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Seventy years of watershed response to floods and changing forestry practices in western Oregon, USA

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Abstract

This study examined the 70-year history of clearcutting of old-growth forest and associated road construction, floods, landslides, large wood in rivers, and channel change in the 64 km^2 Lookout Creek watershed in western Oregon, where forestry practices began in 1950 and largely ceased by the 1980s. Responses differed among three zones with distinctive geomorphic processes within the watershed: a glacially sculpted zone, an earthflow-dominated zone, and a debris slide and debris flow-dominated zone. Watershed response to floods was more related to the timing of road construction and clearcuts, past geomorphic events, and forest dynamics than to flood magnitude. Even small (1–3 year) floods generated geomorphic responses in the period of initial road construction and logging (1950–1964) and during ongoing logging in the early part of a 30-year period between large flood events (1966–1995). The floods of 1964/65, 15 years after the onset of logging, produced much larger geomorphic responses than the flood of record (1996), more than a decade after logging ceased. Geomorphic response was negligible for the third largest event on record (2011) during the last period (1997–2020), when former clearcuts were 20 to 70-year-old forest plantations. Watershed response in each of five distinct time periods depended on conditions created during prior periods in the three zones. Understanding of watershed response to forestry requires integrated observation of forestry practices, floods, landslide susceptibility, wood delivery and movement, and channel change on time scales that capture responses to past and ongoing management practices and geophysical and biological factors and events.

KEYWORDS

channel adjustment, disturbance cascade, harvesting, large wood, process domains, sediment supply, stochastic forcing

1 | INTRODUCTION

Watershed response to forestry practices in mountain landscapes involves a series of phenomena that may have overlapping and cascading properties: logging and associated road construction; major storms; landslides of various types; the dynamics of large wood in rivers; and channel change in response to movement of sediment and large wood through the river network. Relationships among limited combinations of these factors have been investigated at many locations in the Pacific Northwest of the United States, a region known for large, long-lived conifer forests, abundant precipitation, erodible mountainous terrain, and extensive forestry operations.

In steep lands of the Pacific Northwest, clearcutting and roads affect flood processes through multiple mechanisms. Roads speed water routing, and after forest harvest, soil moisture and snow accumulation and melt rate increase, leading to higher peak flow magnitude in both small and large floods (e.g., Jones, 2000; Jones & Grant, 1996; Jones & Perkins, 2010; Wemple et al., 1996). Oversteepened slopes created by cut-and-fill road construction, water routing on road surfaces and in roadside ditches, and increased soil moisture in cleared areas greatly increase landslide frequency from roads and clearcuts relative to forested areas (Dyrness, 1967; Fredriksen, 1970; Madej & Ozaki, 1996; Swanson & Dyrness, 1975; Swanson & Lienkaemper, 1985). Landslides contribute sediment and large wood (commonly defined as >10 cm diameter, >1 m length) to channel networks during major floods (Beschta, 1978; Dyrness, 1967; Fransen et al., 2001; Imaizumi et al., 2008; Luce & Black, 1999; Swanson & Dyrness, 1975; Wemple et al., 2001). Geomorphic processes on hillslopes and in channels entrain, transport, and deposit large wood within river networks (Bigelow et al., 2007; Harmon et al., 1986). Large wood delivery and movement influence sediment movement, riparian disturbance, and channel change (Gurnell et al., 2002; Jackson & Sturm, 2002; Johnson et al., 2000; Nakamura et al., 2000). Forestry practices can alter wood delivery and transport (Czarnomski et al., 2008; Hartman et al., 1996; Reid & Hassan, 2020; Scott & Wohl, 2018). All these processes contribute to channel change (Lyons & Beschta, 1983; Swanson et al., 1998).

Many studies have examined how flood events coinciding with active forestry affect sediment and wood delivery to stream channels (e.g., see review in Sidle et al., 1985), but few studies examine channel network response to landslides of several types, including rapid processes, such as debris slides, streamside slides, and debris flows, as well as slow processes, such as earthflows. In addition, forestry practices change over time, and legacies of past land-use activities may continue to influence ecosystem structure and function for decades or centuries after those activities have ceased (Foster et al., 2003). Large areas of US federal forest land were subjected to clearcutting and road construction for several decades in the mid-20th century, but in recent decades the intensity of clearcutting and the construction of new roads has declined as management objectives have changed (Johnson & Swanson, 2009). However, few studies have examined how legacies of clearcut and road effects on stream channel networks play out over multiple decades after the cessation of active forestry.

This study examines these questions by bringing together data from multiple long-term studies of forestry land use, floods, landslides, large wood, and channel changes over the period from 1950 to 2020 in Lookout Creek in the H.J. Andrews Experimental Forest (hereafter 'Andrews Forest'), western Oregon, USA. We examine how major floods, in conjunction with forestry, interacted with different suites of geomorphic processes in several contrasting 'process domains'—discrete regions within channel networks in which dynamics respond to distinctly different geophysical conditions and disturbance regimes (Montgomery, 1999). Based on scour and deposition in repeatedly measured cross-sections and repeated wood mapping, we evaluate how storm events and forestry disturbances drive sediment inputs to channel networks, and how transport processes generate spatial and temporal patterns of flux and storage of sediment and wood within the network ('stochastic forcing'; sensu Benda & Dunne, 1997). We assess how slow (e.g., earthflow) and fast (e.g., debris slide, debris flow) geomorphic processes interact in sequence down the sediment transport flow path to create a cascade of events that form an ecological disturbance cascade (Nakamura et al., 2000). Overall, this study attempts to identify the time scales and spatial scales of watershed response to changing forestry practices, floods, and geomorphic response in steep, forested watersheds of the Pacific Northwest, USA.

2 | STUDY SITE

Lookout Creek is a 64 km^2, fifth-order mountain watershed within the Andrews Forest, located on the western slope of the Cascade Range, Oregon, USA (Figure 1). The Andrews Forest was established by the U.S. Forest Service in 1948 and has been a National Science Foundation-funded Long-Term Ecological Research (LTER) site since 1980. Elevation in the watershed ranges from 410 to 1630 m. Geology consists of Miocene to Pleistocene volcanic rocks of various types (Priest et al., 1988; Swanson & James, 1975) typical of the Western Cascades (Peck et al., 1964). The climate is marine temperate with mean annual temperature of 9°C. Mean annual precipitation ranges from 2200 to 2700 mm depending on elevation and slope orientation. More than 80% of precipitation occurs between October and April (Bierlmaier & McKee, 1989; Crampe et al., 2021; Jones & Perkins, 2010). Average (1998–2007) snow water equivalent peaks in February at 100 mm at low elevation and in April at 750 mm at high elevation (Jones & Perkins, 2010). In 1948, vegetation in the Lookout Creek watershed was native forest—mature and old-growth conifer forest dominated by Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja plicata*), regenerated after fires of ca. 1500 CE and the mid-1800s CE (Tepley et al., 2013). Road construction and clearcutting of forest began in 1950; by 1995 there were 119 km of roads and 25% of the watershed had been clearcut (Jones & Grant, 1996). The remainder of the study area is occupied by roads (3.7%) (Wemple et al., 1996) and native forest (71.3%).

Study sites are located in three broad zones with contrasting geologic history and geomorphic processes: a glacially sculpted zone (two reaches in Mack Creek: MAC, MCC), an earthflow-dominated zone (one reach in middle Lookout Creek: LOM), and a debris slide and debris flow-dominated zone (one reach in lower Lookout Creek: LOL) (Figure 1, Table 1). The glacially sculpted zone is developed on hard lava flow and ashflow bedrock (Swanson & James, 1975) and is characterized by relatively smooth terrain, cirques, truncated spur ridges, and U-shaped valleys that have been only superficially modified by subsequent geomorphic processes. The earthflow-dominated zone is developed on volcaniclastic rocks with substantial shrink–swell clays capped by hard rocks (Swanson & James, 1975). It contains some large landslide features (some exceeding 1 km^2), such as the active Lookout Creek earthflow (Pyles et al., 1987; Swanson & Swanston, 1977) (Figure 1), as well as an earlier inactive earthflow that constrains the valley floor downstream of LOM. These earthflows are discrete landforms bounded by headscarps, lateral scarps, and bulbous toes onto near-horizontal landforms (e.g., river terraces) or into streams. Within these features, slopes are 5–10° and topography is irregular with undrained depressions, scarps, and disrupted stream drainage patterns. Active earthflows have movement rates of centimetres per year based on direct measurements and deformation of roads and trees (Swanson & Swanston, 1977; Wong, 1991). Elsewhere in this zone are areas whose moderate steepness, surface roughness, and drainage network structure appear to be the product of much earlier land movements which have coalesced and been modified by other geomorphic processes. The debris flow-dominated zone is developed on weak volcaniclastic rocks (Swanson & James, 1975), is highly dissected and characterized by steep slopes (33°), V-shaped valleys, and steep narrow stream drainages (Dyrness, 1967). The

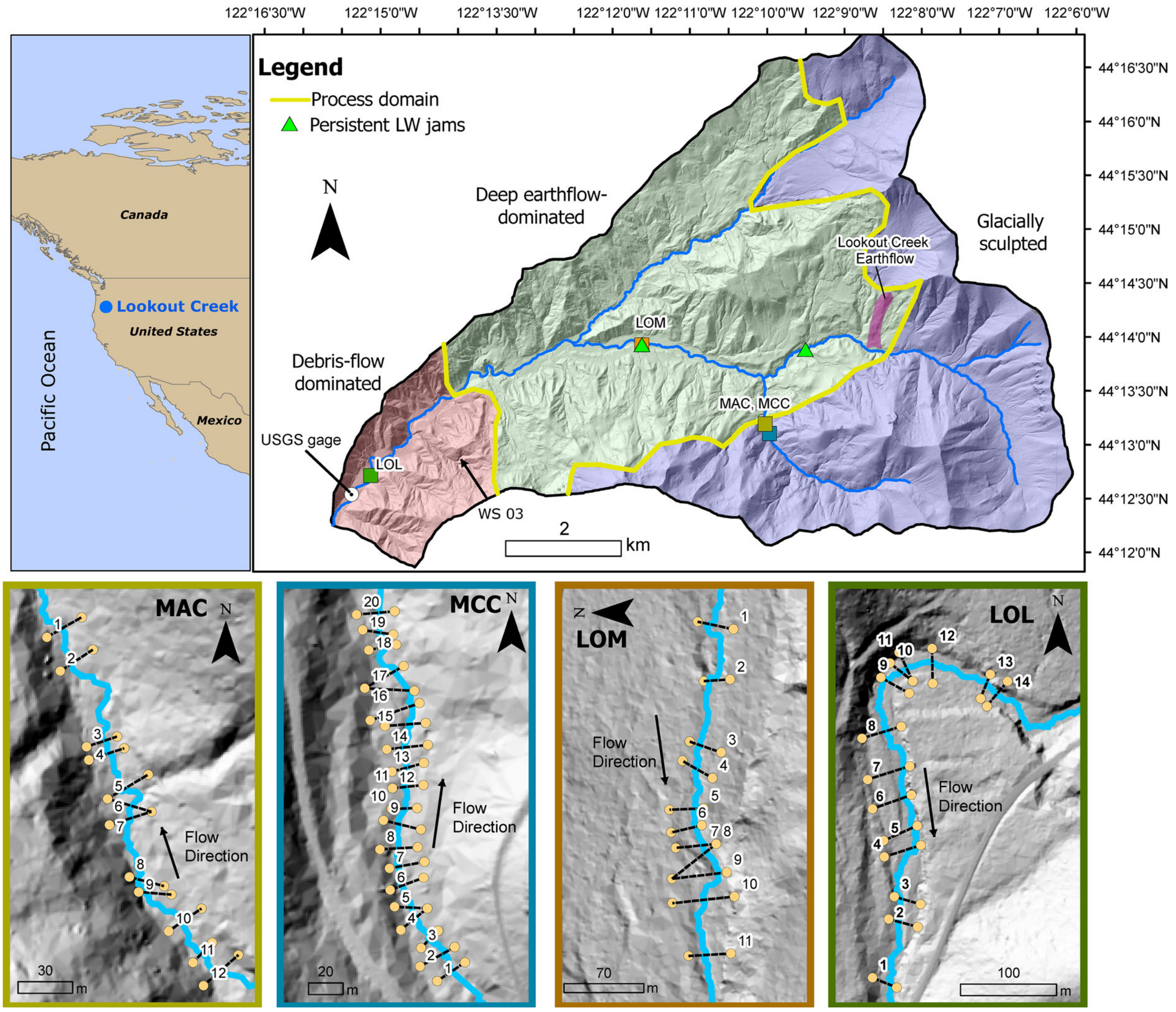

FIGURE 1 Location of Lookout Creek in western Oregon, USA (top left). Shaded relief of LiDAR bare-earth imagery of Lookout Creek, showing three litho-topographic zones (bounded by yellow lines, see text), location of the USGS gage (no. 14161500), locations of two persistent wood jams (green triangles, Figure S1), locations of study reaches (coloured squares) (top right), and location of watershed 3 (WS 03). Details of LiDAR bare-earth topography, locations of monitored cross-sections, and direction of flow (arrows) in four study reaches: MAC, MCC, LOM, and LOL (bottom panels). See Table 1 for study site descriptions.

boundaries of these litho-topographic units are apparent on LiDAR imagery (Figure 1), and they generally correspond with earlier (pre-LiDAR) geologic mapping (Swanson & James, 1975; Swanson & Swanston, 1977).

Permanent stream cross-sections (hereafter also denoted XS) were established in 1978 within the three litho-topographic zones (Figure 1, Table 1) (Johnson & Swanson, 2014). Study reaches range from 212 to 440 m in length and vary in drainage area, gradient, and confinement of the valley floor and channel (Table 1, Figure 1). The third-order MAC and MCC reaches (drainage area 5.5–5.7 km^2) are located in a steep (gradient 0.1 m/m), narrow valley floor (28–31 m) in a glacially sculpted mountain valley. The channel bed in MAC and MCC is structured by a lag deposit of boulders up to 1.5 m in diameter from past glacial episodes (Lambert, 1997), overlain by patches of contemporary mobile bed sediment (D_{50} of 6.5–8.5 cm) (Figure 1). The fourth-order LOM reach (drainage area 32 km^2) lies in a gentler (gradient 0.032 m/m), unconfined, wide valley floor (235 m) with deep alluvial fill aggraded over at least 7000+ years upstream of an earthflow-induced constriction of the channel several kilometres downstream (Swanson & James, 1975) (Figure 1). The channel bed in LOM is structured by lag deposits of large (0.5–1 m diameter) boulders derived from fluvio-glacial outwash overlain by a contemporary mobile bed (D_{50} of 14.5 cm). The fifth-order LOL reach (drainage area 62 km^2) is located in a relatively gentle (gradient 0.015 m/m), confined valley floor (66 m). Its channel bed is structured by a lag deposit of large (0.5–1 m diameter) boulders derived from debris flows from tributary watersheds, overlain by a contemporary mobile bed (D_{50} of 10.3 cm) (Table 1).

3 | METHODS

3.1 | Synthesis of existing Lookout Creek data

We assembled historical data on forestry land use, floods, landslides, large wood, and channel change since 1950. Forest harvest and road construction were mapped from aerial photographs (Jones & Grant, 1996; Lienkaemper & Swanson, 2005) combined with spatial datasets for vegetation cover (Lienkaemper & Schulze, 2015), historic salvage sale locations (McKee & Valentine, 2005), and LiDAR

TABLE 1 Characteristics of the study reaches in Lookout Creek, H.J. Andrews Experimental Forest

Reach name	Mack Creek old growth (MAC)	Mack Creek clearcut (MCC)	Middle Lookout (LOM)	Lower Lookout (LOL)
[1] Number of cross-sections	12	20	11	14
[2] Drainage area (km^2)	5.5	5.7	32	62.0
[1] Elevation at lower end (m)	764	730	583	428
[3] Mean channel gradient (m/m)	0.1	0.096	0.032	0.015
[1] Median grain size (D_{50}) in 1995 (cm)	8.5	6.5	14.5	10.3
Bankfull mean channel depth/width (m) in 1995	0.55/11.3	0.44/10.5	0.88/25.9	0.81/25.6
[4] Mean valley width (m)	31	28	235	66
[5] Reach length (m)	212	220	295	440
[6] Instream wood volume (m^3/ha)	352	<30	206–466	80–143
Streamside forest condition (in 2020)	Old growth	50-Year-old forest planted after clearcut in 1960s	Old growth and 50-year-old forest planted after clearcuts in 1950s–1960s	
[7] Large wood delivery processes and mobility, 1950–2020	Toppling; immobile for >100 years	Toppling; cut logs washed downstream in 1964/65	Fluvial delivery and toppling, accumulating in two large wood jams	Fluvial delivery and toppling, almost completely removed by floods in 1964/65, 1972, 1996
[8] Number of inventoried debris slides upstream, 1950–2020	0	0	46	173
[8] Volume of material delivered by debris flows to upstream channels 1950–1965 (m^3/km^2)	0	0	870	2300

[1]Johnson and Swanson (2014).
[2]LiDAR derived (Spies, 2016).
[3]Faustini (2000).
[4]Delineated manually considering previous mapping (Grant & Swanson, 1995).
[5]Delineated in ArcGIS Pro based on cross-section endpoints located on LiDAR-derived DEM.
[6]Volume of wood (m^3/ha in 100 m reaches) measured in late 1990s and early 2000s. Sources: for LOM and LOL, Czarnomski (2003). Lower end of range is wood storage in stream segments with harvest within 40 m on one side of the stream, upper end of range is wood storage in stream segments with no harvest within 40 m. Volume for MAC from Meleason et al. (2003). Volume for MCC from Faustini (2000), Faustini and Jones (2003), and Czarnomski et al. (2008).
[7]Large wood delivery processes based on Lienkaemper and Swanson (1987), Meleason (2011) and Gregory and Lienkaemper (2013).
[8]Number and total volume of debris slides from Swanson (2014). Total volume of inventoried debris slides from 1950 to 1965 upstream of LOL was ~170, 000 m^3, of which 62% (~105,000 m^3) was delivered to channels, which is 1,700m^3/km^2 delivered to channels in the 62 km^2 watershed upstream of LOL. Total volume of debris slides from 1950 to 1965 upstream of LOM was ~35 000 m^3, of which 62% (~22 000 m^3) was delivered to channels, which is 700 m^3/km^2 delivered to channels in the 32 km^2 sub-basin upstream of LOM.

(Spies, 2016) into an online spatial compilation (H.J. Andrews Experimental Forest, 2019). These data were used to assess the historic land-use change in the watershed and to calculate the cumulative percentage of area clearcut and the cumulative density of roads (Jones, 2003).

Annual peak flow data at the mouth of Lookout Creek since 1950 were obtained from the U.S. Geological Survey gage no. 14161500 and at Mack Creek since 1980 from an Andrews Forest gage (Johnson & Rothacher, 2016) (Figures 1 and 2). Return periods were estimated for both records with the Weibull plotting position equation (Linsley et al., 1974).

Mass movements in the Andrews Forest were described in eyewitness accounts and inventoried in a series of field campaigns conducted from the 1950s to the present (Dyrness, 1967; Jones & Wemple, 2005; Swanson & Dyrness, 1975). We assembled and analysed a previously unpublished dataset of landslides over the period 1950 to 2020 (Swanson, 2014). Our analysis considered four types of landslides that are important components of the geomorphic system: (1) *debris slides*, which are small, rapid movements of soil and vegetation down steep hillslopes; (2) *debris flows*, which rapidly transport soil, sediment, and vegetation down steep, narrow stream channels; (3) *earthflows*, which are large, thick (5+ m), slow, long-lived deposits of colluvium and may encroach on stream channels; and (4) *stream-side slides*, which are small, rapid, and common at the toes of active earthflows (Swanson & James, 1975). Using this dataset (Swanson, 2014) we mapped and analysed the spatial and temporal patterns of landslide locations and volumes relative to forestry activities (clearcuts and roads) and landforms (the stream network and litho-topographic zones shown in Figure 1). A landslide was considered to be road-related if it occurred within 10 m of the road

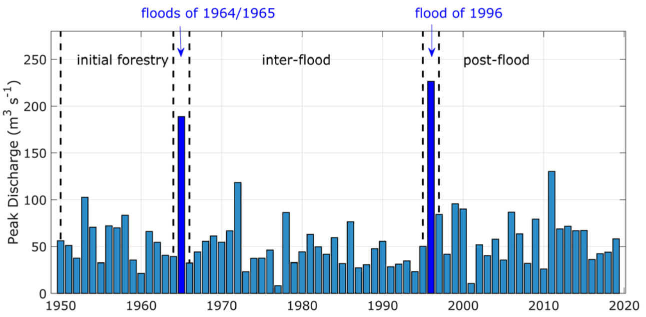

FIGURE 2 Annual peak flows by water year at Lookout Creek gage (no. 14161500), 1950 to 2020. Channel cross-sections were monitored from 1978 to 2011. The three highest peak flows at Lookout Creek from 1950 to 2020 were: February 1996 (227 m^3/s or 3.7 m^3/s/km^2, return period 72 years), December 1964/January 1965 (189 m^3/s or 3.0 m^3/s/km^2, return period 36 years), and January 2011 (130 m^3/s or 2.1 m^3/s/km^2, return period 24 years) (Figure 2, Table S5).

centreline, an area which encompasses the cutslope, fillslope, and road surface.

Large wood (pieces ≥10 cm in diameter and ≥1 m in length) was inventoried annually in MAC from 1986 to 2008 (Faustini & Jones, 2003; Gregory & Lienkaemper, 2013). Large wood was mapped in LOL starting in the late 1970s, and large wood jams were documented in the LOM reach and upstream in the early 1970s (Lienkaemper & Swanson, 1987; Swanson et al., 1976). Wood storage was inventoried along the entire length of the mainstem and principal tributaries in 2001 (Czarnomski, 2003; Dreher, 2004; Figure S1). Large (>1 m diameter) boulders were inventoried at 100 m intervals along the mainstem of Lookout Creek in 1995 and 1996 (Lambert, 1997).

Flood effects on channels were documented in eyewitness accounts and post-flood surveys (Johnson et al., 2000; Nakamura et al., 2000; Swanson et al., 1998). Channel cross-sections were surveyed during the summer at 1 to 6-year intervals from 1978 to 2011 following methods in Johnson and Swanson (2014) and Faustini (2000) (see details in the online Supplementary Material). Channel change since 2011 has been minor, and no further surveys have been conducted.

3.2 | Analysis of channel change

Cross-sectional areas of scour and deposition were calculated for all pairs of consecutive survey years (year-pairs) following methods in Faustini (2000) and Goodman (2020) (see the online Supplementary Material; Tables S1 and S2, Figure S2). The reworked area was defined as the sum of scour and deposition, and net deposition was defined as deposition minus scour (Figure S2). Negative values of net deposition indicate net scour. The reworked area and net deposition were determined for each cross-section, and 'reach-averaged' values were determined for each reach. The reach-averaged reworked depth was defined as the mean cross-sectional reworked area divided by the mean channel width in each reach. The cumulative net deposition was calculated for each cross-section by summing net deposition values starting in 1978; positive values indicate aggradation and negative values indicate scour relative to 1978. Changes in thalweg elevation were also calculated, with positive changes in thalweg elevation indicating localized aggradation and negative changes in thalweg elevation indicating localized scour.

Linear regressions were fitted to relate the reach-averaged reworked area (dependent variable) to the unit-area peak flow (independent variable) from the Lookout Creek gage (USGS no. 14161500) for LOM and LOL, or the Mack Creek gage for MAC and MCC. Regressions included only those years in which at least 75% of cross-sections were surveyed (Goodman, 2020) (Table S1).

4 | RESULTS

Changing forestry practices interacted with geomorphic processes in five distinct sub-periods within the study period (1950–2020): (1) 1950 to November 1964—initial clearcutting and road construction; (2) December 1964 to January 1965—first major flood; (3) February 1965 to 1995—inter-flood period; (4) 1996—second major flood; and (5) 1997 to 2020—post-flood period (Table 2, Figure 2).

4.1 | Initial forestry period, 1950–November 1964

Road construction and clearcutting began in 1950 and were concentrated in the lower portion of the basin (Figure 3a; Jones & Grant, 1996). Logging consisted of clearcutting patches of native (post-wildfire) old-growth and mature forest, with cable yarding to landings on steep slopes and tractor yarding on gentle slopes. Initial clearcuts lacked riparian buffers, and by the end of the 1960s, 20–40% of streamside length in fourth and fifth-order channels had clearcuts within 40 m of the stream (Czarnomski et al., 2008). Logging slash was burned. By November 1964, 13% of the area upstream of LOL and 12% of the area upstream of LOM had been clearcut, and 32 debris slides had occurred, with a total volume of 51 784 m^3 (Figure 3a, Table S6). In addition, 75% of the road network had been constructed, and 3.3 km of channel length had been affected by debris flows (Figure 4a). Over half (56%) of debris slides, 53% of debris slide volume, and one-third of debris flows originated from roads (Tables S3, S6, and S7). There were no documented episodes of large wood movement, and, anecdotally, no major channel changes.

4.2 | Floods of December 1964 and January 1965

A series of four large flows (70–188 m^3/s) occurred within two weeks in December 1964 and January 1965, including the second largest event (36-year return period) in Lookout Creek in the period of record (Figure 2). These events produced 82 inventoried debris slides >75 m^3 (Table 2, Figure 3b, Table S3). Debris slides were concentrated on weak rocks (SW portion of basin, Figure 3b), and they were strongly related to clearcuts and roads (Dyrness, 1967; Fredriksen, 1963, 1965; Snyder, 2000; Swanson & Dyrness, 1975; Wemple et al., 2001). Seventy percent of inventoried debris slides, 74% of debris slide volume, and more than 75% of debris flows originated from roads and clearcuts (Dyrness, 1967; Snyder, 2000; Wallenstein & Swanson, 1996) (Table 2, Figures 3b and 4b, Tables S3 and S7).

TABLE 2 Floods, clearcuts and roads, geomorphic processes, wood movement, and channel response at Lookout Creek in five sub-periods of the study period (1950 to 2020). Cumulative values for these periods are in Figures 3 and 4 and Tables S6 and S7. Source: Tables S3–S7

	1 - Initial entry, 1950–Nov 1964	2 - first flood, Dec 1964–Jan 1965	3 - inter-flood, Feb 1965–1995	4 - second flood, 1996	5 - post-logging and flood, 1997–2020
Flood return period (years) (date)	14 (1953)	36 (1964)	18 (1972)	72 (1996)	24 (2011)
Clearcutting (% of basin)	13	2	10	None	None
Roads (km/%)	94/75	11/9	21/16	None	None
Debris slides	32	82	27	41	1
Debris slide volume (m^3)	51 784	120 737	30 111	30 812	300
Debris flows length (m)	3550	10 500	500	8600	0
Large wood input	Low	Very high	Low	High	Low/none
Large wood movement		Fluvial transport, large wood jams formed	Fluvial transport	Fluvial transport, large wood jams unchanged	Fluvial transport
Channel response	Small	Small (third order); large (fourth, fifth order)	Small	Small	Small

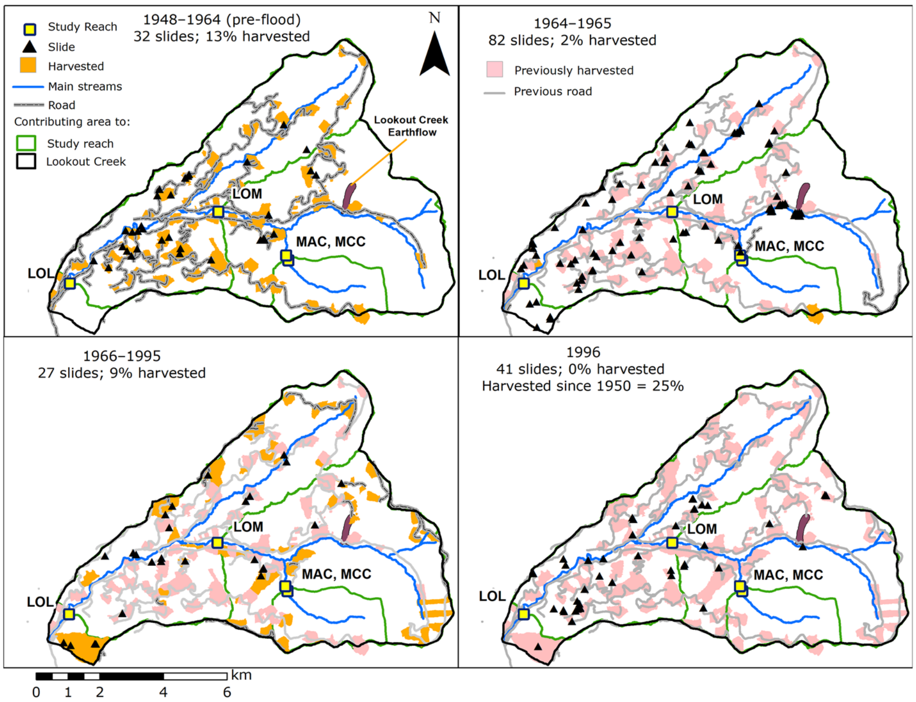

FIGURE 3 Spatial distribution of clearcuts (orange polygons for current period, pink for previous period) and inventoried debris slides and stream-side slides >75 m^3 (black triangles) for four periods demarcated by large floods: 1948–November 1964; 1964–1965; 1966–1995; and 1996. Instrumented cross-sections (yellow squares) in Lookout Creek are indicated with their contributing watershed areas (green lines). *Source*: Swanson (2014) and H.J. Andrews Experimental Forest (2019).

Compared with native forest, slide erosion volume per unit area was 2.8 times greater from clearcuts, and 39 times greater along road rights of way (defined as 10 m zone on either side of road centreline, including cutslope and fillslope) (Swanson & Dyrness, 1975) (Tables S4 and Table S6).

Debris flows in 1964/65 delivered large amounts of wood and sediment to the mainstem, including several massive pulses of large wood delivered to the road at the mouth of the 1 km^2 Watershed 3 (Figure 1) and directly into Lookout Creek on 21–23 December 1964 (Figure 5a). Eyewitness accounts and immediate post-flood surveys report that debris slides from roads delivered material to the Watershed 3 channel in 1961 (Dyrness, 1967; Fredriksen, 1963); roads were the source of 90% of the >30 000 m^3 contributed to channels of this basin in 1964; and the 1964 debris flows flushed large wood out of Watershed 3 that had accumulated in channels from old-growth forest over many decades and perhaps centuries (Fredriksen, 1965, 1970).

Although no direct observations of the 1964 flood were made at Mack Creek, retrospective interpretations suggest that the MAC channel was unchanged, but cut logs in the clearcut (MCC) may have been flushed downstream (Swanson et al., 1976). Additional retrospective study suggests that seven slides from the toe of the Lookout

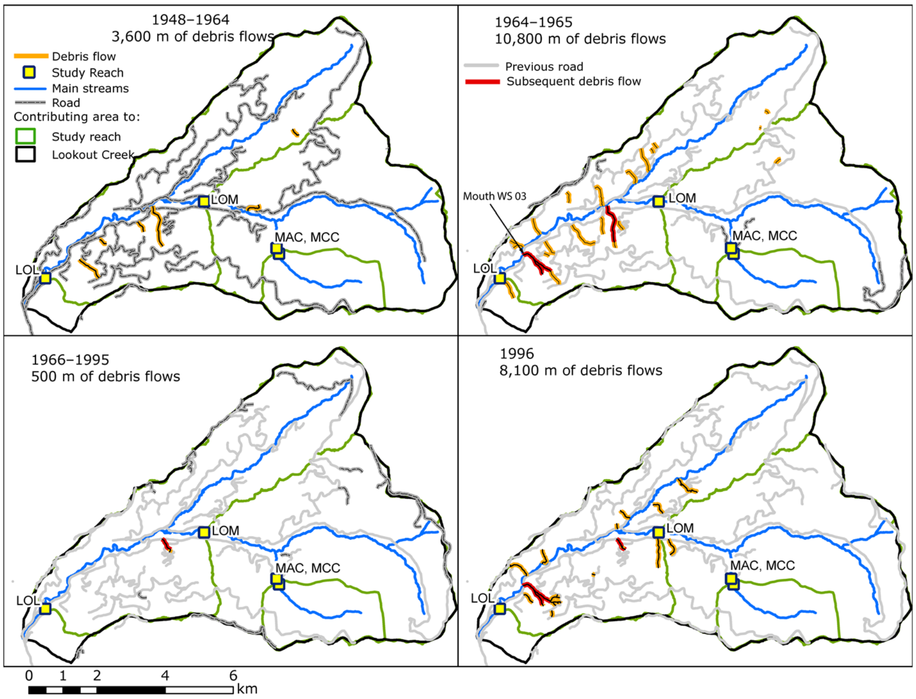

FIGURE 4 Spatial distribution of debris flows (orange lines for current period and red lines for subsequent debris flows in a channel segment with one or more prior debris flows) and roads (dark grey lines for current period, light grey lines for previous period) for four periods demarcated by large floods: 1948–November 1964; 1964–1965; 1966–1995; and 1996. Instrumented cross-sections (yellow squares) in Lookout Creek are indicated with their contributing watershed areas (green lines). *Sources*: Snyder (2000) and Swanson (2014).

Creek earthflow totalling >5000 m^3 (Figure 3b) moved as a wood-rich flood surge and deposited a major wood jam ~1.5 km downstream; a 3–4 m-thick sediment deposit accumulated upstream of the wood jam (Figure 1, Figure S1, Table 2) (Swanson & Swanston, 1977). The flood also created a second major wood jam at XS 9 and 10 in LOM (Figure 6, Figure S1), which accumulated an estimated 1–2 m of sediment (Faustini, 2000). The 1964/65 floods apparently removed all large wood from LOL, deposited fluvially transported wood on banks, and created a gravel bar at XS 6 to 8 whose crest was 2 m above the low-flow channel (Figure 7).

4.3 | Inter-flood period, February 1965–1995

Road construction and clearcutting slowed and ceased completely by the early 1990s (Table 2, Figure 3c) (Jones & Grant, 1996). The largest peak flow in Lookout Creek during this time period was in 1972; it was an 18-year return period event and the fourth largest on record (Figure 2, Table S5). Twenty-six additional debris slides occurred by 1972, with one additional debris slide and one debris flow by 1986 (Figure 4c, Tables S3, S6, and S7). Ninety-two percent of inventoried debris slides and slide volume and 100% of debris flows during this period originated from roads and clearcuts (Figures 3c and 4c, Tables S3 and S7) (Snyder, 2000). There was little change in wood in LOM, but large wood from adjacent streambanks toppled into LOL in the 1980s and early 1990s (Figure 7). From 1978 to 1995, channel change was small and related to flow for events with <8-year return period (in Lookout Creek) and <10-year period (in Mack Creek for 1980–1995) (Figure 8, Table S8). No reach-scale net deposition or scour was observed at the four study reaches during this period (Figure 9). At LOM, some deposition (10–20 m^2, Figure 10a) and thalweg aggradation (0.2–0.6 m, Figure 10b) occurred at XS 7, upstream of the large wood jam. At LOL, some scour (−9 to −20 m^2, Figure 11a) and minor thalweg adjustment (Figure 11b) occurred at XS 9, just downstream of the sharp bend.

4.4 | Flood of February 1996

The flood of February 1996 was the largest event on record, with a 72-year return period (in Lookout Creek), slightly higher than 1964/65 (Figure 2, Table 2) and a 41-year return period (in Mack Creek). Forty-one debris slides occurred in Lookout Creek (Table S3). Spatial patterns of debris slides and debris flows in 1996 were nearly identical to patterns triggered by floods in the 1950 to 1995 period (Figures 3 and 4) (Swanson et al., 1998). Fifty-four percent of inventoried debris slides, 65% of debris slide volume, and 50% of debris flows originated from roads and post-clearcut planted forest (Figures 3d and 4d, Tables S3, S6, and S7) (Snyder, 2000; Wallenstein & Swanson, 1996). Debris slide volume per square kilometre from roads was more than 40 times greater than that from forest (Table S4). From 1946 to 1996, debris flows in Lookout Creek were 50 times more frequent from roads (48% of events, 3.7% of the landscape) and almost two times more frequent from clearcuts and planted forest (15% of events, 25% of landscape) compared with native forest (37% of events, 71.3% of landscape) (Table S7) (Snyder, 2000; Swanson et al., 1998; Wemple & Jones, 2003).

Eyewitness accounts and post-flood inventories indicate that much less large wood and stored sediment was exported in debris flows from tributary channels in 1996 than in 1964/65, despite the greater peak flow (Figure 5b). Only one slide occurred at the toe of the Lookout Creek earthflow upstream of LOM (Figure 3d). Most large wood and boulders remained in place in MAC and MCC (Swanson et al., 1998). Additional channel-spanning old-growth logs floated into the wood jam in LOM (Figure 6) (Faustini, 2000). Eyewitness accounts and video document large wood transport in LOL, where all large wood was scoured and fluvially transported wood was deposited on banks and the crest of the 1960s-era mid-channel bar between XS 6 and 8 (Figure 7).

Channel change during the 1996 event was greater than predicted from linear regression at all four study reaches (Figure 8, Table S8). Net channel change was negligible in the old-growth reach

FIGURE 5 Photographs of debris flow deposits on the road passing by the mouth of the Watershed 3 stream (entering from the upper right) where it reaches Lookout Creek (lower left) (see location in Figure 4). (a) Pile of large wood delivered by the third pulse of multiple debris flows from watershed 3 on the night of 22–23 December 1964. Two previous pulses occurred during the night and early morning of 21–22 December (Fredriksen, 1965). Thirty-two landslides moved an estimated 30 000 m^3 of sediment (300 m^3/ha) in the watershed. Twenty-nine of the 32 landslides were adjacent to stream channels, and 93% of the material originated from road-related slides (Fredriksen, 1970). (b) Deposit from debris flows on the night of 6–7 February 1996 showing fewer very large wood pieces in 1996 compared to 1964. Note human figures for scale indicated by white arrows. Photo credits: 1964, Dick Fredriksen; 1996, Al Levno.

(MAC) and negative (net scour) in the clearcut reach (MCC), where large wood had been removed from the channel in the mid-1960s (Figure 9). Only a single piece of large wood >10 m in length was present within the channel in MCC in 1996, compared with 51 pieces in the old-growth MAC reach, and the reach without large wood (MCC) experienced scour and coarsening of the bed surface, whereas the reach with large wood (MAC) experienced aggradation upstream of large wood (Faustini & Jones, 2003; Goodman, 2020).

Significant reach-scale deposition occurred at LOM, but scour balanced deposition, with no net reach-scale change at LOL (Figure 9). Deposition at LOM was concentrated at XS 6 to 8, just upstream of the large wood jam (Figure 10a), where the thalweg aggraded as much as 1 m (Figure 10b), and this aggradation was accompanied by significant fining of the bed surface (Faustini, 2000). Scour at LOL was concentrated at XS 7 to 9, just downstream of a sharp, bedrock-controlled bend (Figure 11a): the thalweg incised by as much as 2 m (Figure 11b). Eyewitness accounts document bedload transport of large boulders during the peak flow. This portion of LOL had Shields stress ratios >12 based on a 2D model of the 1996 flood event, and median grain size Shields stress ratios (Shields stress/critical Shields stress) > 2 indicated that the bed was fully mobile (Wilcock & McArdell, 1993) at all LOL cross-sections (Cromer, 2021). Deposition in excess of 1 m also occurred at the downstream end of LOL (XS 1 to 4) (Figure 11b).

4.5 | Post-flood and forestry period, 1997–2020

No road construction or clearcutting occurred in this period (Table 2). Forest cover established quickly in clearcuts (Nesje, 1996), and by 2020 clearcuts were plantations aged 40 to 70 years. The flood of 2011 was the third highest on record, with a 24-year return period (in Lookout Creek). No debris slides or debris flows were observed in this period. Additional large trees continued to topple into MAC (Gregory & Lienkaemper, 2013), LOM (Figure 6; Faustini, 2000), and LOL (Figure 7), and the flood of 2011 rotated or slightly moved some large wood in LOL (Figure 7). Channel changes after 1996 were small and related to discharge for events with <24-year return period in Lookout Creek and <20-year return period in Mack Creek (Figure 8, open symbols, Table S8). No major reach-scale channel change occurred in the four study reaches, although downcutting progressed at LOL from 1997 to 2000 (Figure 9). At LOM, gradual downcutting (i.e., loss of cumulative aggradation) occurred upstream of the large wood jam (Figure 10). At LOL, downcutting progressed from 1997 to the mid-2000s at XS 5 and 6, with aggradation at XS 1 to 4 (Figure 11).

5 | DISCUSSION

This 70-year study provides insights into watershed response to forestry activities. A key outcome was that watershed response to floods depended on the history of disturbance, including road construction, logging, and geomorphic processes triggered by past floods, and changes in forest and road conditions following cessation of logging. As a result, geomorphic response was distinctive in each period. In the early road and logging period (before 1964 and in the early part of the inter-flood period after 1965), peak flows with 1 to 3-year return periods were sufficient to generate debris slides from roads and clearcuts. In the most recent post-flood period (1997–2020), more than four decades after cessation of road construction and most logging (in 1975), a 23-year return period peak flow in 2011 in Lookout Creek generated no inventoried debris slides and flows.

Geomorphic response to flood events was more related to the timing of clearcuts and roads, past geomorphic events, and forest dynamics than to flood magnitude. The debris slide record (Figure 3) clearly indicates that the hillslope response was greater to the flood of 1964/65, which occurred during a period of rapid road construction and logging of old growth, compared with the flood of record in 1996, which occurred two decades after road construction and most logging had ended. Although cross-section monitoring did not begin until 1977, four forms of field evidence presented here support the assertion that the 1964/65 flood also produced the largest channel response: (1) debris slides delivered large amounts of sediment to channels in 1964/65 (Figure 3); (2) debris flows delivered large

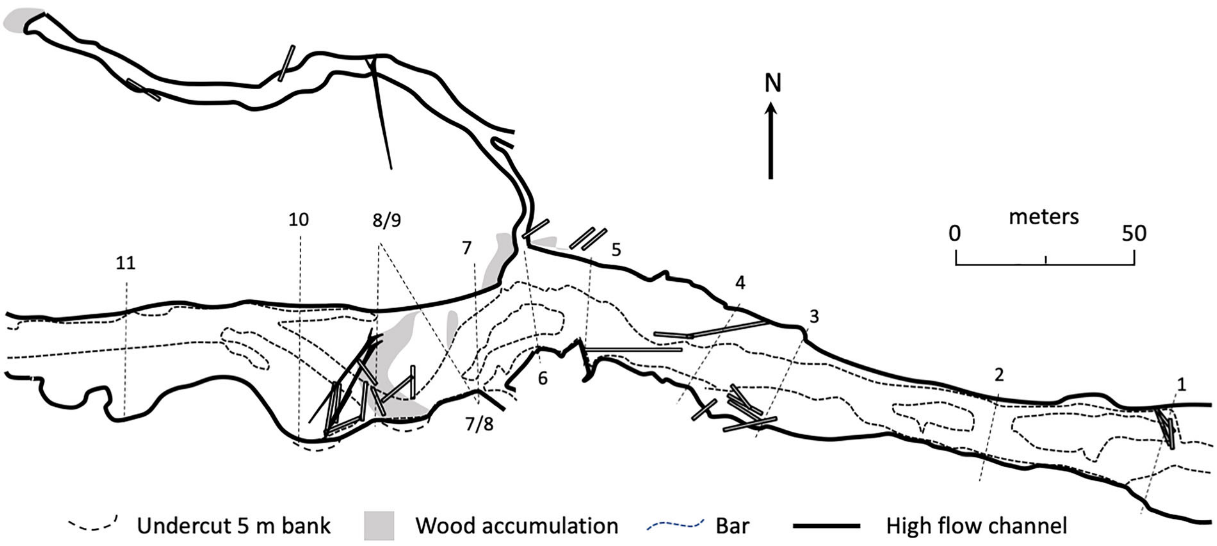

FIGURE 6 Spatial arrangement of wood in LOM, 1996. In-stream wood affected sediment transport and channel change in this reach. A large wood jam at XS 7 to 9 was emplaced in the floods of 1964/65 and it accumulated a large, thick wedge of sediment upstream. Additional channel-spanning old-growth logs were emplaced in the flood of 1996, and additional large wood toppled in from the undercut bank at XS 9 in 1997 to 2000 (Faustini, 2000). Wood movement is limited in this reach because of the gentle gradient, wide valley floor, and high-flow secondary channels (e.g., at XS 6), which limit the capacity of the channel to float large wood. Field investigations indicated this wood arrangement was largely unchanged by 2022, except for a toppled old-growth tree and some fluvially transported wood forming a new jam at XS 4. Maps were created by John Faustini (Faustini, 2000) and ground-truthed by J. Jones and F. Swanson in 2022.

amounts of sediment and large wood to channels in 1964/65 (Figures 4 and 5); (3) the flood of 1964/65 deposited large wood on stream banks and in channels (Figures 6 and 7); and (4) the flood of 1964/65 created large mid-channel bars and wood jams, which were datable based on ages of post-flood regenerating riparian vegetation (alders) and the states of wood decomposition, and these channel features were not subsequently modified by the flood of 1996 (Figures 7 and 9–11).

The 70-year history of Lookout Creek also provides some insights into published concepts about watershed response: process domains (Montgomery, 1999), stochastic forcing (Benda & Dunne, 1997), disturbance cascades (Nakamura et al., 2000), and sediment and wood budgets and routing (Swanson et al., 1982).

Contrasting geomorphic processes and channel response occurred in three distinct 'litho-topgraphic' units, or process domains (Montgomery, 1999). Channel response was negligible in steep, third-order channels with lag deposits of large boulders from former glaciation (MAC, MCC), where little logging occurred and no debris slides or debris flows were observed, both in a reach with abundant large wood and where large wood had been removed (Faustini & Jones, 2003). In contrast, persistent aggradation occurred upstream of a very large wood jam in an unconfined fourth-order channel (LOM) in a wide valley floor formed by valley constriction by an ancient large earthflow, and downstream of an active large earthflow that delivered large volumes of sediment and wood to the channel. In a third zone, logging and roads on steep, erodible slopes triggered debris slides and debris flows that scoured large wood and deposited a large gravel bar in a fifth-order channel (LOL) during the first major flood, but scoured both large wood and sediment in the second major flood.

In Lookout Creek, sediment loading to channels resulted from the interaction of major floods with disturbance in the form of roads and clearcuts, providing an example of 'stochastic forcing' (Benda & Dunne, 1997). Stochastic forcing refers to the frequency, magnitude, and spatial distribution of sediment influx to channels as stochastic characteristics that result from the interaction between topography, climate, and biotic processes (Benda & Dunne (1997). In contrast to the Oregon Coast Range example in Benda and Dunne (1997), the vast majority of slides in Lookout Creek did not originate from zero-order basins, but rather from roads, clearcuts, and earthflow toes. Nevertheless, as in the stochastic forcing concept, an important factor in geomorphic response to floods was the time elapsed since a prior major flood event, during which large wood and sediment could accumulate in positions where they could be mobilized. For example, debris slides and debris flows contributed less large wood to the mainstem channel in 1996 than in 1964/65; we infer that this lesser response occurred because the early events removed large wood that had accumulated over centuries, and the 30 years between the two flood events was likely insufficient to contribute much additional large wood or sediment to landscape positions where it could be mobilized by the flood. We also infer that fewer debris slides and streamside slides occurred from the toe of the Lookout Creek earthflow in 1996 than in 1964/65, because the measured rates of earthflow movement and constriction of the channel (Swanson & Swanston, 1977) over this 30-year period were less than had occurred prior to the 1964 flood, so less sediment and wood was adjacent to the channel and available for fluvial transport.

In Lookout Creek, slow and fast geomorphic processes interact in sequence down the sediment transport flow path to create a cascade of events that form an ecological disturbance cascade (Nakamura et al., 2000). From this perspective, the stream and riparian landscape are viewed through time as a network containing a shifting mosaic of disturbance patches—linear and often parallel zones of disturbance created by cascading geomorphological processes (Nakamura

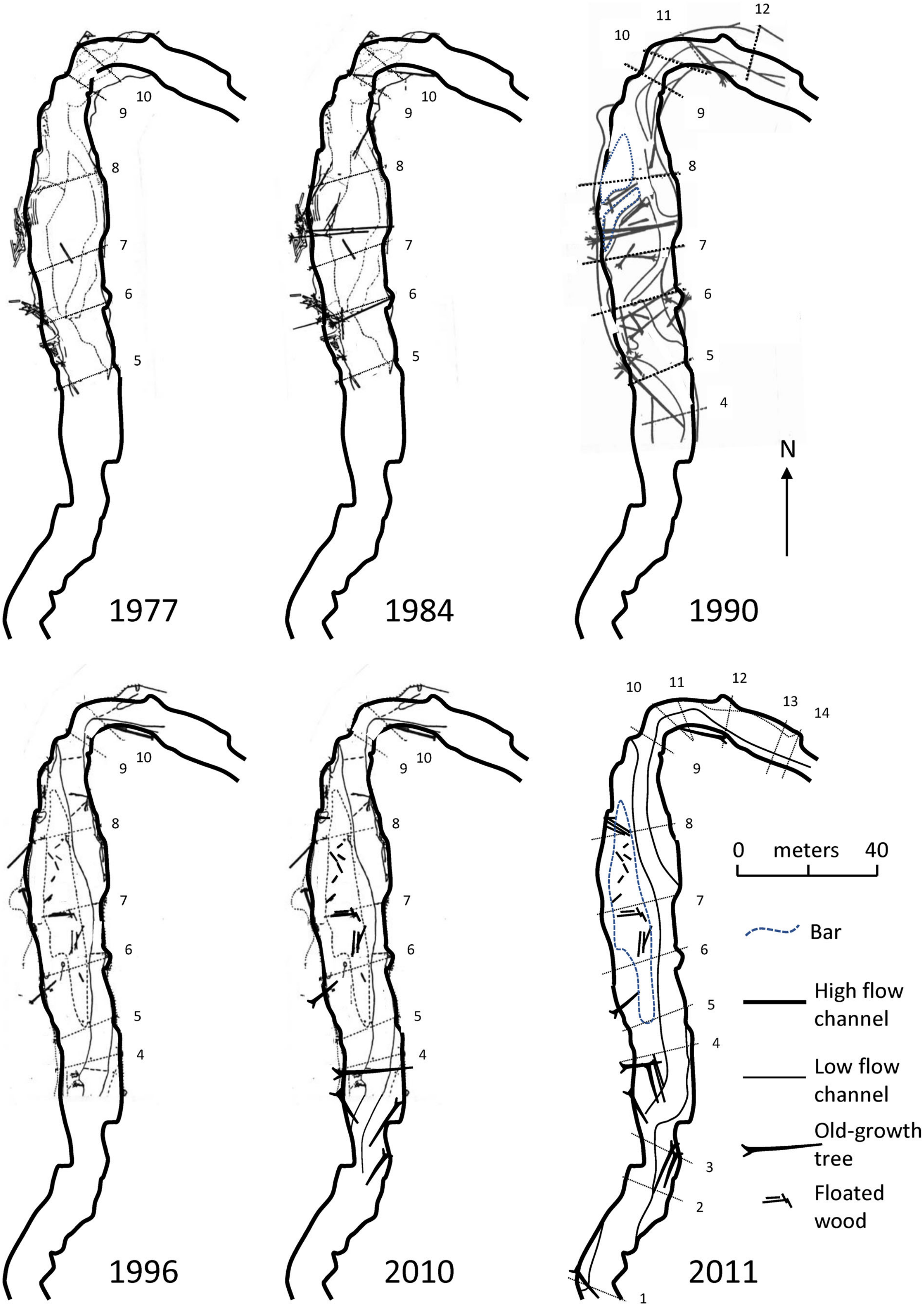

FIGURE 7 Legend on next page.

FIGURE 7 Spatial arrangement and temporal dynamics of wood in LOL, 1977–2011. (a) In 1977, 12 years after floods of 1964/65 and 5 years after flood of 1972. Floods of 1964/65 had deposited a mid-channel bar (XS 5 to 8) and removed channel-spanning wood, and only a few batches of fluvially transported wood pieces were present on channel margins and the crest of the mid-channel bar (XS 5 to 8). (b) By 1984, a few channel-spanning old-growth trees had toppled from stream banks; these were suspended above the bankfull stage. (c) By 1990, additional toppled old-growth trees were suspended above bankfull stage. (d) By summer of 1996, all large channel-spanning logs had been removed by the flood of February 1996, and only a few batches of fluvially transported wood pieces were present on channel margins and the crest of the bar. The 1960s-era mid-channel bar (XS 5 to 8) was not modified. Flow over the crest of the bar was sufficiently deep to topple ~30-year-old alders that had established after the 1964 flood, but it left some of them partially rooted and tipped in the downstream direction (wood pieces at XS 6 and 7). The flow also rolled logs (10–30 cm in diameter and several metres in length) over the bar surface and left them lodged perpendicular to the flow direction against boulders protruding above the bar surface (wood pieces at XS 7). (e) By 2010, a few old-growth trees had toppled into the reach; one spanned the channel, while two rested on channel bars downstream of XS 4. (f) By summer of 2011, after the flood of January 2011, a portion of the channel-spanning log had rotated and accumulated additional wood pieces, and one of the two other large pieces moved slightly downstream (near XS 3). A few additional old-growth trees have toppled into the reach since 2011, with only minor rearrangement of wood pieces as of 2022. Maps were created by (a, b) George Lienkaemper, (c) Futoshi Nakamura, (d) John Faustini, (e) Jung-il Seo, and (f) students in the 2011 eco-informatics Summer Institute, and maps were ground-truthed annually by J. Jones and F. Swanson since 1991.

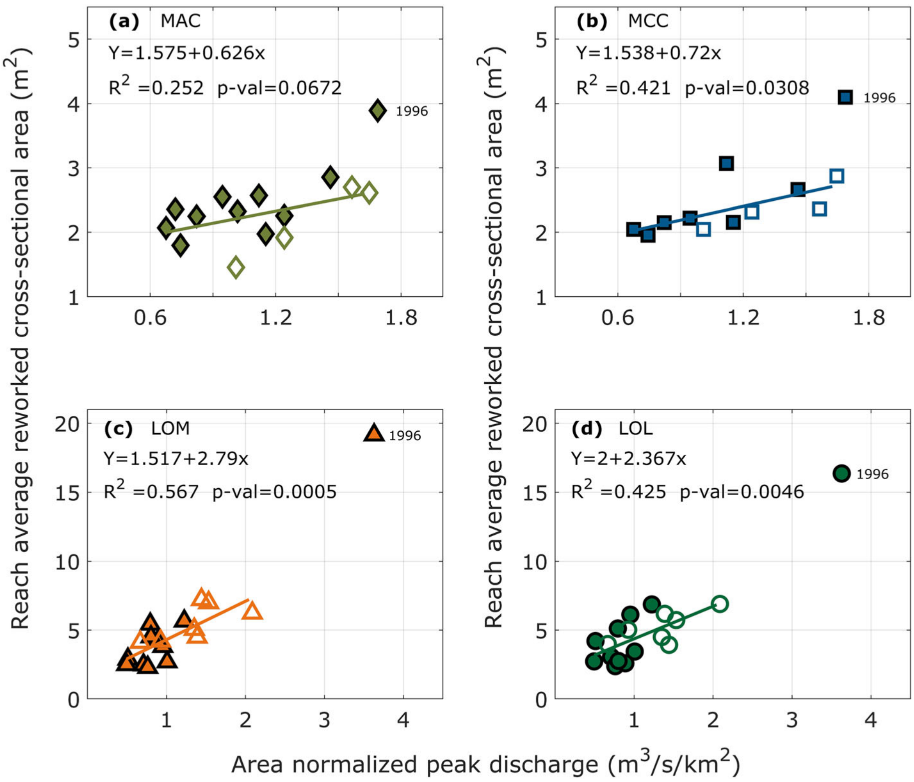

FIGURE 8 Reach average reworked channel area (i.e., scour plus deposition) vs. peak flow (a) MAC, (b) MCC, (c) LOM, (d) LOL as a function of unit-area discharge (Table S5) for the period 1978 to 2011. Solid lines represent linear regression excluding 1996. Peak flows up to 1996 (closed symbols) and after 1996 (open symbols) are from USGS gage no. 14161500 for LOM and LOL and from a gage at Mack Creek for MAC and MCC (Johnson & Rothacher, 2016). In the linear regression equations, *y* is the reworked area and *x* is the largest unit-area peak flow between survey dates.

et al., 2000). Slow geomorphic processes observed in this study included the gradual accumulation of toppled large wood and stored sediment in channels and the gradual constriction of channels by earthflows, while fast geomorphic processes included debris slides, debris flows, streamside slides, temporary dams, and wood-rich flood surges. Fast processes created large wood jams and mid-channel bars, which delivered sediment downstream slowly over decades.

This history of wood and sediment routing in response to storms and forest management reveals a sequence of distinct periods of watershed response on a stage set by underlying lithologic, landform ('process domains'), and forest conditions. The timing of storms and their intersection with progressive road construction and logging in a watershed is stochastic. However, changes in land-use practices (e.g., cessation of forestry, changes in road location and construction methods) and aspects of watershed 'memory' (e.g., histories of wood loading in key debris flow-prone channels, sediment stored in channels, channel constriction by earthflow toes) create significant differences in watershed response over time, in ways that are not captured by process domain and stochastic-forcing concepts, but could be captured by sediment and wood budget and routing approaches (e.g., Swanson et al., 1982).

Many studies have examined the effects of forestry on floods (e.g., Eisenbies et al., 2007; Jones & Grant, 1996; Moore & Wondzell, 2005), landslides of various types (Guthrie, 2002; Jakob, 2000; Swanson & Dyrness, 1975), wood in streams (Czarnomski et al., 2008; Reid & Hassan, 2020; Scott & Wohl, 2018), or channel change (Lyons & Beschta, 1983; Stott & Mount, 2004; Tonina et al., 2008). However, this synthesis reveals that it is difficult to draw generalizations from such studies because forestry practices, forest condition, flood occurrences, landslide susceptibility, wood delivery and movement, and channel change are all interconnected and changing on multiple time scales. To understand watershed

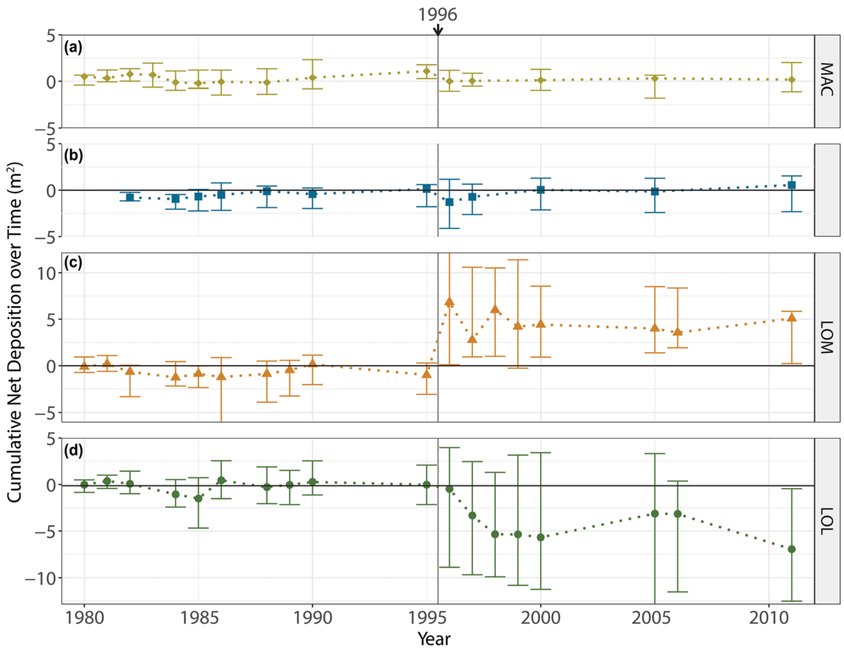

FIGURE 9 Median (dots) and interquartile range (bars) of cumulative net deposition (m^2) relative to 1978 (1981 for MCC) at (a) MAC, (b) MCC, (c) LOM, (d) LOL. Vertical line indicates the flood of 1996.

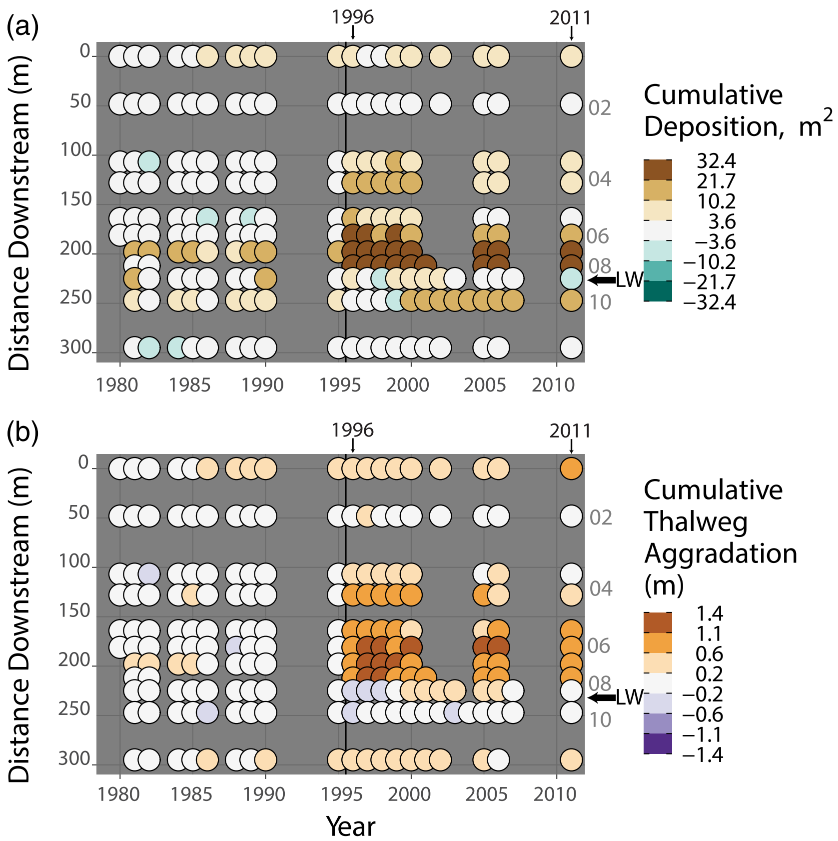

FIGURE 10 Cumulative net deposition and thalweg aggradation at the 11 cross-sections in the middle Lookout reach (rows), by year, 1978 to 2011 (columns); vertical line indicates flood of 1996. Values are colour-coded based on the 50th, 75th, and 90th percentiles of the absolute values of the dataset. (a) Positive (brown) and negative (blue-green) values of cumulative deposition over time by cross-section. (b) Positive (orange) and negative (purple) values of cumulative thalweg aggradation (m) over time by cross-section. The distance downstream is measured from the reach starting point (cross-section #1). Arrow marked LW denotes location of the large wood jam (see also Figures 1 and 6, Figure S1).

response to forestry requires observation of all of these processes on time scales that capture how they respond to past and changing geophysical, ecological, and social processes and events. Key aspects of the response of the Lookout Creek watershed over 70 years (1950–2020) depended on the interactions among past geologic events (e.g., explosive volcanism, glaciation), past geomorphic events (e.g., earthflow movement), climate (e.g., flood magnitude and timing), the forest condition (mature and old-growth forest vs. post-clearcut plantations), and forest dynamics (e.g., time required to grow trees large enough to provide a source for instream large wood). Watershed response also crucially depended on how geophysical and biological processes interacted with social processes, including the initial decision to build roads and convert old-growth forest to plantations, the technology available for forestry of that time (1950s and 1960s), and the decision to reduce and eventually cease road construction and logging in the watershed.

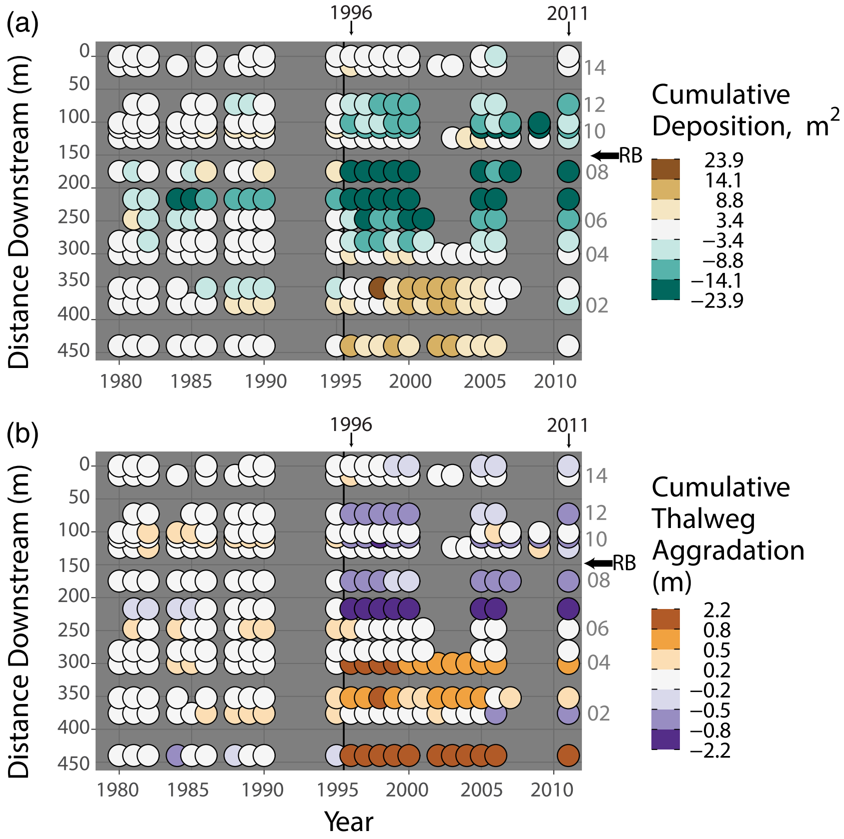

FIGURE 11 Cumulative net deposition and thalweg aggradation at the 14 cross-sections in the lower Lookout reach (rows), by year, 1978 to 2011 (columns); vertical line indicates flood of 1996. Values are colour-coded based on the 50th, 75th, and 90th percentiles of the absolute values of the dataset. (a) Positive (brown) and negative (blue-green) values of cumulative deposition over time by cross-section. (b) Positive (orange) and negative (purple) values of cumulative thalweg aggradation (m) over time by cross-section. The distance downstream is measured from the reach starting point (cross-section #1). Arrow marked RB denotes location of the sharp bedrock-controlled river bend (see Figure 7).

6 | CONCLUSION

A 70-year study of geomorphic process response to clearcutting and associated roads and two major floods in the 64 km^2 Lookout Creek watershed in western Oregon illustrates several key aspects of watershed response to forestry. Forestry practices (roads and clearcuts) initially affected channel response by enhancing the supply of sediment and wood during large events and by increasing the capacity of geomorphic processes to deliver wood and sediment during a flood. The geologic history and dominant geomorphic processes varied among sub-areas within the watershed and influenced watershed response. Watershed response differed in each of five time periods with varied clearcut and road conditions and flood sizes, and the response in each period depended upon processes and features from previous periods. Today, almost five decades after the cessation of active road construction and logging, the watershed appears to have partially recovered from initial forestry activities, but recent fire and a warming climate will continue to modify the watershed. This synthesis of 70 years of observations reveals how watershed response depends upon the interactions among multiple, evolving factors, including geologic and geomorphic history, flood magnitude and timing, forest condition and forest dynamics, and changing forest management. Understanding of watershed response to forestry requires long-term study from this synthetic perspective.

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DATA AVAILABILITY STATEMENT

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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