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RESEARCH AND OBSERVATORY CATCHMENTS: THE LEGACY AND THE FUTURE

WILEY

Fifty years of runoff response to conversion of old-growth forest to planted forest in the H. J. Andrews Forest, Oregon, USA

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Abstract

Long-term watershed experiments provide the opportunity to understand forest hydrology responses to past logging, road construction, forest regrowth, and their interactions with climate and geomorphic processes such as road-related landslides. We examined a 50-year record from paired-watershed experiments in the H. J. Andrews Experimental Forest, Oregon, USA in which 125 to 450-year-old conifer forests were harvested in the 1960s and 1970s and converted to planted conifer forests. We evaluated how quickflow and delayed flow for 1222 events in treated and reference watersheds changed by season after clearcutting and road construction, including 50 years of growth of planted forest, major floods, and multi-decade reductions in snowpack. Quickflow runoff early in the water year (fall) increased by up to +99% in the first decade, declining to below pre-harvest levels (−1% to −15%) by the third to fifth decade after clearcutting. Fall delayed flow responded more dramatically than quickflow and fell below pre-treatment levels in all watersheds by the fifth decade, consistent with increased transpiration in the planted forests. Quickflow increased less (+12% to 70%) during the winter and spring but remained higher than pre-treatment levels throughout the fourth or fifth decade, potentially impacted by post-harvest burning, roads, and landslides. Quickflow remained high throughout the 50-year period of study, and much higher than delayed flow in the last two decades in a watershed in which road-related changes in flow routing and debris flows after the flood of record increased network connectivity. A long-term decline in regional snowpack was not clearly associated with responses of treated vs. reference watersheds. Hydrologic processes altered by harvest of old-growth conifer forest more than 50 years ago (transpiration, interception, snowmelt, and flow routing) continued to modify streamflow, with no clear evidence of hydrologic recovery. These findings underscore the importance of continued long-term watershed experiments.

KEYWORDS
debris flows, declining snowpack, Douglas-fir, hydrograph separation, hydrologic recovery

1 | INTRODUCTION

Harvest of old native forest and its replacement with planted forests may modify hydrologic processes for many decades. In the Pacific Northwest of the USA, harvesting of old-growth forests followed by replanting with native tree species has profoundly affected both high and low streamflow (Jones, 2000; Jones & Post, 2004; Moore & Wondzell, 2005; Perry & Jones, 2017; Rothacher, 1970; Surfleet &

Skaugset, 2013). Peak discharge increased after clearcutting of old-growth forest, and these increases persisted for several decades, as planted forests grew (Jones, 2000; Jones & Post, 2004; Moore & Wondzell, 2005). These findings indicate that 'hydrologic recovery', a concept widely used in the applied hydrology literature, may not accurately describe the long-term effects of forest change on hydrology. However, few studies have examined how runoff changes over periods of half a century.

Forest harvest and regrowth of planted forest influence both quickflow and delayed flow. Quickflow is delivered rapidly to the stream during a storm event (Hewlett & Helvey, 1970), while delayed flow is delivered slowly (Hall, 1968); both are represented as runoff coefficients (Buttle et al., 2019; Hewlett & Hibbert, 1967; Nippgen et al., 2011; Perkins & Jones, 2008; Woodruff & Hewlett, 1970). Recent studies across western North America have documented multi-decade reductions in dry-season low flows (i.e., delayed flow) after replacement of old-growth forest with planted forest (Gronsdahl et al., 2019; Hicks et al., 1991; Keppeler & Ziemer, 1990; Perry & Jones, 2017; Segura et al., 2020). Early studies also documented initial increases in quickflow after harvest in deciduous (Bent, 2001; Hornbeck, 1973; Swift et al., 1988), boreal (Guillemette et al., 2005), and conifer forests (Harr et al., 1975; Jones, 2000; Ziemer, 1981). Data from long-term, paired watersheds has been fundamental to our understanding of hydrologic response to changing forests and climate (Jackson et al., 2018; Jones, 2000; Jones et al., 2012; Turner et al., 2003). However, few studies have focused on how quickflow and delayed flow respond to forest harvest and growth of planted forests over multiple decades (Buttle et al., 2019) or seasons (Grant et al., 2008).

Several mechanisms may affect the hydrology of conifer forests in rain-and-snow dominated regions (Figure 1). Interception depends on leaf area and epiphyte communities, which differ between young and old forests (Pypker et al., 2005, 2006a). Transpiration varies with the age and height of the forest (Moore et al., 2004). Road construction and debris flows associated with major floods may alter water flow paths, affecting the partitioning of quickflow versus delayed flow (Wemple et al., 2001; Wemple & Jones, 2003). Snowpack accumulation is higher and snowmelt rate may increase in recently cut canopy openings compared to areas under forest (Berris & Harr, 1987; Harr, 1986; Jennings & Jones, 2015; Jones & Perkins, 2010; Marks et al., 1998). Moreover, snowpack has been declining as climate warms in the western USA (Mote et al., 2005). It is not known how these various factors have affected streamflow over a half century.

This study addresses these gaps by examining changes in quickflow and delayed flow over a 50-year period in small paired-watershed experiments in the H. J. Andrews Experimental Forest in western Oregon, USA (hereafter 'Andrews Forest'). The period of study encompasses clearcutting of old-growth forest, growth of planted forest, major regional flood events, and long-term reductions in snowpack. Prior studies showed that peak discharges of all size classes in all seasons remained elevated 25 years after harvest of old-growth forest (Jones, 2000; Jones & Grant, 1996). In this study, we examine a post-harvest record that is twice as long as those used in earlier studies and evaluate ratios of quickflow and delayed flow to event precipitation rather than peak discharge. We addressed the following questions:

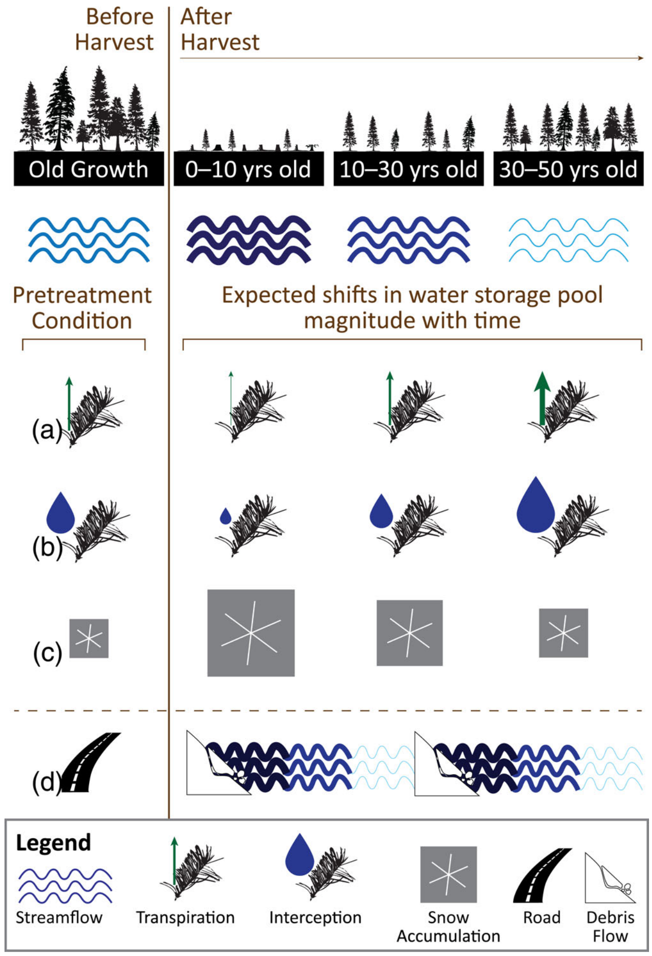

FIGURE 1 Expected response over time in a treated watershed after harvest in terms of water storage pool magnitude. (a) Transpiration decreases initially in the treated watershed but then increases as the planted forest grows, potentially reaching higher levels than in the pre-treatment forest. (b) Canopy interception also decreases initially in the treated watershed but then increases as the planted forest grows. (c) Snow accumulation increases initially in the treated watershed but then decreases as the planted forest grows. (d) The presence of roads during the pre-treatment period may cause increases in streamflow, as roads enhance hydrologic connectivity within the watershed. Roads can also interact with debris flows during large floods to modify flow routing and increase overall streamflow response

1. How do runoff coefficients in planted forests differ from those in reference old-growth forests over a 50-year time period which encompasses major floods and changing climate?
2. What mechanisms may account for these long-term responses?
3. What are the implications of these responses for forest hydrology?

2 | MATERIALS AND METHODS

2.1 | Study area

This study analyses long-term hydrometric records collected at the Andrews Forest in the Western Cascade Range of Oregon, USA

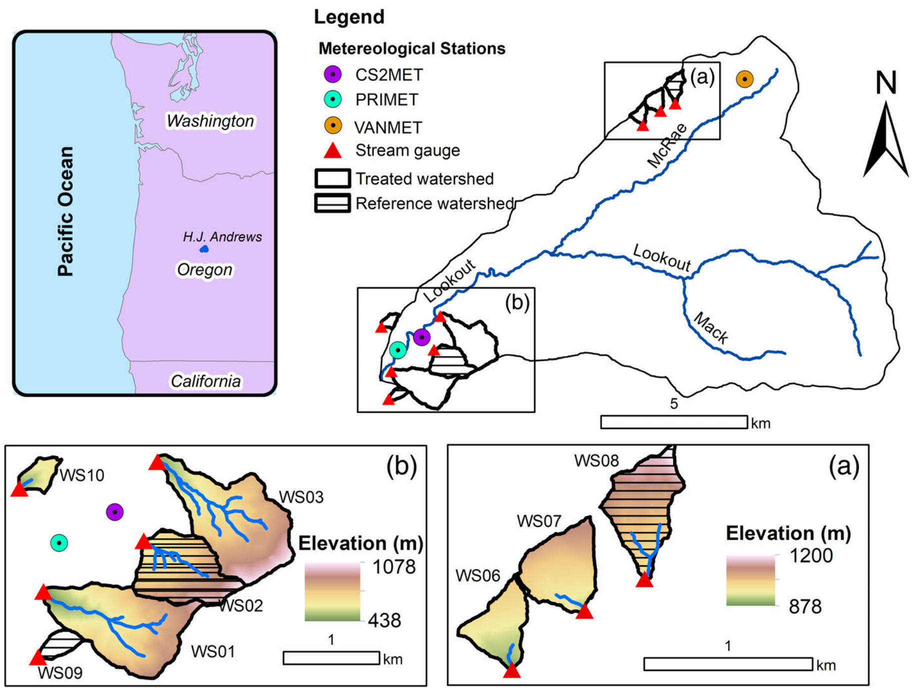

FIGURE 2 Location of the Andrews Forest. Hatched areas indicate reference watersheds, circles represent the locations of climate stations used in this study (CS2MET, PRIMET, and VANMET), and triangles represent the locations of the stream gauges. Enlargements A and B show basin elevation derived from LiDAR (Spies, 2016)

(Figure 2). The geology of the Andrews Forest is shaped by volcanism. Areas below 760 m (WS 09 and WS 10 and lower portions of WS 01, WS 02, and WS 03) are generally underlain by hydrothermally altered volcaniclastic rocks consisting of massive, reddish and buff-coloured tuffs and breccias derived from mudflows and pyroclastic flows from the Oligocene to early Miocene epochs (33–20 mya). Areas between 760 and 1200 m (upper elevation of WS 01, WS 02, and WS 03) are underlain by two units from the middle to late Miocene (14–5 mya): a lower unit containing welded and non-welded ash flows and an upper ridge-forming unit containing basalt and andesite lava flows. WS 06, WS 07, and WS 08 lack the hard ridge-forming unit (Swanson & James, 1975).

Mean slope gradients exceed 60% in WS 01, WS 02, WS 03, WS 09, and WS 10, but slope gradients are ~30% in WS 06, WS 07, and WS 08. Much of the area of WS 03 is characterized by slumps and benches resulting from hard, resistant rock overlying softer, more erosive rock, and following road construction in 1959, road-related debris flows scoured the channel in 1961, 1964–1965, and 1996 (Dyrness, 1967; Fredriksen, 1963, 1965; Snyder, 2000; Swanson & Dyrness, 1975; Wemple et al., 2001). WS 10, which lacks roads, also experienced debris flows in 1986 and 1996. Few or no debris flows have been documented in the other experimental watersheds since 1950.

Three paired watershed experiments were established at slightly different times and different elevation ranges in the Andrews Forest: WS 01, WS 02, and WS 03 (1952–present), WS 06, WS 07, and WS 08 (1963–present), and WS 09 and WS 10 (1968–present; Jones, 2000; Table 1). There are three reference watersheds (WS 02, WS 08, and WS 09) and five treated watersheds (WS 01, WS 03, WS 06, WS 07, and WS 10; Table 1). Forests in WS 02 originated after fires in 1500 CE and the mid-1800s CE. Forests in WS 08 originated after fires in 1500 CE (30% of area) and the mid-1800s CE (70% of area). Forests in WS 09 were affected by frequent low-severity fire, with establishment dates ranging from 1500 CE to the early 1900s CE (Swanson & Jones, 2002). Three watersheds were 100% clearcut (WS 01 in 1962–1966, WS 06 in 1974, and WS 10 in 1975); one (WS 07) had a shelterwood cut (1974) followed by removal of the remaining old-growth (1984), and then a pre-commercial thin (2001), and one (WS 03) had roads (1959) and 25% patch clearcutting (1963; Table 1). As of 2020, forests that had been planted in the clearcut areas ranged in age from 45 to 56 years (Table 1).

Mean annual precipitation is 2350 mm, and mean annual temperature is 9°C (at 436 m.a.s.l). More than 80% of precipitation occurs between October and April during long-duration, low-intensity frontal storms (Swanson & Jones, 2002). WS 09 and WS 10 are predominantly in the rain zone; WS 01, WS 02, and WS 03 span the rain, transient snow, and seasonal snow zones; and WS 06, WS 07 and WS 08 are in the seasonal snow zone, where the snowpack can persist from November to June (Harr & McCorison, 1979; Perkins & Jones, 2008; Swanson & Jones, 2002). Regional snow water equivalent has declined since 1930 with cycles that are negatively related to the Pacific Decadal Oscillation (warmer sea surface temperature along the west coast of North America = less snow at the Andrews Forest and in the Oregon Cascade Range). This decline is likely associated with this reoccurring climate pattern and regional climate warming (Figure S1). Despite this decline, there was no change over the study period in the frequency of large storm events (i.e., precipitation above 150 mm) likely to have a significant snow component (i.e., mean minimum daily temperature below 1°C in the preceding 2 days before the storm; Figure S2).

2.2 | Hydrometric data

High resolution, 15-min rainfall data were compiled from two precipitation gauges to create a time series of precipitation for the period of study (1958–2017). These precipitation data have been collected at

TABLE 1 Description of forest management techniques and physical attributes of study watersheds (WS) for the period of study (1958–2017)

WS	Area (ha)	Elevation range (m)	Forest treatment[a] date and age in 2020	Logging method	Pre- and post-treatment years of record[b]
01	95.9	439–1027	100% clearcut 1962–1966, broadcast burn 1966, 53 years	100% skyline yarded	1958–1961 (4): 1967–2017 (51)
02	60.7	545–1079	Reference, 175–500 years	N/A	NA
03[c]	101.2	471–1080	Roads 1959 (3.0 km/km^{-2}). 25% patch cut 1963, broadcast burn 1963, 56 years	25% high-lead cable yarded	1958–1962 (5): 1964–2017 (54)
06	13	878–1029	Roads 1974 (4.6 km/km^{-2}). 100% clearcut 1974, broadcast burn 1975, 45 years	90% high-lead cable yarded, 10% tractor yarded	1964–1973 (10): 1975–2017 (43)
07[d]	15.4	918–1102	Roads 1974 (1.5 km/km^{-2}). 60% shelterwood cut 1974, broadcast burn lower half of basin 1975, remaining overstory cut 1984, 12% basal area thin 2001, 46 years	40% skyline, 60% tractor yarded	1964–1973 (10): 1975–2017 (43)
08	21.4	962–1182	Reference, 175–500 years	N/A	N/A
09	9.0	424–733	Reference, 125–500 years	N/A	N/A
10	10	461–679	100% clearcut 1975, no burn, 45 y	100% high-lead cable yarded	1969–1974 (6): 1976–2017 (42)

[a]Road density is indicated (Jones, 2000).
[b]Although some streamflow records began in 1952, precipitation records began in 1958, so that is the earliest date for this study.
[c]Because matched precipitation and streamflow data began in 1958, analyses for WS 03 used 1958–1962 as the reference period. Therefore, analyses for WS 03 examine the effect of patch cutting relative to the period with roads.
[d]Analyses are based on time since the first treatment in WS 07 in 1974.

the Andrews Forest starting in the 1958 water year at the Climatic Station near WS 02 (CS2MET) and in 1979 at the Primary Meteorological Station (PRIMET; Figure 2; Table S1). To compensate for missing data and effects of sensor replacement, the precipitation time series was compiled from CS2MET (water years 1958–1994) and PRIMET (water years 1995–2017; Crampe, 2020). High resolution, 15-min discharge data were also compiled for all watersheds (Johnson et al., 2019). Missing data were infrequent, except for WS 07, which lacked data between 1988 and 1994. Changes in gauging made it impractical to determine the pre-treatment relationship between WS 09 and WS 10, thus WS 02 was used as the reference for WS 10 as in Jones (2000).

2.3 | Seasonal event-based runoff coefficients

Runoff coefficients for quickflow and delayed flow were calculated for each event and averaged by season and water year. Seasons were fall (September–November), winter (December–February), and spring (March–May), consistent with prior studies (Jones, 2000). Summer (June–August) was not included in this analysis because of the limited number of storms during these dry months.

Prior studies at this and other sites defined the beginning of each event based on a threshold of precipitation or streamflow after some time interval of zero or low precipitation, and the end of each event based either on a pre-determined time interval or the beginning of the next event (McGuire & McDonnell, 2010; Penna et al., 2011, 2016; van Verseveld et al., 2009). In this study, an event was defined as >20 mm of precipitation accumulated after an interval of >24 h of no precipitation. Runoff coefficients were calculated as the total accumulated (area weighted) quickflow (Q_F) or delayed flow (Q_D) divided by the total accumulated precipitation (P) in each event:

$$R = \frac{Q_F}{P} \text{ or } R = \frac{Q_D}{P} \quad (1)$$

The start time of the event was defined from the first positive value of precipitation. The end of the event was defined as the 15-min time step just prior to the onset of the next precipitation event. Hence, the entire time series was divided into a series of events. Events that according to our definition were longer than 30 days were not included in the analysis. This resulted in a sample of 1276 events (1222 in fall, winter, and spring, and 54 in the summer). The analysis considered only fall, winter, and spring events, producing a grand total of 8681 events analysed across all seven watersheds for their periods of record. Our results were not significantly altered when events were defined differently by ending each event 24 h after the last pulse of precipitation (Table S2).

Delayed flow was defined as the lowest discharge value throughout the event, and quickflow (Q_F) was defined as the difference between total flow and delayed flow (Q_D; Figure 3). We tested two alternative hydrograph separation methods: Hewlett and Hibbert (1967) (hereafter 'H&H'), and the more complex scheme of Chapman and Maxwell (1996) (hereafter 'C&M'). The three methods produced similar

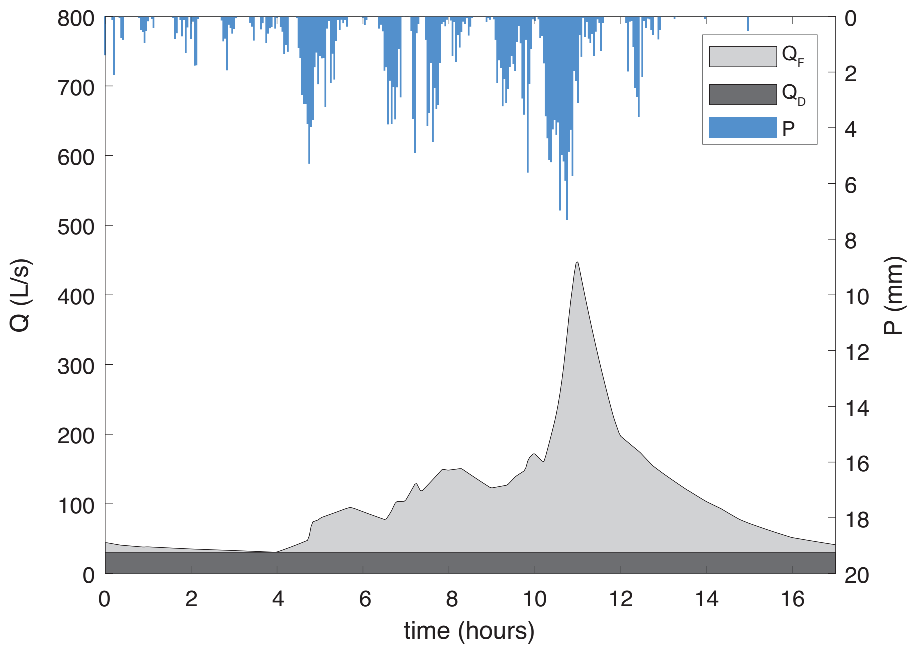

FIGURE 3 Example of hydrograph separation for an event. The discharge is separated into quickflow (Q_F) and delayed flow (Q_D). Precipitation input is in blue. The quickflow runoff coefficient is $= \frac{Q_F}{P}$ and the delayed flow runoff coefficient is $= \frac{Q_D}{P}$

runoff coefficients in the fall, and our method and the C&M method produced similar runoff coefficients in winter and spring (Figures S3–S5 and Table S3). Although both our method and H&H used a horizontal line as the basis for flow separation, the use of the start of the event in H&H versus the use of the lowest flow in our method produced larger quickflow runoff coefficients in our method for events with high streamflow at the beginning of the event (Figure S6). Although the C&M method produced similar runoff coefficients to our method, the use of a pre-set fraction of streamflow at the onset of the flow in the C&M method produced higher quickflow runoff coefficients than our method when the lowest flow in the event exceeded the C&M pre-set fraction (Figure S7).

The effect of the treatment was estimated by comparing the relationship of streamflow at the treated versus reference watersheds between the pre-treatment and post-treatment periods, consistent with previous studies (Jones, 2000; Jones & Grant, 1996; Jones & Post, 2004; Perry & Jones, 2017; Segura et al., 2020). The pre-treatment relationship (R_P) was defined as the average of the ratios of runoff coefficients (for quickflow and for delayed flow) for the treated (R_T) and reference (R_R) watersheds for all events (i) in the pre-treatment period:

$$R_P = \overline{\left(\frac{R_{Ti}}{R_{Ri}}\right)} \tag{2}$$

A pre-treatment ratio R_P was determined for each season (fall, winter, and spring). The treatment effect for each post-treatment event, R_i, was defined as the percent difference of the ratio of the treated versus reference runoff coefficients for each event i relative to the pre-treatment ratio R_P:

$$R_i = 100 \times \left[\left(\frac{R_{Ti}}{R_{Ri}} - R_P\right) \div R_P\right] \tag{3}$$

where $\frac{R_{Ti}}{R_{Ri}}$ is the ratio of the runoff coefficients for event i in the treated watershed (R_{Ti}) and the reference watershed (R_{Ri}). Values of R_i for both quickflow and delayed flow were calculated for all events i for all treated-reference watershed pairs. WS 02 was the reference for WS 01, 03, and 10; WS 08 was the reference for WS 06 and 07 (Table 1). Averages of R_i were computed for each season of each water year by decade for the post-harvest period. Values of that were persistent and non-random exceedances of the interquartile range (25th and 75th percentiles) of R_i for quickflow and delayed flow during the post-treatment period were interpreted to represent a significant effect. The distributions of quickflow R_P and delayed flow R_P of each watershed pair were not normally distributed (Figures S8 and S9). Temporal trends in the runoff coefficients for reference watersheds were analysed using the Mann-Kendall test (Mann, 1945) and Sen slope (Sen, 1968) in Matlab (Burkey, 2006) to test for stationarity of the reference watersheds.

3 | RESULTS

3.1 | Characteristics of precipitation events, quickflow, and runoff coefficients at reference watersheds

Event size and duration in winter and spring did not change over the study period (1958–2017), but fall event size ($\tau = -0.2$, *p-value* $= 0.02$) and duration ($\tau = -0.176$, *p-value* $= 0.05$) declined significantly (Figure S10). Precipitation event size varied by season and was greatest in December (Figure 4). Precipitation events were most frequent in November (>50% of fall events, or 195 out of 380 events) and least frequent in September (59 events, 5%). Precipitation events

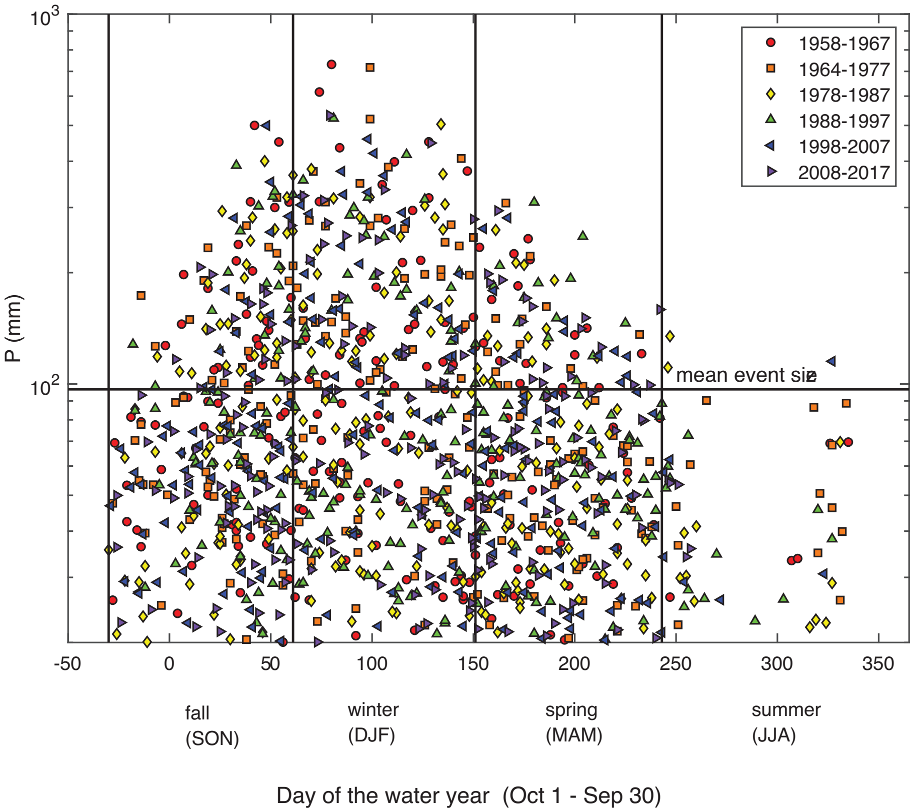

FIGURE 4 Size of precipitation events used in the analysis by Julian day on a water year basis (Julian day 1 = October 1)

smaller than the mean (864 out of 1276 across all seasons) were more frequent in the fall (261 events, 69% of fall events) and spring (303 events, 77% of spring events) than in the winter (249 events, 55% of winter events; Figure 4).

Quickflow (Q_F) at the reference watersheds varied by season and was highest in the winter (Figure S11). Quickflow distributions were very similar among the three reference watersheds (Figure S11). Large events (Q_F > 100 mm) were rare, representing <10% of events at WS 02, 9% at WS 08, and 11% at WS 09, and more than two-thirds of these events occurred in winter. Small events (Q_F < 10 mm) were common, representing 46% of events at WS 02, 47% at WS 08, and 39% at WS 09, as were intermediate size events (Q_F 10–100 mm), representing 44% of events at WS 02, 44% events at WS 08, and 50% events at WS 09. Small and intermediate events were evenly distributed among fall, winter, and spring. Seasonal runoff coefficients in the reference watersheds of the Andrews Forest (WS 02, 08, and 09) were stationary over the period of study (1958–2017; Figure 5).

3.2 | Quickflow responses in paired watersheds

Quickflow runoff coefficients in the fall increased significantly, and more than in winter or spring, in all watersheds in the first decade after harvest of old-growth forest (Table 2 and Figure 6). In 100% clearcut and burned watersheds (WS 01 and WS 06), fall quickflow increased by 88%–99% in the first decade, declined to 19%–40% in the second decade, and fell below pre-retreatment levels to −7% or −15% in the third to fifth decades. In the clearcut watershed that was not burned (WS 10) fall quickflow increased less (49%) in the first decade but also fell below pre-treatment levels to −10% to −15% by the third and fourth decade. In the shelterwood watershed (WS 07), fall quickflow increased by 66% in the first decade after the shelterwood cut, 65% after removal of the overstory, and 33% and 12% in the third and fourth decades respectively. In the 25% patch cut watershed with roads (WS 03), fall quickflow increased by 35% in the first decade, 14% in the second decade, and 7%–8% in the third and fifth decades (Table 2 and Figure 6).

Quickflow runoff coefficients in the winter also increased significantly, but less than in fall or spring, in all watersheds in the first decade after harvest of old-growth forest (Table 2 and Figure 6). In 100% clearcut watersheds (WS 01, WS 06, and WS 10) winter quickflow increased by 23%–26% in the first decade, 26%–38% in the second decade, 18%–21% in the third decade, 15% (at WS 06 only) in the fourth decade, and 7%–16% (at WS 06 and WS 10 only) in the fifth decade. In the shelterwood watershed (WS 07), winter quickflow increased by 18% in the first decade after the shelterwood cut, 42% after removal of the overstory, and 21% and 9% in the third and fourth decades respectively. In the 25% patch cut watershed with roads (WS 03), winter quickflow increased by 7%–12% in the first three decades and by 22%–23% in the fourth and fifth decades.

Quickflow runoff coefficients in the spring also increased significantly, more than in winter but less than in fall, in all watersheds in the first decade after harvest of old-growth forest (Table 2 and Figure 6). In 100% clearcut watersheds (WS 01, WS 06, and WS 10), spring quickflow increased by 40%–70% in the first decade, 44%–65% in the second decade, 26%–38% in the third decade, 26%–32%

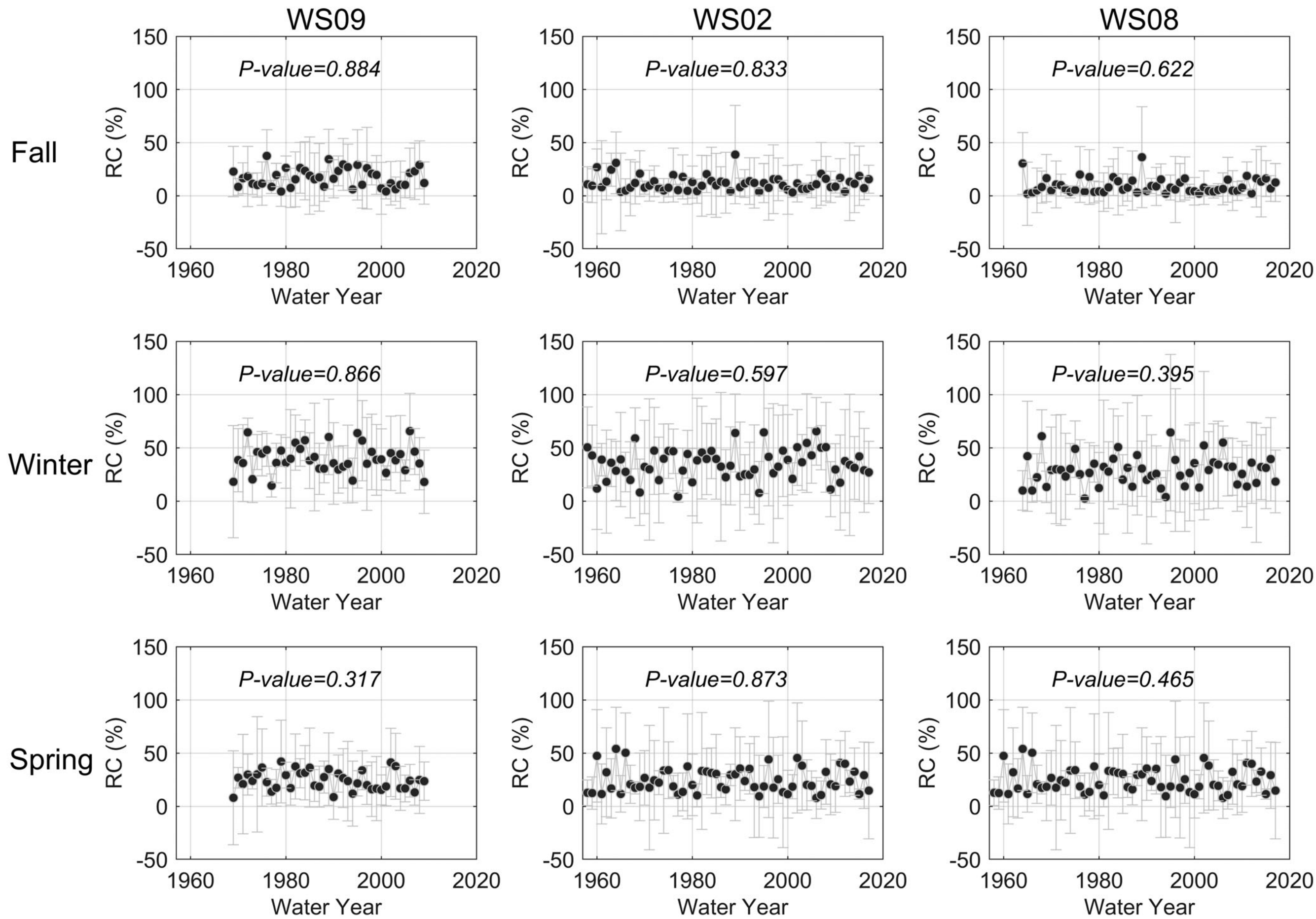

FIGURE 5 Mean annual event-based runoff coefficient for three seasons (fall, winter, and spring) for the reference watersheds (WS 09, WS 02, and WS 08) through the available record. The error bars correspond to interquartile ranges. *p*-Values of the relationship between median runoff coefficient and water year are provided. The trend was analysed with the Mann-Kendall test (Mann, 1945) and Sen slope (Sen, 1968) in Matlab (Burkey, 2006). $p > 0.05$ indicates that the null hypothesis of no time trend cannot be rejected

in the fourth decade (at WS 06 and WS 10 only), and up to 23% in the fifth decade (at WS 10 only). In the shelterwood watershed (WS 07), spring quickflow increased by 39% in the first decade after the shelterwood cut, 40% after removal of the overstory, and 24% and 15% in the third and fourth decades, respectively. In the 25% patch cut watershed (WS 03) with roads, spring quickflow increased by 13%–22% in the first three decades, and 20%–27% in the fourth and fifth decades (Table 2 and Figure 6).

3.3 | Delayed flow and total flow responses in paired watersheds

Quickflow and delayed flow responded differently over time and by season in all watersheds except a 100% clearcut, burned watershed at low elevation (WS 01), in which temporal patterns of quickflow and delayed flow were similar (Tables 2 and 3 and Figure 7; Figures S12–S14). In the fall season, delayed flow increased more (55%–161%) than quickflow (35% and 99%) in the first decade, and then fell below pre-treatment levels (−31% to −48%) in all watersheds in the fourth and fifth decades (except in WS 10 in the fifth decade; Table 3 and Figure 7; Figure S14). In small, 100% clearcut watersheds that were burned (WS 06) and not burned (WS 10), delayed flow in the fall initially increased more than quickflow, and fell below pre-treatment levels by the third decade, whereas delayed flow in the spring increased less than quickflow and did not fall below pre-treatment levels (Tables 2 and 3 and Figure 7). In the high elevation clearcut (WS 06) and shelterwood cut (WS 07) watersheds, delayed flow increased less than quickflow in the second to fifth decades in both winter and spring, and in the shelterwood cut (WS 07), delayed flow in winter and spring fell below pre-treatment levels by the fifth decade (Figure 7). In contrast, in the 25% patch cut watershed with roads (WS 03), the change in quickflow became larger than that for delayed flow in winter and spring of the fourth and fifth decades (Figure 7).

4 | DISCUSSION

Many studies have been published about the paired-watershed experiments at the Andrews Forest, and, like all long-term catchment studies, these experiments continue to provide valuable new insights in

TABLE 2 Average percent change of the ratio of the treated versus reference quickflow runoff coefficients for each event relative to the pre-treatment ratio by season and decade for five watershed pairs

		Pre-treatment				R_i, % change relative to pre-treatment period, by decade after treatment					No. of events per 10-year increment					
Season	**WS**	R_P	R_{P25}	R_{P75}	*n*	0–10	11–20	21–30	31–40	41–50	0–10	11–20	21–30	31–40	41–50	*N*, *N′*
Fall	01	1.0	−7.7	5.8	24	**99**	**40**	**32**	2	**−9**	59	68	55	68	69	50, 45
	03	1.1	−7.5	3.7	33	**35**	**14**	**8**	−1	**7**	60	59	59	63	75	50, 37
	06	0.7	−7.4	5.7	60	**88**	**19**	**−8**	**−15**	**−7**	62	55	70	70	21	43, 37
	07[a]	0.5	−12.4	8.7	60	**66**	**65**	**33**	**12**	6	62	20	70	70	21	36, 30
	10	1.5	−8.4	3.7	35	**49**	6	**−15**	**−10**	3	66	55	67	71	14	42, 35
Winter	01	1.3	−15.5	14.2	31	**23**	**38**	**21**	12	−10	56	71	75	73	75	50, 31
	03	1.0	−11.4	6.7	40	**12**	**10**	**7**	**22**	**23**	69	71	70	79	71	49, 32
	06	1.0	−8.1	3.1	76	**24**	**35**	**18**	**15**	**7**	41	71	79	68	30	43, 39
	07[a]	0.7	−6.0	7.9	76	**18**	**42**	**21**	**9**	5	41	71	27	68	30	36, 27
	10	1.6	−8.5	11.6	47	**26**	**26**	**21**	11	**16**	37	74	77	70	22	42, 31
Spring	01	1.1	−15.5	14.2	26	**50**	**65**	**38**	12	−10	62	65	70	67	75	50, 38
	03	0.9	−11.4	6.7	31	**22**	**13**	**19**	**20**	**27**	55	62	69	68	78	49, 42
	06	0.9	−8.1	3.1	55	**40**	**44**	**26**	**26**	2	65	66	68	80	19	43, 38
	07[a]	0.7	−6.0	7.9	55	**39**	**40**	**24**	**15**	1	65	25	61	80	19	36, 23
	10	1.2	−8.5	11.6	38	**70**	**49**	**37**	**32**	**23**	63	71	68	76	14	42, 39

Note: For each season and pair of treated and reference watersheds, columns show the pre-treatment average runoff coefficient ratio (R_P), the 25th and 75th percentiles of its distribution (R_{P25} and R_{P75}) and number of events (*n*); the average percent change relative to the pre-treatment period (R_i) for 10 year intervals after the end of treatment; the number of events per decade; the number of years with data for the post-harvest period (*N*); and the number of years (*N′*) for which R_i is outside the confidence envelope of $R_{P25} < R_P < R_{P75}$. Bold font = percent changes outside the envelope.

[a]The second decade in WS 07 corresponds to the first decade after 100% clearcutting (Table 1).

hydrology. The novel contributions of this study are (1) the use of runoff coefficients, which enabled separate detection of trends in event precipitation as well as changes in runoff response to precipitation and forestry treatments; (2) separation of event streamflow into quickflow and delayed flow, which enabled interpretations about changes in flow partitioning; and (3) extension of the analysed record to include the third to fifth decade of growth of planted forests in the treated watersheds. Here we focus principally on the insights from these novel analyses.

Experimental treatments, including clearcutting, roads, and growth of planted forests over the 50-year study period provided the opportunity to evaluate several hydrologic mechanisms and their interactions with seasonal variation and long-term trends in precipitation amount and form (rain vs. snow; Figure 1). Old-growth forests have very high leaf area (Marshall & Waring, 1986) and associated high interception capacity compared to young forest (Pypker et al., 2005, 2006b). The much lower leaf area just after clearcutting initially increases soil moisture, especially in fall and winter (Adams et al., 1991). Reduced interception leads to greater snow accumulation and more rapid snowmelt in canopy openings than under forest in this region, and therefore clearcutting enhances rain-on-snow floods (Harr, 1986; Jennings & Jones, 2015; Jones & Perkins, 2010; Marks et al., 1998). However, as densely planted young forests grow over 40–50 years, interception capacity increases and rates of transpiration exceed those in the old-growth reference watersheds during spring, summer, and early fall (Moore et al., 2004). These changes progressively create soil moisture deficits that develop over 20–50 years after clearcutting, especially in spring, summer, and fall in this seasonally dry climate (Perry & Jones, 2017; Segura et al., 2020). In addition, the construction of forest roads in WS 03, WS 06, and WS 07, and subsequent road-related debris flows in WS 03 (Fredriksen, 1963, 1965, 1970; Wemple et al., 2001) provided the opportunity to evaluate multi-decade effects of roads on flow routing and streamflow events (Jones, 2000; Wemple & Jones, 2003). Multi-decade reductions in snowpack in the region (Mote et al., 2018) might also affect winter and spring runoff in reference and treated watersheds.

Although the results of this study were consistent with prior studies for the first 25 years after clearcutting (Jones, 2000; Jones & Grant, 1996), several previously undocumented responses emerged in the third to fifth decades after treatment, including apparent effects of forest growth on canopy interception and transpiration, as well as effects of roads and major floods on flow routing.

4.1 | Effects of forest growth

Planted Douglas-fir forests grew to 50 years of age during the study, and event runoff remained distinct from those in the reference watersheds, which contain mature and old-growth forests (175–500 years of age). Several lines of evidence suggest that 30 to 50-year-old forests intercept and transpire more water than mature and old forests, depleting soil moisture, and reducing streamflow. These lines of

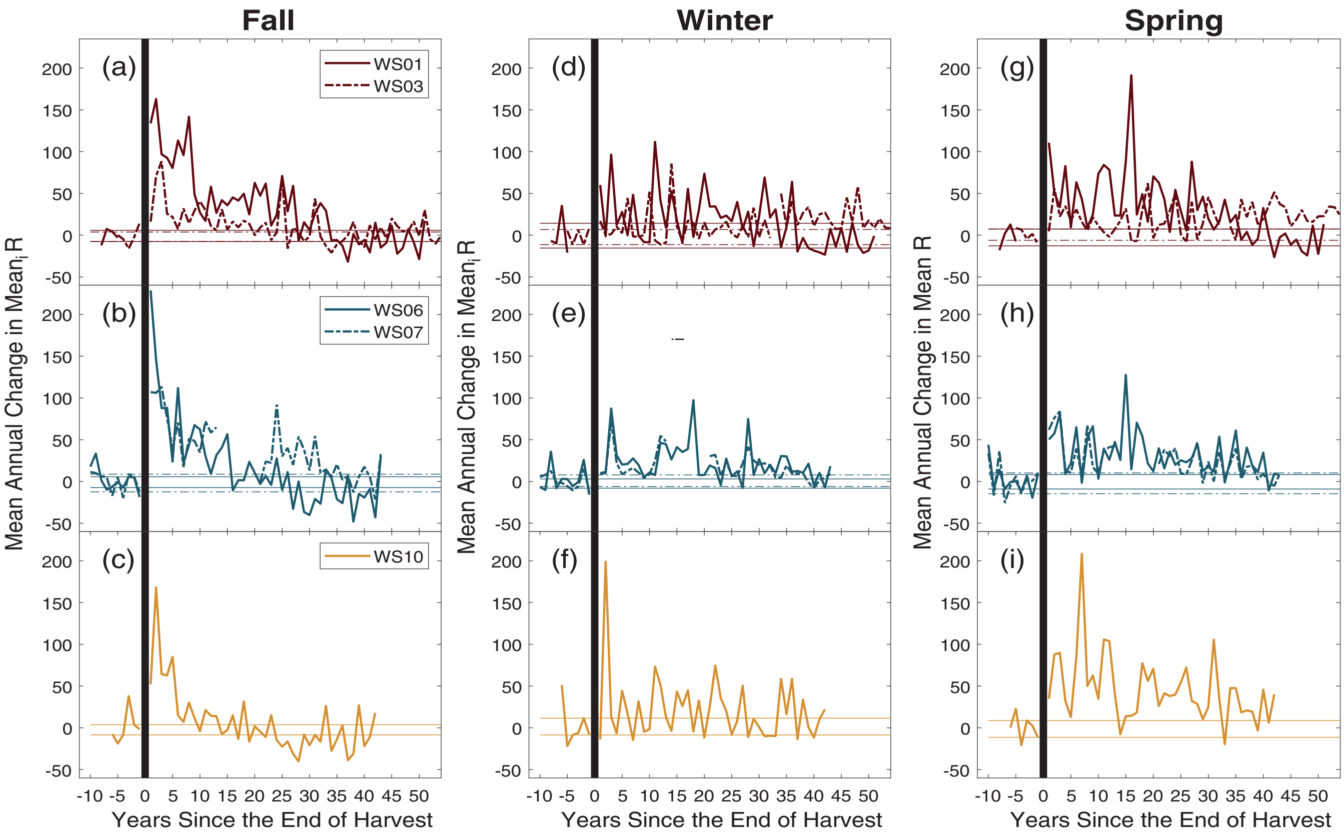

FIGURE 6 Change in mean annual quickflow R_i (% difference of the ratio of the treated vs. reference runoff coefficients for each event *i* relative to the pre-treatment ratio) through time for five watershed pairs. The *x*-axis is years since the end of the harvesting period (Table 1). Watersheds that were clearcut (WS 01, WS 06, and WS 10) are shown with a solid line, while those that were patch cut (WS 03 and WS 07) are shown in dashed lines. Panels (a)–(c) correspond to the fall season, panels (d)–(f) correspond to the winter season, and panels (g)–(i) correspond to the spring season. Horizontal lines indicate the CI: 25th and 75th percentile of the pre-treatment event runoff coefficient distribution (Table 2; Figure S8), with solid lines for clearcut watersheds and dashed lines for patch cuts. Detailed plots for each catchment pair and each season are included in the Supporting Information section (Figures S15–S29)

evidence include: (1) the progressive reduction of quickflow and the even more rapid reduction of delayed flow in the fall to below pre-treatment levels in the third to fifth decade after 100% clearcutting (WS 01, WS 06, WS 10) or shelterwood followed by removal of the remainder of the canopy (WS 07); (2) the faster reversal of quickflow in the fall from surplus to deficit in WS 06, where planted forests have grown more rapidly and have larger basal area (Perry & Jones, 2017) compared to WS 01; and (3) the smaller initial response of fall quickflow after clearcutting in WS 10, where no slash burning was conducted and residual shrubs and small deciduous trees sprouted abundantly compared to WS 01 and WS 06, which were burned after clearcutting. These observations are supported by detailed long-term studies in these watersheds documenting vegetation basal area, species composition, and post-clearcut succession (Halpern & Lutz, 2013; Lutz & Halpern, 2006), mechanistic studies of transpiration in conifers and deciduous trees (Moore et al., 2011), and models of hydrologic and climate effects on carbon assimilation (Emmingham & Waring, 1977). Several recent studies have documented the progressive development of deficits in summer daily flow in watersheds with 30 to 50-year-old forests (Gronsdahl et al., 2019; Perry & Jones, 2017; Segura et al., 2020). Collectively these findings imply that planted forests increasingly deplete deep soil moisture or prevent soil moisture recharge, especially in the relatively dry summer and fall in this marine west-coast climate. These effects may have been compounded by a long-term reduction in precipitation event size in the fall, shown in this study.

In the upper-elevation watersheds, forest growth appears to have modified interception and transpiration, and interacted with the seasonal snowpack, producing distinct responses of runoff in these watersheds (100% clearcut, WS 06, and shelterwood with complete canopy removal, WS 07) compared to 100% clearcut watersheds at low elevation where snowpack is transient (WS 01, WS 10). The initial increase and gradual reduction in quickflow in winter and spring in WS 06 and WS 07 over four or five decades is consistent with the interpretation that greater snowpack accumulation and more rapid melt in canopy gaps enhances winter event runoff (Berris & Harr, 1987; Harr, 1986; Jennings & Jones, 2015; Marks et al., 1998), and that this effect would diminish as the increasingly dense canopies of 30 to 50-year-old forest intercept and sublimate more snow than the mature and old-growth reference. However, above-zero daytime temperatures in winter and spring throughout the study period

TABLE 3 Average percent change of the ratio of the treated versus reference delayed flow runoff coefficients for each event relative to the pre-treatment ratio by season and decade for five watershed pairs

		Pre-treatment				R_i, % change relative to pre-treatment period, by decade after treatment					No. of events per 10-year increment					
Season	WS	R_P	R_{P25}	R_{P75}	n	0–10	11–20	21–30	31–40	41–50	0–10	11–20	21–30	31–40	41–50	N, N′
Fall	01	0.85	−20.6	27.6	24	**114**	**23**	**56**	**−31**	**−38**	59	68	55	68	69	50, 38
	03	1.63	−25.6	22.0	33	**86**	4	**73**	−15	**−34**	60	59	59	63	75	50, 33
	06	1.17	−9.4	7.6	60	**161**	**79**	**−18**	**−44**	**−44**	62	55	70	70	21	43, 41
	07[a]	1.20	−34.8	29.5	60	**55**	28	−3	−28	**−36**	62	20	70	70	21	36, 16
	10	0.85	−15.4	27.9	35	**114**	16	**−38**	**−48**	**−18**	66	55	67	71	14	42, 34
Winter	01	0.69	−6.2	5.8	31	**22**	**35**	**46**	5	−3	56	71	75	73	75	50, 42
	03	0.93	−4.4	3.5	40	**9**	**7**	**16**	**5**	**10**	69	71	70	79	71	49, 42
	06	1.50	−17.1	−2.5	76	**40**	**23**	**1**	−9	−7	41	71	79	68	30	43, 33
	07[a]	1.00	−13.6	0.9	76	**23**	**11**	**1**	−11	**−16**	41	71	27	68	30	36, 16
	10	0.83	−9.8	9.7	47	**31**	**18**	−4	−2	−2	37	74	77	70	22	42, 26
Spring	01	0.63	−6.2	5.8	26	**43**	**42**	**32**	**10**	0	62	65	70	67	75	50, 44
	03	0.93	−4.4	3.5	31	**32**	**9**	**21**	**5**	**4**	55	62	69	68	78	49, 36
	06	1.28	−17.1	−2.5	55	**30**	**39**	**16**	**3**	**−3**	65	66	68	80	19	43, 35
	07[a]	0.95	−13.6	0.9	55	**10**	**7**	**5**	−6	**−14**	65	25	61	80	19	36, 21
	10	0.75	−9.8	9.7	38	**18**	8	5	3	6	63	71	68	76	14	42, 32

Note: For each season and pair of treated and reference watersheds, columns show the pre-treatment average runoff coefficient ratio (R_P), the 25th and 75th percentiles of its distribution (R_{P25} and R_{P75}) and number of events (*n*); the average percent change relative to the pre-treatment period (R_i) for 10 year intervals after the end of treatment; the number of events per decade; the number of years with data for the post-harvest period (*N*); and the number of years (*N*′) for which R_i is outside the confidence envelope of $R_{P25} < R_P < R_{P75}$. Bold font = percent changes outside the envelope.
[a]The second decade in WS 07 corresponds to the first decade after 100% clearcutting (Table 1).

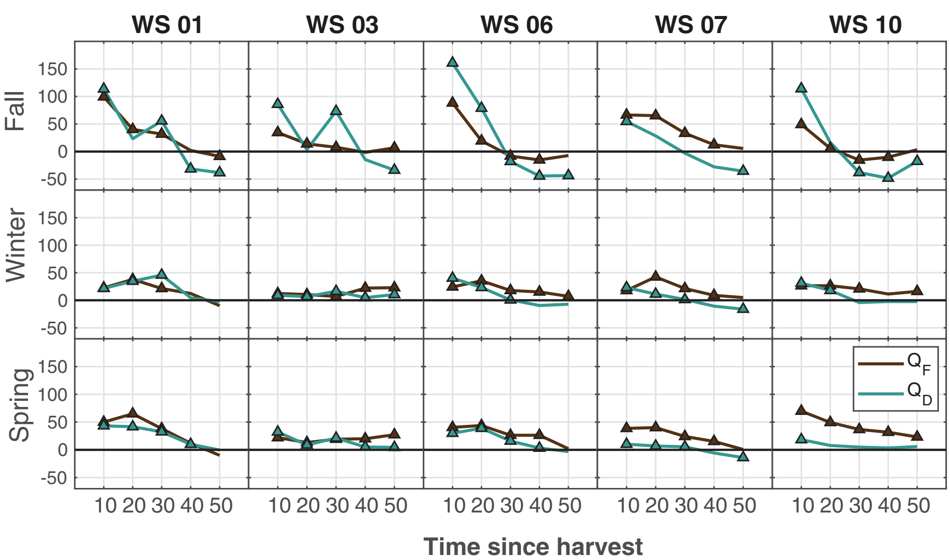

FIGURE 7 Decadal change in R_i (% difference of the ratio of the treated vs. reference runoff coefficients for each event *i* relative to the pre-treatment ratio) based on quickflow (Q_F) and delayed flow (Q_D) through time for five watershed pairs in three seasons. The *x*-axis is years since the end of the harvesting period. WS 01, WS 06, and WS 10 were clearcut, while WS 03 and WS 07 were patch cut. Triangles indicate significant differences compared to the pre-treatment period (i.e., outside the 25th and 75th percentile confidence interval; Tables 2–3)

enabled conifers to photosynthesize and transpire in winter, even in the seasonal snow zone (Emmingham & Waring, 1977). Hence, increases in both transpiration and interception may account for the smaller increases in winter and spring delayed flow compared to quickflow in the upper-elevation watersheds in the seasonal snow zone (WS 06 and WS 07), compared to a lower-elevation watershed in the transient snow zone (WS 01).

4.2 | Legacy effects of clearcutting and roads

The construction of roads, which is commonly associated with logging, exacerbated runoff response to patch-clearcutting in all seasons. Multiple lines of evidence indicate that the construction of roads modifies flow routing, and that roads interact with major floods, producing landslides that can scour channels, leading to multi-decade, intensifying effects of road construction on runoff. These lines of evidence include (1) runoff increases in the 25% patch cut watershed with roads (WS 03) were larger than expected relative to responses in the 100% clearcut watershed without roads (WS 01; Jones & Grant, 1996); (2) after road-related debris flows were initiated soon after the flood of record in 1996, quickflow increases in winter and spring became larger in the fourth and fifth decades in the patch-cut watershed with roads (WS 03), whereas they declined in 100% clearcut watersheds without roads (WS 01, WS 10). These observations are supported by mechanistic and observational studies documenting several episodes of post-road construction debris flows that scoured much of the stream channel in WS 03 (Fredriksen, 1963, 1965, 1970; Snyder, 2000; Swanson et al., 1998; Wemple et al., 2001), as well as studies of road and culvert effects on flow routing and event hydrographs (Wemple et al., 1996; Wemple & Jones, 2003). Clearcutting and reduction in root strength also can contribute to increased debris flows, which occurred in 1986 and 1996 in WS 10 (Wemple et al., 2001), potentially contributing to persistent increases in winter and spring quickflow in the third to fifth decades in this watershed.

4.3 | Geomorphic and ecological consequences of elevated quickflow

Persistent increases in quickflow runoff in winter and spring through the fourth or fifth decade after clearcutting or partial harvest in almost all watersheds have significant implications for the geomorphology and stream ecology of these small streams, even though many of the events that remained elevated were not large floods. Early research asserted that most geomorphic work is accomplished by a dominant discharge (Knighton, 1998) or effective discharge (Dunne & Leopold, 1978; Wolman & Miller, 1960), which was often assumed to be approximately equivalent to the bankfull discharge. However, flows of many different sizes can carry sediment (Segura & Pitlick, 2010). Indeed, flows above the mean annual flow often carry 80% of the annual discharge and most of the bed load in gravel bed channels (Andrews, 1994; Mueller & Pitlick, 2005; Torizzo & Pitlick, 2004; Whiting et al., 1999). In fact, given the heterogeneous forces and grain sizes in the channel bed of alluvial rivers, a portion of the channel bed is mobilized even at moderate flows (Monsalve et al., 2020; Segura & Pitlick, 2015). These findings indicate that the long-term effects of clearcutting and planted forests on streamflow and resulting sediment movement are relevant to ecological processes such as primary production (Katz et al., 2018; Segura et al., 2011), fish habitat (Gronsdahl et al., 2019), and available habitat for aquatic ecosystems (Ward et al., 2020).

4.4 | Implications for hydrologic recovery

The continued, distinct streamflow responses in planted Douglas-fir forests over 50 years relative to the reference mature and old-growth forests (175–500 years of age) raises questions about when, or if, hydrologic processes in planted forests will become similar to those of the mature and old-growth reference forests. Little or no evidence of hydrologic recovery was observed. Rather, clearcutting of old-growth forest and road construction impose disturbances unlike natural disturbances such as wildfire or windthrow. These disturbances result in altered watershed response to extreme flood events, and trigger landslides and debris flows, which scour channels and alter the partitioning of precipitation into quickflow and delayed flow. Planting of trees sets in motion patterns of forest growth that are unlike natural regeneration after natural disturbances, producing young forests whose rates of transpiration and interception are capable of reducing runoff below pre-harvest levels in fall, winter, and spring.

Over multiple decades, the scope of long-term watershed studies is evolving and expanding, as knowledge grows about ecosystems. Long-term watershed studies are revealing the multi-decadal interaction of forest disturbance with regional nitrogen deposition (Oda et al., 2018), the effects of invasive insect outbreaks on streamflow (Brantley et al., 2015), and how streamflow responds to climate change (Caldwell et al., 2016; Creed et al., 2014). The responses we see are not recovery; instead, these watersheds and the ecosystems within them are headed off into some new states which differ from the pre-treatment conditions or the current condition of the reference watersheds.

The 70-year-old experiment at the Andrews Forest continues to provide insight about the long-term effects of forest disturbance based not only on the analysis of hydrometric data, but, as illustrated above, on accompanying mechanistic studies, which enable generalizations beyond the specific site (McDonnell et al., 2018). The distinctive responses of delayed flow and quickflow, which are new findings of this study, focus attention on the need for improved quantification of the temporal–spatial variability of below-ground water storage, a topic that remains elusive in forested environments. Further studies are needed to assess how factors such as geology, geomorphology, and snow affect water flow pathways and water transit times (Segura et al., 2019). Work is also needed to quantify how young forests (30–50 years old) partition water into interception, transpiration, quickflow and delayed flow, in order to close the water balance and, ultimately, to predict the tradeoffs between wood production and water availability to downstream communities and ecosystems. To start addressing these questions, experiments are needed to characterize water in different pools (e.g., precipitation, streamflow, ground water) through the use of tracers such as water stable isotopes, which can quantify the elusive underground storage capacity. However, our aim must be to go beyond the computation of metrics such as the mean transit time (McGuire & McDonnell, 2006) or the fraction of young water (Kirchner, 2016) to find explicit mechanistic links between physiographic drivers of water movement and water storage in the landscape.

5 | CONCLUSION

The analysis of the seasonal variability in quickflow and delayed flow over 50 years in five treated watersheds revealed initial increases in quickflow of up to 99% in the fall, 42% in the winter, and 70% in the spring. Over the subsequent five decades, quickflow runoff in the fall decreased to levels below pre-harvest (−1% to −15%) by the third to fifth decade, apparently as the result of increased evapotranspiration in planted forests. The delayed flow response after treatment was similar but changed faster, reaching significant declines by the fifth decade in all watersheds, suggesting persistent decline in groundwater recharge. Quickflow in the winter and spring remained higher than pre-treatment (12%–70%) and larger than delayed flow in a high elevation watershed in which higher interception capacity of 30 to 50-year-old plantations appear to limit snow accumulation and groundwater recharge. The flood of record in the third decade after clearcutting and roads led to road-related debris flows, which modified hydrologic flow paths and increased quickflow—more than delayed flow—in the fourth and fifth decade after treatment. Collectively, these results indicate that streamflow in the treated watersheds is continuing to change in response to new and evolving factors, rather than returning to pre-treatment conditions.

It is often asked of long-term studies, 'When will this study end?' Although the watershed experiments at the H. J. Andrews Forest have been in place for nearly 70 years, the forests and streams continue to change and reveal unexpected hydrologic responses from clearcutting of old-growth forest, construction of roads, and growth of planted forests. Maintenance of these long-term experiments, and continued research on the resulting long-term data, provide important insights into hydrological processes that cannot be gained by other approaches and contribute key information for management and restoration of ecosystems.

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DATA AVAILABILITY STATEMENT

All the hydrometric data used in this study were provided by the H.J. Andrews Experimental Forest and Long Term Ecological Research program, administered cooperatively by the USDA Forest Service Pacific Northwest Research Station, Oregon State University, and the Willamette National Forest. These data are freely available from the H. J. Andrews Experimental Forest research program (http://andrewsforest.oregonstate.edu/).

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SUPPORTING INFORMATION

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

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