978 were also responsible for significant channel changes in the lower reaches of Riley Creek. Each storm lasted for several days and had an estimated return period of 10 years or more. Environmental damage from the storms were observed across Haida Gwaii and included the washout of several bridges, culverts, and roads and at least 1000 landslides for the 1978 storm alone (Septer and Schwab, 1995). Field observations and air photo interpretation show that reach R1 at Riley Creek experienced a number of avulsions and instances of major channel widening (Fig. 4). Based on 1966 and 1979 air photos, the channel widened, on average by 4 m during this time period, contributing substantial quantities of LW to the channel through bank erosion.

Large wood input from gullies for both streams was negligible except for reach G2, where it composed 13% of inputs. Inputs from landslides (excluding landslides from gullies) are episodic in nature, which is apparent from the data plotted in Fig. 5. Landslides delivered LW to both channels in 28 separate failures that mainly occurred during five storm events over the landslide inventory record. The largest storm event in Riley Creek (Fig. 5A) occurred in 1917 and delivered a total of 6136 m^3, or 67%, of the total LW volume delivered by landslides. In Gregory Creek (Fig. 5B), two landslide events (1917 and 1978) delivered about 71% of the total LW input to the creek, with the most recent event accounting for about 23% of the total input from landslides. Overall, the total landslide delivery of LW to Gregory and Riley creeks is 8588 m^3 and 9201 m^3, respectively.

Landslides dominate LW input to Riley and Gregory creeks. For reach R2 in Riley Creek (Fig. 3B), landslides delivered about 61% of the LW to the channel, which is about 2.3 times greater than the input because of bank erosion. Because of buffering of the channel by an extensive valley bottom, landslides did not deliver any LW to reaches R1 and R3 (Fig. 3C). Landslides nonetheless contributed about 1.4 times more LW than bank erosion to Riley Creek as a whole. For Gregory Creek, landslides delivered between 38 and 47% of the total modeled LW inputs for three out of four reaches (Fig. 3E–I). The input of LW to a reach from fluvial transport is also important. Overall, fluvial transport accounts for 14 and 26% of the total LW load for Riley and Gregory creeks, respectively, and is most noticeable in reaches R1 and G1. In terms of input magnitude to reaches, fluvial transport is ranked third relative to other sources, exceeded by landslides and bank erosion.

A summary of stored LW characteristics for Gregory and Riley creeks is given in Table 5. Overall, there are 52 and 106 log jams in Gregory and Riley creeks, respectively, with the highest frequency in the logged reach (R2). Total in-channel storage of LW is 10,585 and 18,457 m^3 in Gregory and Riley creeks, respectively; and average storage volume of LW per kilometer of stream channel is 1253 and 1040 m^3 km^{-1} for Gregory and Riley creeks, respectively. Most of the in-channel LW in Gregory and Riley creeks was found in jams (>50%), except for reach R3 for which the proportion in jams was 13%. Mean weighted age is 50 years and 40 years, respectively, for Gregory and Riley creeks.

In terms of mass balance, recruitment rates of LW are 46 and 35 m^3 km^{-1} y^{-1}; average storage of LW over the study period LW is 14.5 and 12.5 m^3 km^{-1}; and average depletion rates are 30 and 37 m^3 km^{-1} y^{-1} for Gregory and Riley creeks, respectively. A strict comparison of recruitment and storage rates indicates that for Gregory and Riley creeks, the recruitment of LW is greater than LW storage by a factor of 3.2 and 2.8, respectively.

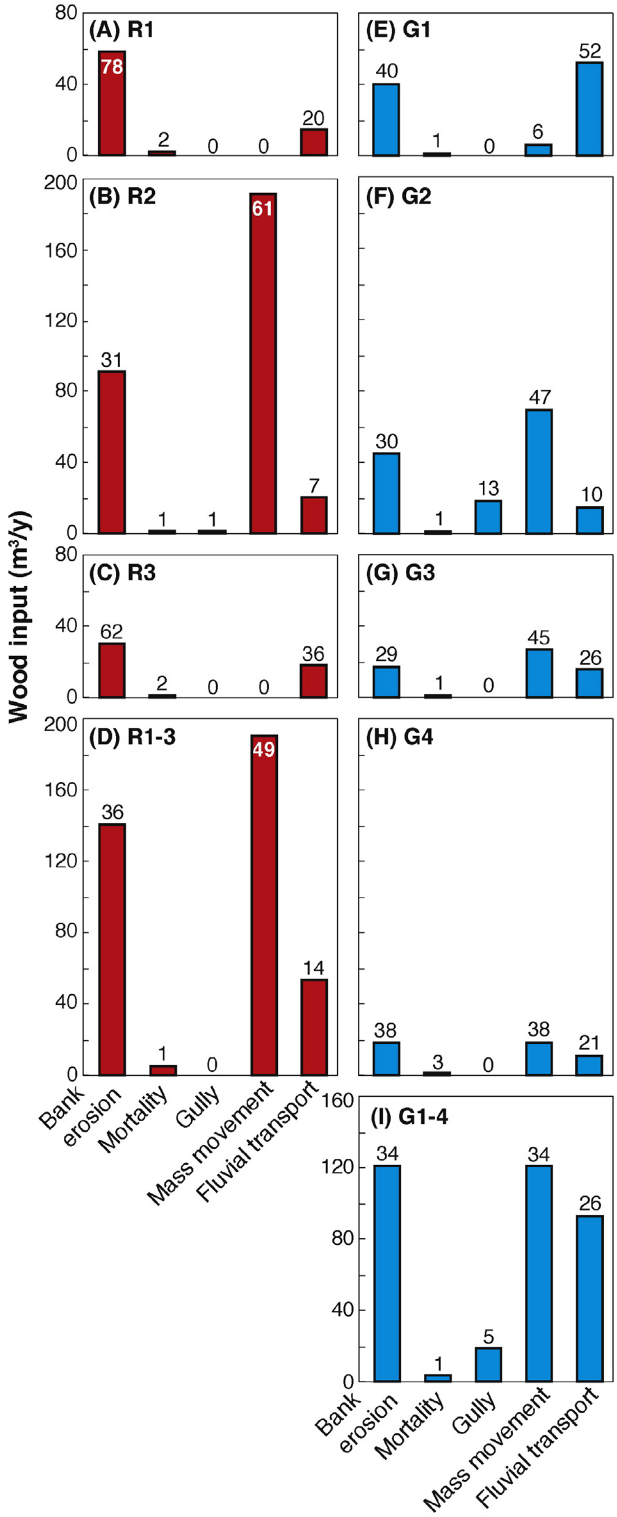

Fig. 3. Large wood recruitment rates and proportions of total input to Gregory and Riley creeks from mass movement, bank erosion, mortality, and gully. Values above each bar indicate the proportion of each LW source to the stream relative to the total. Uncertainty surrounding each input can be found in Table 4.

5.2. Large wood dynamics simulation

The LW budget was calculated for Riley and Gregory creek reaches with a 100-year window ending in 1989. Prior to the model window start, the model was run for a simulated 300-year period with riparian inputs to allow for equilibrium V_o. In Gregory Creek, landslide scars predating the 100-year window were noted and estimates of their material contribution were included in the 300 year pre-model period. The total measured storage is the current storage of LW in each channel (as of 1988 to 1990 as the surveys were undertaken during three successive field seasons).

Results from the decay and LW transport framework are presented in Fig. 6A–I. With the 1978 storm included, results for Riley R1 (Fig. 6A) are good, ~15% below the observed values. In addition to other sources, LW inputs for reach R2 (Fig. 6B) in Riley Creek include LW delivered from mass movement, most of which occurred during the 1917 and 1978 storm events (apparent in the modeled storage peaks). Furthermore, the riparian vegetation along the reach was logged between 1973 and 1978, resulting in different rates of LW input post-

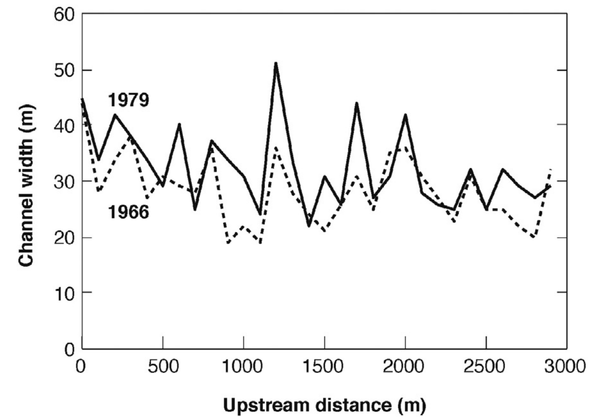

Fig. 4. Change in channel width in reach R1 in Riley Creek because of the large rain storms in the 1970s.

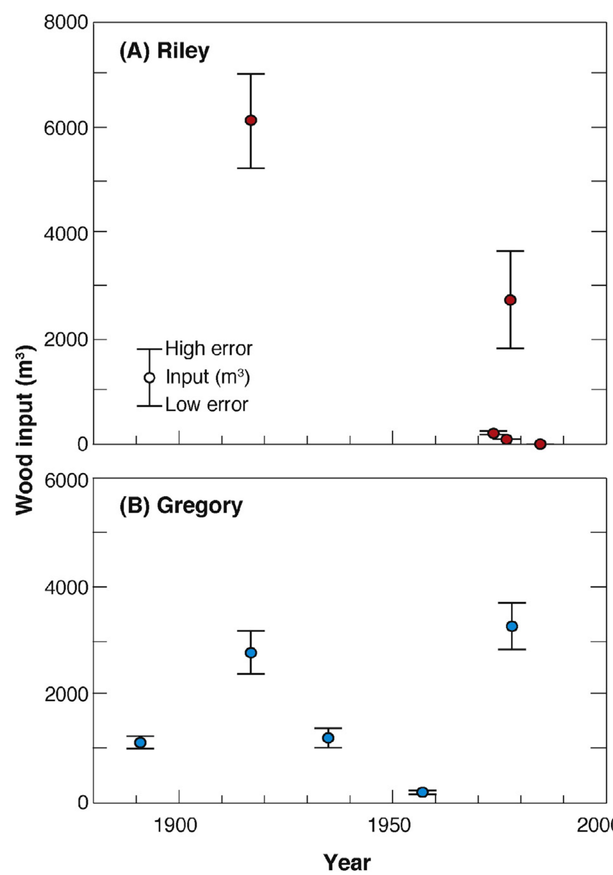

Fig. 5. Large wood delivery from landslides for Riley Creek (A) and Gregory Creek (B).

Table 5
Characteristics of LW stored within the study reaches as surveyed during 1988–89 in Riley and Gregory creeks (Hogan et al., 1998b).

Reach	Total LW storage (m^3)	Mean LW storage (m^3/km)	Number of jams	Jam spacing (m)	Jam age (y)				% of LW stored in jams	% of Mobile LW
					Youngest	Oldest	Range	Mean		
Riley Creek										
R1	5762	1449	30	123	10	92	82	56	70	22
R2[a]	10,311	1740	67	96	4	94	90	39	60	24
R3	2384	1039	9	115	9	50	41	21	13	51
R1–R3	18,457	1513	106							
Gregory Creek										
G1	3572	1381	13	186	7	71	64	52	51	39
G2	3476	1747	12	175	10	80	70	51	64	24
G3	1506	1358	10	112	50	70	20	61	77	9
G4	2031	707	17	172	11	85	74	52	81	14
G1–G4	10,585	1237	52							

[a] The reach was logged between 1973 and 1978.

logging relative to pre-logging. The model underpredicts observed storage in R2 by a greater margin, close to 30%, and below the lower bound of the 95% confidence interval of the observed storage (Fig. 5B). Reaches R3 and R1 are similar in terms of land use, sources of LW input, and buffering by a flat valley bottom, though no evidence exists of major channel avulsion from the 1978 storm in R3. For reach R3 (Fig. 6C), the LW

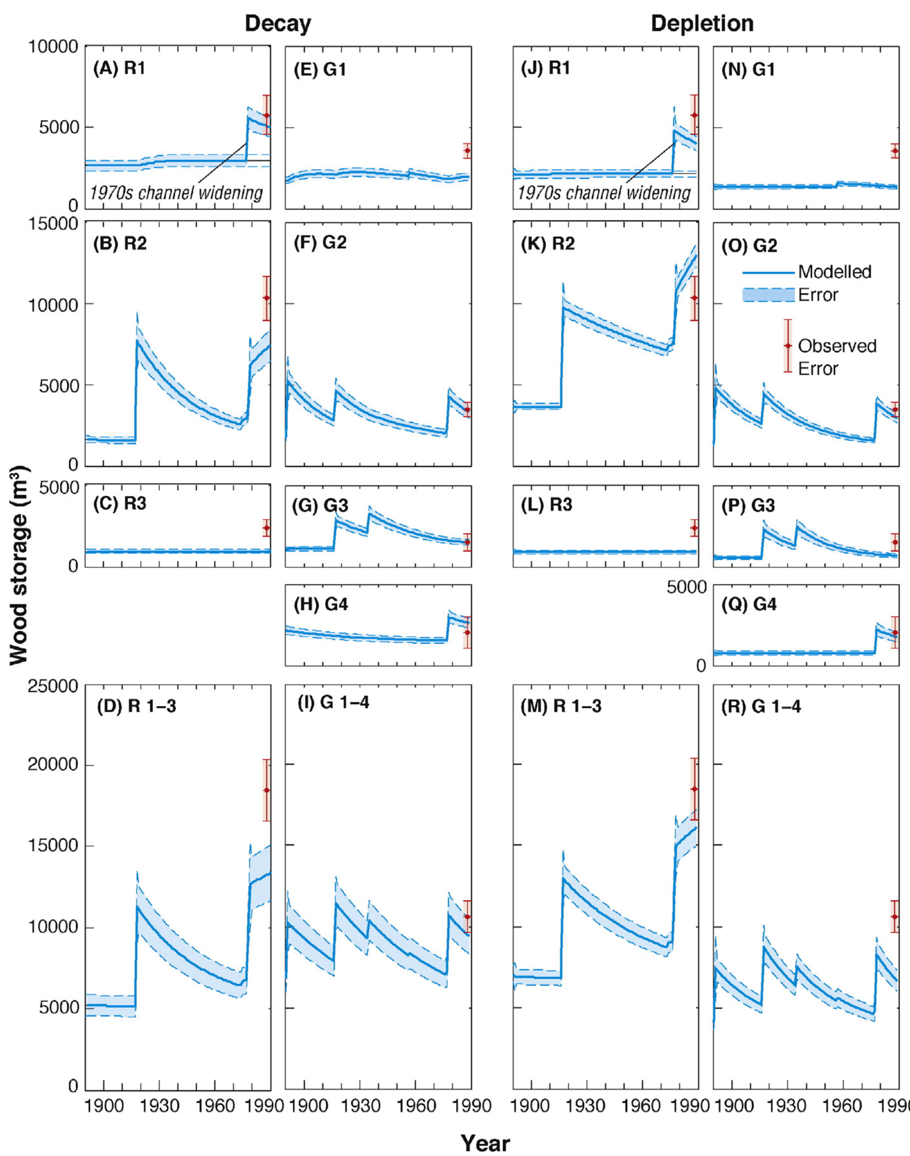

Fig. 6. Modeled and measured LW volumes in Gregory and Riley creeks. Observed LW storage values are based upon 1988–1989 field data. Error bars for measured and modeled storage represent 95% confidence intervals. The large increase in modeled storage values in reach R1 (circled area) represents the episodic input from major storms-related channel widening in the 1970s.

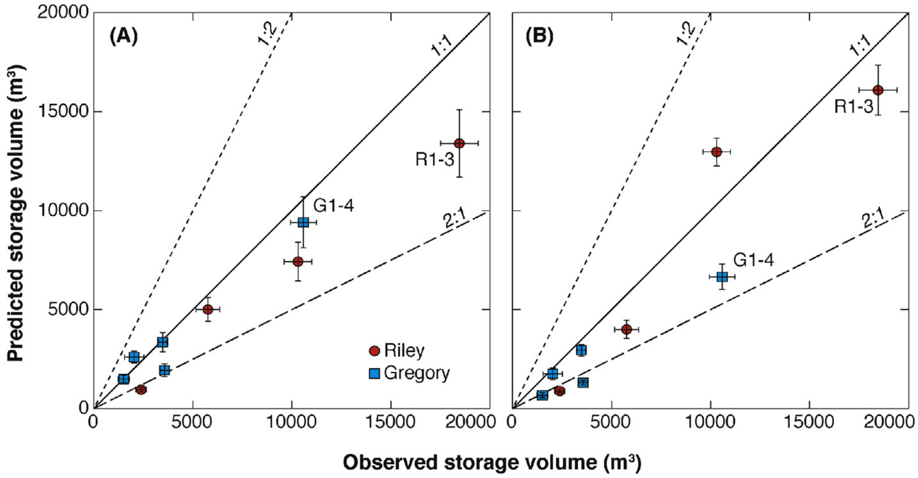

Fig. 7. Modeled vs measured (1988–1989) LW storage for Gregory and Riley creeks.

storage was underpredicted substantially, with a modeled estimate ~40% of the observed. No episodic input to R3 occurred over the 100-year period; therefore storage remains effectively constant. For the combined reaches (R1–R3, Fig. 6D), the model predictions are about 27% lower than the measured LW storage. Temporal patterns are dominated by the episodic input of hillslope material and the 1978 storm; and storage appears to be on an increasing trajectory as the study period closes, a result of the elevated post-logging rate of bank erosion in R2.

Better results were obtained for most reaches in Gregory Creek (Fig. 6E–I). Similar to reach R1 in Riley Creek, hillslope input does not play a dominant role in reach G1 of Gregory Creek because of valley bottom buffering. As in reach R1, the model underpredicted the LW storage in reach G1, but by over 45%. Most of the mass movement input to G2 (Fig. 6F) occurred during major events in 1890, 1917, and 1978. Reach G2 is unique among study reaches because it is the only reach with significant inputs from gullies, leading to high overall input from mass movement. For this reach, the model accurately predicted the amount of stored LW in the channel; the modeled volume was only 4% lower than the observed (Fig. 6F). Similar results were obtained for reach G3 (Fig. 6G), with predicted values within 1% of observed. Reaches G2 and G3 show substantial variability in storage through time, a product of episodic input of hillslope material. For reach G4 (Fig. 6H), hillslope input occurring in 1978 increased storage dramatically, and the model overpredicted the amount of stored LW by about 28% (but still within the 95% confidence interval). Finally, the overall prediction for Gregory Creek reaches (G1–G4, Fig. 6I) was 11% lower than the observed, just outside the error bounds. For Gregory Creek, the comparison of predicted vs observed storage for all reaches plots close to the 1:1 line (Fig. 7).

A comparison of results of the two creeks for the depletion based model is presented in Fig. 6J–R. For all reaches, results from the depletion model differed from those of the decay model (see Fig. 7 for comparison). For R1 (Fig. 6J), predicted storage was just under 70% of observed, slightly below the 95% confidence interval and slightly less than predicted with the decay-transport model. However, R2 (Fig. 6K) storage was overestimated by 25%, outside of the upper confidence interval. Storage for R3 (Fig. 6L) was similarly underestimated as for the decay-transport model, at 37% of observed. For the entire basin (Fig. 6M), model results were within 15% of observed values, an ~10% improvement over the decay-transport model results.

For Gregory Creek, a decrease in prediction accuracy was observed in three of four reaches. The prediction for G1 (Fig. 6N) dropped by ~20% of observed and has the poorest overall performance, at 36% of observed. Predictions for G2 (Fig. 6O) also decreased by 10%, though are still within 15% of observed values and close to the lower confidence interval. Predictions for G3 (Fig. 6P) dropped by nearly 50%, the largest change in prediction of any reach. Predicted values for G4 (Fig. 6Q) were lower but more accurate (~15% underestimation) than for the decay-transport model. Overall, basin-wide predictions (Fig. 6R) were close to 40% lower than observed, a poorer result than with the decay-transport approach.

6. Discussion

The paper examines reach-scale LW dynamics in Gregory and Riley creeks in Haida Gwaii, British Columbia. The study develops a detailed reach-scale LW budget to examine the relative importance of LW sources in the study creeks over roughly 100 years, using a decay–transport and depletion framework. The model presented here can be interpreted as a hybrid between a purely predictive and accounting-type tool, which relies heavily on parameterization with field data.

Our approach makes it possible to identify how specific components of the budget change between reaches within the same basin and between basins. This study also highlights the impact of logging on LW dynamics in streams as several areas of the basins (including the riparian zone in R2) were logged during the preceding decades. Large wood inputs to each reach are compared with surveyed LW storage and losses from the reaches in the form of decay, transport, or depletion. The study focuses on the recruitment components of the LW budget over relatively long time scales.

Large wood recruitment from bank erosion dominates LW inputs to the two lowermost reaches of Gregory (G1) and Riley (R1) creeks and the uppermost reach (R3) in Riley Creek. These reaches had little or no inputs from mass movement sources because they are buffered by a low-gradient valley bottom. For the rest of the reaches, LW recruitment from mass movement accounted for half or more of the total LW input. In spite of the buffering along most of R1, the results for the combined reaches of Riley Creek (R1–R3) show that mass movement delivery dominates LW inputs at the basin scale. For the combined reaches (G1–G4) in Gregory Creek, bank erosion and mass movement are of the same proportion and combined account for more than 90% of the LW inputs to the channel, despite having ~1.5 times more LW (by volume) growing in the riparian areas than on adjacent hillslopes (Table 2). However, the significance of hillslope material delivery is somewhat difficult to assess at certain timescales because of the stochastic nature of slope failures. With respect to geomorphology, climate, and vegetation, Gregory and Riley creeks are fairly similar to watersheds throughout coastal British Columbia. The geology of the region does contain a more erodible lithology than that commonly found along the coast of B.C., but landslide rates are similar to those found elsewhere in the Coast Ranges (Paulson, 1997; Campbell and Church, 2003; Brardinoni and Church, 2004). This suggests that in forested watersheds with steep and coupled terrain, hillslope delivery (mass movement and gully) of LW is generally an important source of LW for stream channels.

Several studies of LW dynamics in headwater streams confirm the relative importance of mass movement as an LW source (e.g., Nakamura and Swanson, 1993; May and Gresswell, 2003). Bank erosion can also be a major source of LW to channels. For example, Benda et al. (2002) reported that bank erosion was the dominant LW input source to streams, in many cases an order of magnitude larger than mortality inputs. In contrast, King et al. (2013) found that mortality and windthrow dominate LW inputs to small, headwater stream in the Interior of British Columbia. Large wood input from mortality was surprisingly low for Riley and Gregory Creek in comparison to rates reported in the literature (e.g., King et al., 2013) as stand-replacing disturbances, such as wildfires, are relatively rare in this region (Daniels and Gray, 2006). Total LW storage is higher in Gregory and Riley creeks than in southeast Alaska (Martin and Benda, 2001) or in northwest Washington (McHenry et al., 1998), but is similar (1000–2000 m^3 km^{-1}) to the upper range found in northern California (Benda et al., 2002). We also assumed a random fall direction in Eq. (9) given the presence of relatively wide and flat valley bottoms adjacent to our study reaches. Van Sickle and Gregory (1990) show that directing all trees towards the channel will increase delivery by a factor of 3.

Modeled storage is of a similar magnitude to measured storage for Gregory and Riley Creeks, and reasonable LW storage predictions were made for both channels using both models. Overall, the decay-transport model yielded better results for Gregory than Riley creek (Fig. 7A). Prior to the inclusion of LW input from major storms in the 1970s, the model significantly underpredicted the amount of stored LW in reach R1. However, adding the input from the storms in the 1970s greatly improved prediction in this reach. For the decay-transport model, the greatest discrepancy between predicted and observed storage was obtained for reach R3. Field inspections revealed a stable channel in this reach, with no evidence of channel widening in the 1970s.

For the depletion model, the underprediction of storage is greater than that of the decay-transport model, with two exceptions. Reach

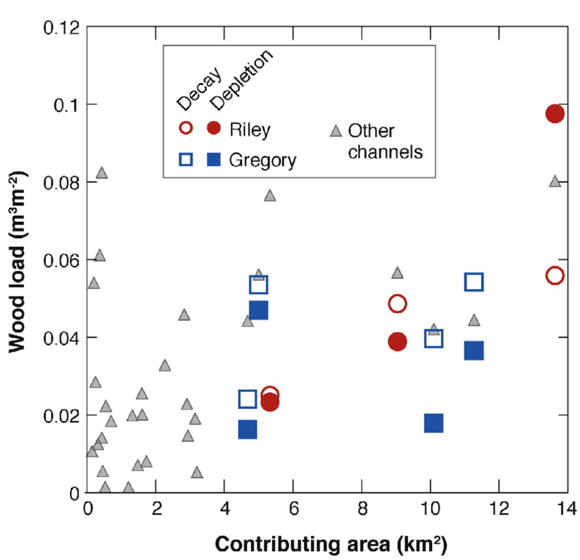

Fig. 8. Large wood storage volumes vs drainage basin area. Volumes of LW were first standardized by channel unit area to account for differences in channel width. Frequency plots of the data revealed nonnormal and often multimodal distributions of LW storage. These patterns were observed through space along individual reaches and through time when comparing the sequence of individual model runs. Comparison among the central tendencies of each reach was enabled by bootstrap resampling. Each distribution was sampled with replacement and the median value of each sample was calculated. The mean of 100,000 samples is given in the figure. Standard deviation averaged 34% of the mean.

R2 in Riley Creek obtained a much greater storage value with the depletion model, and consequently the total basin storage (e.g., R1–3) was greater than the decay-transport model. This storage overprediction by the depletion model can be attributed to the exclusion of explicit LW transport. In reach R2, channel dimensions are conducive to the transport of LW and, based on the Eaton et al. (2012) model, substantial output of LW because of transport occurs (see Fig. 3A). The lower storage value predicted in R1 with the depletion model relative to the decay-transport confirms this finding, as R1 was a major recipient of LW transported from R2. Though smaller in magnitude, the reduction in storage in G1 with the depletion relative to the decay model is also likely attributable to the same exclusion of transport. For reaches with lower observed storage (e.g. G2, G4), both models predict storage to a similar degree, likely a product of the simpler LW loss mechanisms and limited transport. Collectively, our results suggest that LW transport can be an important component of a reach balance in relatively small streams, as an input and as an output term.

As modeled LW storage could be compared to measured values at only one point in time, we used space-for-time validation to examine whether the range in storage values over time in the modeled reaches might be observed elsewhere in the Haida Gwaii archipelago. We selected 23 reaches from 10 different watersheds (for details see Hogan et al., 1998a), including logged and unlogged and hillslope-coupled and decoupled reaches. The coupled reaches included a range of mass wasting histories. Data collection techniques were identical to those described for Riley and Gregory creeks and field work was contemporaneous with the aforementioned sites. In Fig. 8, we present LW storage volumes standardized by channel unit area to account for differences in channel width. Although several studies (e.g., Gurnell et al., 2002; Gurnell, 2013; Wohl, 2013) demonstrated relations between channel width and LW storage, we did not observe this in our study. The results show a general trend of increasing LW storage with contributing adjacent basin area, although there is considerable variability in the distribution (Fig. 8). This is most apparent in the reaches with the smallest contribution area and influenced by coupling and the occurrence of mass wasting events in 1978. Although our modeled reaches plot near the upper range of adjacent basin areas of our measured reaches, results are still within the general range of our measured reaches. This suggests that our approach of simulating LW dynamics in mountain streams can generate results within the range of those found in similar natural environments.

Murphy and Koski (1989) argued that a channel reach in equilibrium with respect to the storage of LW would have rates of recruitment similar to depletion rates and a stable age distribution, and therefore changes in ΔS would be negligible. In our study reaches R3 and G1, this appears to be the case; our model results show that, barring any mass movement input or an imbalance in transport into and out of a reach, consistent riparian inputs and unchanging decay rate lead to a constant storage level in the channel. In reaches R1, R2, G2, G3, and G4, the large contributions of LW from mass movement inputs appear to temporarily shift storage in a dramatic fashion in the short term (see Fig. 6). However, equilibrium storage appears to return to these reaches within 50 to 100 years of major mass movement input, more quickly for landslide inputs of smaller magnitude, or if hillslope inputs are frequent and consistent (such as within reach G2). These results suggest that in coupled reaches, ΔS cannot be considered negligible in the short term.

Given the historical uncertainty and lack of accuracy in estimating recruitment rates of LW, our results seem to suggest that the model predicts LW storage fairly well. Uncertainty associated with prediction arises from several factors. Variability in stand volumes leads to variability in assessing LW recruitment rates; it seems reasonable to assume that this variability will be similar for recruitment from all sources and that error would be linearly scaled among recruitment processes. Variability in space and time of bank retreat will also create differences in bank erosion-induced recruitment rates. Similarly, differences in rates of average stand mortality will also lead to variability in mortality recruitment rates. Uncertainty in assessing LW inputs from landsliding may form the largest component of model uncertainty, arising from our inability to accurately measure landslide areas and from error in identifying older, smaller landslides. Hillslope inputs are based on 1:20,000 scale mapping, therefore small features are apt to be generalized.

This modeling exercise used VRI data including only trees 0.175 m in diameter, while the field data used in validation includes all logs 0.1 m in diameter. This may help to explain (at least in part) some of the underprediction associated with our modeling results. However, this difference in measurement criteria may be partially offset by the CWD data, as it was truncated at logs 0.075 m in diameter. In addition, tree volumes derived from the VRI data were restricted to the stem and did not include any branches. In coastal old growth forests in our study area, tree branches are often large enough in diameter and length as to fit the definition of LW used in the field inventory of LW storage. The VRI data do allow for an estimate of total tree biomass and suggest that generally, including branches of all sizes would increase recruitment volumes by 20%.

Although considered in the model, high variability in forest regeneration rates within gullies contributes to the uncertainty of our input estimation. In this study, it was assumed that all of the LW mobilized by a slope failure actually entered the channel. In reality this in unlikely, and therefore overestimates of LW delivery from landsliding are possible in some instances where even a narrow valley bottom exists. Additional model limitations may stem from the calculation of fluvial LW transport. Using a generalized function is bound to produce error, and the implications of this approach are most apparent in downstream reaches where transport is more important. As channel dimensions decrease upstream, transport magnitude and therefore impact on budget uncertainty decreases. In terms of model output, model performance appears fairly sensitive to the decay or depletion constants used. In this study, we have a good degree of confidence in our values as the quality of field data is high. It is therefore important that the decay constants are calculated with the best possible data and are selected with care.

A corridor of trees is often left along channel banks by land managers to help maintain the ecologic and geomorphic function of a channel (i.e. stream temperature, bank stability, etc.) in the presence of upslope developments such as forest harvesting (logging in our study area preceded this practice). In Canada and the United States, current land management practices often require buffers along stream channels that typically range from 15 to 30 m depending on channel width. In British Columbia, a common objective of such a buffer is to maintain a supply of functional LW to a channel while preventing the delivery of logging debris to streams. However, our results show that ~50% of LW is delivered to the channel from beyond a 30-m distance from the banks of a coupled reach. Therefore, the relative coupling between hillslopes and channels can be used as a way to define areas for management in order to approximate the impact of landslide processes and forest harvesting on rates of LW recruitment and redistribution within a reach over longer time periods.

7. Conclusions

In this study, LW storage volumes were predicted for reaches in two streams on western Graham Island, Haida Gwaii. Simple models using outputs composed of (i) decay and transport and (ii) depletion were used to obtain LW storage results for hillslope coupled and decoupled reaches of these channels and to examine the relative importance of different LW mass balance components.

In Riley and Gregory creeks, mass movement and bank erosion dominate LW inputs to channels. Large wood contributions from mortality processes are minor, likely because stand-replacing disturbances other than landslides are rare. Given the dominance of mass movement processes on LW dynamics in the study streams, LW storage is likely to fluctuate in a way that reflects the episodic nature of the recruitment processes. Time to equilibrium of LW storage in channels ranged between 50 and 120 years and depends on the magnitude and consistency of the LW input events and the local decay rate of LW. Large proportions of stored LW were found in log jams. In coupled reaches, this reflects the dominance of mass wasting as a LW recruitment process as jams (or multiple jams) tend to form near the terminus of a landslide deposit. Jams fix the location of LW during normal flows and reduce the mobility of logs already in transit. In spite of this, LW transport appears to be an

Table A1
Summary values of all error terms.

Term(s)	Uncertainty	Comments
a_i	2.6 y	Based on a comparison between jam ages and the date of landslide and/or flood events known to have initiated log jams in the study watersheds [see Hogan et al., 1998a]. The data also show 1.9 y lag between the event and colonization by nursed trees (i.e. a systematic error-jam age was increased accordingly).
δV_{cwd}	335 m^3/ha unlogged 398 m^3/ha logged	Modeled by fitting a beta distribution to ranges provided by Stevens (1997). Standard deviation error [Wells and Trofymow, 1997]
δk_v	4.5×10^{-4} (yrs^{-1}) Gregory 6.2×10^{-4} (yrs^{-1}) Riley R1, R3 1.2×10^{-3} (yrs^{-1}) Riley R2 unlogged 2.1×10^{-2} (yrs^{-1}) Riley R2 logged	Standard error of the exponent k derived through regression analysis (see Fig. 2).
$\frac{\delta \Delta x}{\lvert \Delta x \rvert}$	1%	Estimated error of measuring reach length with a hip-chain.
$\frac{\delta U_g}{\lvert U_g \rvert}$	32%	Standard error of recharge rate based on values reported in Oden (1994).
$\frac{\delta A_v}{\delta A_v}$	5% Gregory 6% Riley	Computed from reach length measurements and the length of measured valley cross sections. As a conservative estimate, we assumed the length of cross sections may be $\pm$20% given the difficulty of maintaining a straight and perpendicular tape in a relatively wide (up to 250 m) and densely forested valley bottom.
$\frac{\delta V_{sd}}{\lvert V_{sd} \rvert}$, $\frac{\delta D_s}{\lvert D_s \rvert}$ & $\frac{\delta Z_k}{\lvert Z_k \rvert}$	10%	Parameters derived from VRI maps and used to describe characteristics of the forest canopy (volume, height, etc.) have a target error of $\pm$10% at the 95% level of probability (Ministry of Forests and Range, 2007).
$\frac{\delta A_{sf}}{\lvert A_{sf} \rvert}$	10%	Estimated error associated with digitizing the boundaries of the landslide scars and overlaying landslide polygons on the VRI map.
$\frac{\delta S}{\lvert S \rvert}$ & $\frac{\delta Q}{\lvert Q \rvert}$	60%	A conservative estimate based on (i) the general difficulty in identifying and/or measuring all logs in a survey interval and (ii) the relatively broad scale used to quantify the diameter, length, and number of logs that could actually be identified. However, given a sample size of 401 survey intervals for each channel, uncertainties computed using Eq. (A9) are ~6% of S_f.

important component of recruitment and loss to reaches, particularly downstream reaches with wider channels.

For most reaches and for both model approaches, the model predictions were within 30% of the observed stored LW. The decay-transport model yielded better overall results for both basins, but particularly for Gregory Creek and in reaches with a large transport flux term. This simple LW dynamic model appears to be a promising tool to predict LW storage in streams. Though field data requirements are fairly high, a large portion of input data can be obtained from air photo measurements, forest inventory data, and/or regional values where available and appropriate.

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Appendix A

The uncertainty associated with each term in the LW budget was propagated though the model in quadrature following Taylor (1997). Table A1 provides summary values of all general error terms; reach-specific error values are found in Table 4 in the main text. For a given year, the uncertainty in the volume of modeled LW storage (S_m) for the depletion and transport-decay approach was

$$\delta S_m = \sqrt{(\delta I)^2 + (\delta R)^2} \tag{A1}$$

$$\delta S_m = \sqrt{(\delta I)^2 + (\delta Q)^2 + (\delta D)^2} \tag{A2}$$

respectively, where

$$\delta I = \sqrt{(\delta I_m)^2 + (\delta I_{be})^2 + (\delta I_{ms})^2} \tag{A3}$$

$$\delta R = \sqrt{\left((1-e^{-k})\delta V_{t-1}\right)^2 + \left(V_{t-1}e^{-k}\,\delta k\right)^2} \tag{A4}$$

where V_{t-1} and δV_{t-1} are the volume and the volumetric uncertainty, respectively, of stored LW calculated for a model run from the previous year. Eq. (A4) was also used to calculate δD but with appropriate values of k and δk (see Table 4). The δQ was not considered here directly given the theoretical nature of Eq. (16), but at a minimum, were assumed equivalent in proportion to our estimate of δS given in Table A1.

We followed the methods described by Van Sickle and Gregory (1990) for calculating the uncertainty in the volume of a bole segment V_b transferred to the channel. The uncertainty in the modeled input of LW from mortality (δI_m) is then given by

$$\frac{\delta I_m}{|I_m|} = \sqrt{\left(\frac{\delta D_s}{D_s}\right)^2 + \left(\frac{\delta Z_k}{Z_k}\right)^2 + \left(\frac{\delta \Delta x}{\Delta x}\right)^2 + \left(\frac{\delta V_b}{V_b}\right)^2}. \tag{A4}$$

The uncertainty for bank erosion (δI_{be}) considers the two erosion input terms (δI_{bet}) and (δI_{beCWD}) added as

$$\delta I_{be} = \sqrt{(\delta I_{bet})^2 + (\delta I_{beCWD})^2}. \tag{A5}$$

The uncertainty in the modeled input of LW from bank erosion of standing timber (δI_{bet}) is given by

$$\frac{\delta I_{bet}}{|I_{bet}|} = \sqrt{\left(\frac{\delta D_s}{D_s}\right)^2 + \left(\frac{\delta B}{B}\right)^2 + \left(\frac{\delta \Delta x}{\Delta x}\right)^2 + \left(\frac{\delta V_b}{V_b}\right)^2} \tag{A6}$$

where B is the rate of bank erosion. Uncertainty in P_f (see Eqs. 9 and 12) was not considered in Eqs. (A4) or (A6) and is assumed to be negligible relative to other error sources. The uncertainty of CWD transferred to the channel from the riparian forest floor (δI_{beCWD}) through bank erosion is given by

$$\frac{\delta I_{beCWD}}{|I_{beCWD}|} = \sqrt{\left(\frac{\delta V_{CWD}}{V_{CWD}}\right)^2 + \left(\frac{\delta B}{B}\right)^2 + \left(\frac{\delta \Delta x}{\Delta x}\right)^2} \tag{A7}$$

where δB is given as

$$\frac{\delta B}{|B|} = \sqrt{\left(\frac{\delta k_b}{k_b}\right)^2 + \left(\frac{\delta A_v}{A_v}\right)^2} \tag{A8}$$

where δk_v is the uncertainty in valley bottom decay and δA_v is uncertainty in valley bottom area determination. The uncertainties associated with inputs of LW from mass movement derived from standing trees and CWD are given by

$$\frac{\delta I_{\mathrm{ms}}}{|I_{\mathrm{ms}}|} = \sqrt{\left(\frac{\delta D_s}{D_s}\right)^2 + \left(\frac{\delta A_{\mathrm{sf}}}{A_{\mathrm{sf}}}\right)^2 + \left(\frac{\delta I_g}{I_g}\right)^2} \tag{A9}$$

and the uncertainty in total volume of LW residing in a gully at the time of slope failure is given by

$$\frac{\delta I_g}{|I_g|} = \sqrt{\left(\frac{\delta A_{\mathrm{sf}}}{A_{\mathrm{sf}}}\right)^2 + \left(\frac{\delta U_g}{U_g}\right)^2}. \tag{A10}$$

Finally, the uncertainty associated with the field-measured volume of stored LW (S) was summed for each bankfull width estimate as

$$\delta S_n = \sqrt{(\delta S_1)^2 + \ldots + (\delta S_n)^2} \tag{A11}$$

where n is the total number of bankfull widths in each channel survey.

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