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LONG-TERM CHANGES IN STREAMFLOW FOLLOWING LOGGING IN WESTERN OREGON AND ASSOCIATED FISHERIES IMPLICATIONS[1]

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ABSTRACT: The long-term effect of logging on low summer streamflow was investigated with a data set of 36 years. Hydrologic records were analyzed for the period 1953 and 1988 from Watershed (WS) 1 (clearcut logged and burned), WS 2 (unlogged control), and WS 3 (25 percent patch-cut logged and burned) in the H. J. Andrews Experimental Forest, western Cascade Range, Oregon. These records spanned 9-10 years before logging, and 21-25 years after logging and burning. Streamflows in August were the lowest of any month, and were unaffected by occasional heavy rain that occurred at the beginning of summer. August streamflows increased in WS 1 compared to WS 2 by 159 percent following logging in WS 1, but this increase lasted for only eight years following the start of logging in 1962. Water yield in August for 1970-1988 observed from WS 1 was 25 percent less than predicted from the control (WS 2, ANOVA, $p=0.032$).

Water yield in August increased by 59 percent after 25 percent of the area of WS 3 was patch-cut logged and burned in 1963. In contrast to WS 1, however, water yields from WS 3 in August were consistently greater than predicted for 16 years following the start of logging, through to 1978. For the 10 years, 1979-1988, water yield observed in August from WS 3 was not different than predicted from the control (WS 2, ANOVA, p-0.175).

The contrasting responses of WS 1 and 3 to logging are thought to be the result of differences in riparian vegetation caused by different geomorphic conditions. A relatively wide valley floor in WS 1 allowed the development of hardwoods in the riparian zone following logging, but the narrow valley of WS 3 and limited sediment deposits prevented establishment of riparian hardwoods.

Low streamflows during summer have implications for salmonid survival. Reduced streamflow reduces the amount of rearing habitat, thus increasing competition. Combined with high water temperatures, reduced streamflow can lead directly to salmonid mortality by driving salmonids from riffles and glides, and trapping them in drying pools. Low streamflow also increases oxygen depletion caused by leaves from riparian red alders.

(KEY TERMS: streamflow; logging; salmonids; water use; water storage; evapotranspiration; dissolved oxygen.)

INTRODUCTION

Many studies have shown that removal of vegetation by clearcut logging results in increased annual water yield (e.g., Bosch and Hewlett, 1982; Harr, 1983). This increased streamflow is caused by reduction of the water loss associated with vegetation through interception, evaporation, and transpiration. It is generally assumed that some time after clearcut logging, annual water yields will approach prelogging values as vegetation regrows (Kovner, 1956; Rothacher, 1970). The rate of regrowth and concomitant reduction of water yield depends on a number of factors, among which are climate, plant species, soil, and altitude. Studies at the H. J. Andrews Experimental Forest in the Cascade Range of western Oregon (Figure 1) predicted that return of annual water yield to prelogging levels might take about 27 years in this environment (Equation 1, in Harr, 1983).

Whether water yield actually returns to the prelogging level, or to some level above or below it, has not previously be established in the Pacific Northwest of the U.S. Few studies have sufficiently long periods of observation with which to investigate long-term water yield following clearcut logging. In addition, short-duration studies have covered only the period of increased water yield immediately following logging (e.g., the Alsea Watershed Study, Harris, 1977), being terminated before regrowth of vegetation subsequently reduced logging-related flow increases to pretreatment levels. This study examines the long-term effect of timber harvest, taking into account the period of vegetative regrowth following logging.

In certain environments, water yields might decrease following logging. Instead of the expected increase, a small (<20 mm) decrease in annual water

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yield was observed after 25 percent of a watershed was patch-cut logged at Fox Creek, Bull Run Municipal Watershed, on the western slopes of Mt. Hood, Cascade Range, western Oregon (Harr, 1982). The experimental watersheds at Fox Creek extend in elevation from 840 to 1070 m, where fog is common. Interception of wind-blown fog by 46-55 m-tall conifers is an important source of moisture in the Fox Creek watersheds, and fog interception was reduced by removal of vegetation, thereby reducing the annual amount of moisture available at the soil surface (i.e., precipitation plus fog drip) by up to 30 percent compared to prelogging levels. Fog has also been shown to contribute significantly to annual precipitation in coastal forests in Oregon and northern California (Isaac, 1946; Azevedo and Morgan, 1974).

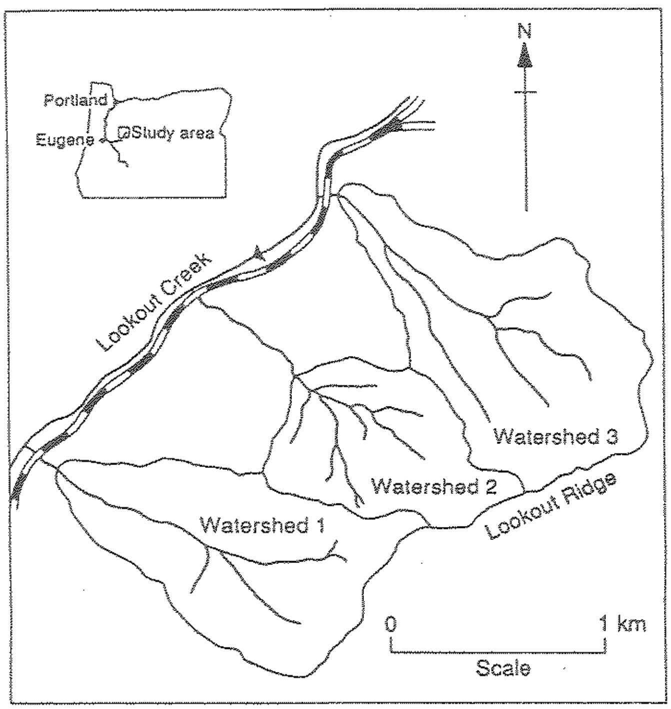

Figure 1. Location of Watersheds 1 and 2 in the H. J. Andrews Experimental Forest, Cascade Range, Oregon (after Rothacher *et al.*, 1967).

Forests have a substantial effect on water yield in environments other than fog zones. Interception of precipitation and transpiration by trees have a pronounced effect on water balance in regions with moderate to high annual precipitation (above about 1500 mm) and dry summers (Pearce and Rowe, 1979). Many of the production forests in western North America occupy such environments, and freshwater resources could be affected as second-growth forest replaces mature forest.

Diminishing water flows from June to September can adversely affect stream inhabitants. Even small reductions in water yield in summer can be detrimental to salmonids. Several studies have suggested that volume of summer rearing habitat is a significant factor affecting fish production (Smoker, 1953; Everest and Sedell, 1984; Elliott, 1985; Hicks, 1990). Also, when flow is reduced, stream temperatures may increase, causing increased stress, disease, and competition among fish. Temperatures preferred by rainbow trout (*Oncorhynchus mykiss*, formerly *Salmo gairdneri*), or optimum for their growth, range from 12 to 22°C. Temperatures of 25°C or above may be lethal (Cherry *et al.*, 1975). Increased yield of coarse sediment following logging can increase the effect of low flows, causing shallowing and widening of stream channels (Lyons and Beschta, 1983; Tripp and Poulin, 1986).

METHODS

Predicting the response of summertime streamflows to forest management activities requires a long period of record, preferably from paired watersheds. One of the few long-term records of changes in water yield from paired watersheds in an environment with moderate to high annual precipitation and dry summers comes from Watersheds (WS) 1, 2, and 3 of the H. J. Andrews Experimental Forest (Figure 1). The study basins have areas of 96 ha, 60 ha, and 101 ha, respectively, and are underlain by volcanic rocks, including andesite and basalt lava flows, and tuff breccias (Rothacher *et al.*, 1967). The watersheds range from 442 to 1082 m, at which elevation the vast majority of precipitation falls as rain (Rothacher *et al.*, 1967). Snow that does fall between 400 and 1100 m elevation in western Oregon is transient, usually melting in 3-4 days during subsequent rain (Harr, 1983), and thus is of little significance to summer streamflows.

Streamflows were calibrated by taking baseline measurements in the unlogged watersheds from 1953 to 1961 for WS 1, and from 1953 to 1962 for WS 3. Logging began in WS 1 in 1962, and continued until 1966. Remaining vegetation and logging slash in WS 1 was burned in October 1966 (Rothacher, 1970). In late 1962 and early 1963, 25 percent of the area of WS 3 was patch-cut logged, and these cleared patches were burned in September 1963. Watershed 2 remained unlogged as a control, with precipitation measured at a climate station in WS 2. Months were grouped by water year (October 1 to September 30) for analysis of streamflow and precipitation.

Water yields for WS 1, 2, and 3, analyzed by Harr (1983), were derived from data transcribed from continuous records using methods that visually estimated instantaneous flow from the water level traces (pers. comm., Don Henshaw, Pacific Northwest Research Station, Corvallis, Oregon). We have reanalyzed results from data digitally transcribed from the original records for part of the prelogging period (1953-1959), and we have added seven more years of data to the analysis of Harr (1983).

Data from the prelogging calibration period were used to relate annual and summer water yields in millimeters from WS 1 and 3 following timber harvest to water yield from the control watershed (WS 2). Calibration periods were nine years for WS 1 (1953-1961) and 10 years for WS 3 (1953-1962). Least-squares regression was used to derive the prelogging relationship between streamflows in WS 1 and 2, and between streamflows in WS 3 and 2. The linear model Y=a+bX was used, where Y=observed water yield from WS 1 or 3 (treated watersheds) and X=observed water yield from WS 2 (unlogged control). Observed water yield from WS 2 was then used to predict water yield expected from WS 1 and 3 before and after logging on the basis of the recalculated regression relationships in Table 1.

RESULTS

Water Yield After Logging

Slope and intercept for regression relationships between WS 1 and 2 from this analysis were very close to those calculated using the same methods by Harr (1983) for July to September (Table 1). The recalculated regressions of prelogging water yields for WS 1 on WS 2 were significant for all months and combinations of months (Table 1). Regression relations for prelogging water yields for WS 3 on WS 2 were also significant for all months and combinations of months, except for July. The regressions of total annual prelogging water yield for both WS 1 and WS 3 on WS 2 were also significant ($p<0.001$, Table 1).

The period of increased summer flow observed following the start of logging in WS 1 compared to the unlogged WS 2 was short-lived (about eight years,

TABLE 1. Results of Least-Squares Linear Regression Analysis of Summer and Annual Water Yields Before Logging for Watershed 1 (1953-1961) and Watershed 3 (1953-1962, depending variables, Y) on Watershed 2 (independent variable, X) in the H. J. Andrews Experimental Forest, Western Oregon Cascades (n=9 for WS 1, n=10 for WS 3). Results from Harr (1983) compared to those from this paper for digitized data. The model used is Y=a+bX.

Time Period	Slope (b)	Intercept (a)	r^2	Significance of Regression Model (p)
		WATERSHED 1 – Clearcut Logged (this paper)		
July	0.461	2.06	0.62	0.012
August	0.544	0.14	0.67	0.007
September	1.001	–2.60	0.89	<0.001
July to August	0.513	1.70	0.72	0.004
July to September	0.704	–2.84	0.80	0.001
Annual	0.944	–97.92	0.96	<0.001
		HARR (1983)		
July to September	0.731	–2.74	0.72	0.004
		WATERSHED 3 – 25 Percent Patch-Cut Logged (this paper)		
July	0.629	8.61	0.20	0.198
August	1.018	0.89	0.74	0.001
September	1.275	–0.14	0.92	<0.001
July to August	0.823	8.59	0.43	0.040
July to September	0.861	11.43	0.63	0.006
Annual	0.839	110.63	0.94	<0.001

Figure 2A). After 1970, observed water yield from WS 1 for August was generally less than that predicted from the model; reduced water yield has occurred for 18 of 19 years (1970-1988). In contrast to WS 1, however, water yields from WS 3 in August were consistently above predicted through 1978, 16 years after the start of logging (Figure 2B).

Differences between observed and predicted water yields for WS 1 were compared for three distinct periods of record (Table 2). The three periods were: (1) 1953-1961 (prelogging calibration), (2) 1962-1969 (the period of increased water yield that included logging and burning, and (3) 1970-1988 (the following 19 years of low water yield). Means were compared with single-classification ANOVA. Differences between observed and predicted water yields for WS 1 increased dramatically following clearcut logging for 1962-1969. The increase in water yield for August

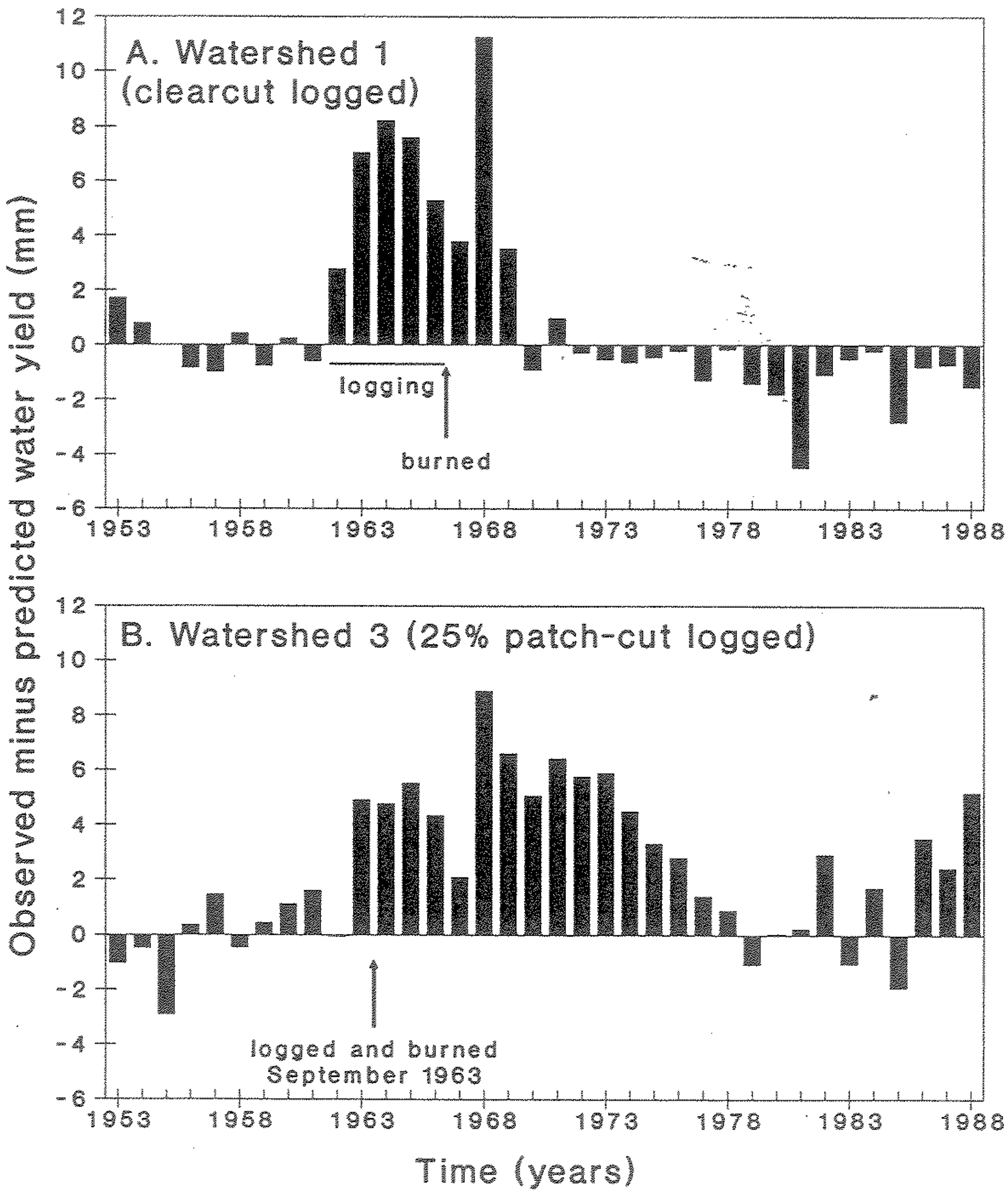

Figure 2. Differences Between Observed and Predicted Water Yield for August from Watershed 1 (A) and Watershed 3 (B) in H. J. Andrews Experimental Forest, Western Oregon Cascades, Before and After Logging (1953-1988).

TABLE 2. Means of Observed and Predicted Water Yields from Watersheds 1, 2, and 3 Before and After Logging (1953-1988) in the H. J. Andrews Experimental Forest, Western Oregon Cascades, for (A) Period of Prelogging Streamflow Calibration, (B) Period of Increased Water Yield During and Immediately Following Logging, and (C) Period of Reduced Water Yield Following Vegetative Regrowth. All water yields increased significantly in the period immediately following logging compared to the prelogging period.

Months	Years of Record	n	Mean Observed Water Yield (mm)	Mean Observed Water Yield (l/s/km²)	Predicted Water Yield (mm)	Mean Observed Minus Predicted Water Yield (mm)	(percent)	mean	se*	Significance of Difference Between Periods A and C** (α)
WATERSHED 1 – Clearcut Logged										
July	(A) 1953-1961	9	9.1	3.40	9.1	0.0	0	0.00	0.11	
	(B) 1962-1969	8	14.7	5.50	6.7	8.1	121	3.01	0.51	0.200
	(C) 1970-1988	19	7.0	2.63	7.9	–0.8	–10	–0.30	0.15	
August	(A) 1953-1961	9	5.7	2.12	5.7	0.0	0	0.00	0.11	
	(B) 1962-1969	8	10.1	3.78	3.9	6.2	159	2.30	0.38	0.032
	(C) 1970-1988	19	3.0	1.11	4.0	–1.0	–25	–0.37	0.10	
September	(A) 1953-1961	9	7.2	2.79	7.2	0.0	0	0.00	0.21	
	(B) 1962-1969	8	11.8	4.57	4.2	7.7	183	2.95	0.72	0.256
	(C) 1970-1988	19	7.4	2.87	6.3	1.2	19	0.45	0.25	
July to August	(A) 1953-1961	9	14.8	2.76	14.8	0.0	0	0.00	0.08	
	(B) 1962-1969	8	24.9	4.64	10.4	14.4	138	2.74	0.32	0.039
	(C) 1970-1988	19	10.0	1.87	11.8	–1.7	–14	–0.33	0.10	
July to September	(A) 1953-1961	9	22.0	2.77	22.0	0.0	0	0.00	0.09	
	(B) 1962-1969	8	36.7	4.62	13.9	22.8	164	2.90	0.39	0.885
	(C) 1970-1988	19	17.5	2.20	17.2	0.3	2	0.03	0.15	
Annual	(A) 1953-1961	9	1377.9	43.69	1377.4	0.4	0	0.01	0.55	
	(B) 1962-1969	8	1439.3	45.64	1073.2	366.1	31	11.61	1.83	<0.001
	(C) 1970-1988	19	1426.8	45.24	1140.1	286.7	25	9.09	0.42	
WATERSHED 2 – Unlogged Control										
July	1953-1988	36	12.7	4.74						
August	1953-1988	36	7.8	2.92						
September	1953-1988	36	8.6	3.33						
July to August	1953-1988	36	20.5	3.83						
July to September	1953-1988	36	29.1	3.67						
Annual	1953-1988	36	1358.6	43.08						
WATERSHED 3 – 25 Percent Patch-Cut Logged										
August	(A) 1953-1962	10	11.2	4.19	11.2	0.0	0	0.00	0.16	
	(B) 1963-1978	16	12.4	4.63	7.8	4.6	59	1.70	0.19	0.175
	(C) 1979-1988	10	9.3	3.47	8.1	1.2	15	0.44	0.27	
September	(A) 1953-1962	10	11.9	4.60	11.9	0.0	0	0.00	0.20	
	(B) 1963-1978	16	14.1	5.43	10.1	4.0	40	1.54	0.25	0.159
	(C) 1979-1988	10	12.4	4.79	11.1	1.3	12	0.51	0.28	
July to August	(A) 1953-1962	10	29.2	5.44	29.1	0.0	0	0.00	0.24	
	(B) 1963-1978	16	28.5	5.32	22.8	5.7	25	1.06	0.21	0.976
	(C) 1979-1988	10	25.9	4.84	26.0	0.0	0	–0.01	0.27	
July to September	(A) 1953-1962	10	41.1	5.17	41.1	0.0	0	0.00	0.17	
	(B) 1963-1978	16	42.6	5.36	33.2	9.4	28	1.19	0.22	0.634
	(C) 1979-1988	10	38.4	4.83	37.2	1.1	3	0.14	0.24	
Annual	(A) 1953-1962	10	1403.7	44.51	1403.4	–0.3	0	0.01	0.59	
	(B) 1963-1978	16	1330.4	42.19	1221.3	109.0	9	3.46	0.48	0.160
	(C) 1979-1988	10	1177.6	37.34	1144.3	33.3	3	1.06	0.40	

*Standard error.

**Means for prelogging calibration period (A) and period of reduced water yield (C) compared with single classification ANOVA.

alone was 159 percent, which corresponds to an increase in specific discharge of 2.3 $l/s/km^2$ (Table 2).

Within three years of the completion of logging and burning on WS 1, regrowth of vegetation had eliminated the increases in summer water yield. Water yields for August over the period 1970-1988 were 25 percent (i.e., 1.0 mm) lower in WS 1 than predicted from WS 2 compared to the prelogging period (1953-1961, p=0.032). Water yields for July and August combined were 14 percent (i.e., 1.7 mm) lower for 1970-1988 than for 1953-1961 (p=0.039, Table 2). Specific discharge for August was 0.37 $l/s/km^2$ lower than predicted for 1970-1988. The differences in observed minus predicted water yields between the 1953-1961 and 1970-1988 periods for July or September alone, or for July to September combined, were not significant (p>0.200).

Water yield in September was extremely variable among years. Rains at the end of summer sometimes began part way through September, and sometimes occurred after the end of September. For the period 1953-1988 the coefficient of variation of streamflow from the control watershed, WS 2, was 62 percent for September, but only 41 percent for August. Variability in streamflow masked the response to logging of September water yield.

There were three distinct periods in the summertime hydrologic record for WS 3 (Figure 2B). These periods were (1) 1953-1962 (prelogging calibration), (2) 1963-1978 (the period of increased water yield following logging and burning), and (3) 1979-1988 (the following 10 years during which water yield appeared to have returned to pretreatment levels). Observed water yield increased compared to predicted by 59 percent for August alone, and by 25 percent for July and August combined, immediately following the start of logging (1963-1978, Table 2). Water yields for 1979-1988 were not significantly different from the 1953-1962 period of prelogging calibration for combinations of July-September yields, or for annual totals (Table 2).

Comparing Figures 2 and 3, it is obvious that the response of annual water yield to logging is not necessarily a good predictor of changes in summer water yield. Differences between patterns of water yield for August and annual water yield are a result of, at least in part, seasonal patterns of precipitation and streamflow for forested watersheds in western Oregon and Washington. About 80 percent of total annual precipitation occurs between October 1 and March 31, leading to low streamflows in late summer. The excess of potential evapotranspiration over precipitation results in a water deficit in the H. J. Andrews Experimental Forest from June to September (Rothacher, 1971). Thus only 2-4 percent of average annual streamflow occurs during July, August, and September (Harr, 1983). For example, streamflow for July 1 to September 30 from WS 2 was 2.4 ± 0.5 percent (mean ± 95 percent confidence intervals, n=36) of annual totals between 1953 and 1988.

We examined predictions that the increase in annual water yield caused by logging would return to zero by 1992, 27 years after 1965 (Harr, 1983). Analyzing data for 1953-1981, Harr (1983) derived the model $Y=513.2-19.1X$ for reducing water yield, where Y=observed increase in annual water yield (in inches) compared to control, and X=time since logging (r^2=0.75, n=16). Adding seven years of record (i.e., 1982-1988 inclusive), we found that the steep decline in annual water yield for WS 1 from 1966 to 1976 flattened out from 1977 to 1988, so that there has been little further reduction in annual water yield (Figure 3A). Water yield from WS 1 for 1970-1988 was still 25 percent greater than for 1953-1961, the prelogging period (p<0.001, Table 2). The model calculated from least squares regression for data for 1965-1988 (the period used by Harr, 1983) was $Y=435.9-9.72X$ (r^2=0.53, p<0.001, n=24), indicates that annual water yields (in millimeters) will return to prelogging values 46 years after logging, in 2011. Annual water yield from WS 3 from 1979 to 1988 was not significantly different from prelogging levels (p=0.160, Table 2, Figure 3B).

Changes in Vegetation

Before logging, the vegetation of the hillslopes of WS 1 was dominated by old-growth (300-500 year old) and mature (125 year old) Douglas-fir (*Pseudotsuga menziesii* (Mirb). Franco), and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) of varying age (Dyrness, 1973). Riparian vegetation consisted largely of old-growth conifers and shade-adapted herbaceous species. Tall conifers suppressed establishment and growth of deciduous vegetation along the channel.

After logging and burning, vegetation gradually reestablished in WS 1 and 3. The recovery has been described elsewhere (Halpern, 1988, 1989), and followed the pattern typical for the Pacific Northwest, with forbs, sprouting hardwoods, and miscellaneous pioneer species initially establishing on the hillslopes; Douglas-fir trees now occupy most slopes. Red alder (*Alnus ruba* Bong.) dominates the riparian zone of WS 1 (pers. comm., F. J. Swanson, Pacific Northwest Research Station, Corvallis, Oregon), and willow (*Salix* spp.), and cottonwood (*Populus trichocarpa* Torr. and Gray) are also established in and adjacent to the stream.

Different geomorphic conditions in the valley floors of WS 1, 2, and 3 have determined the development of riparian vegetation. Watershed 1, with a relatively

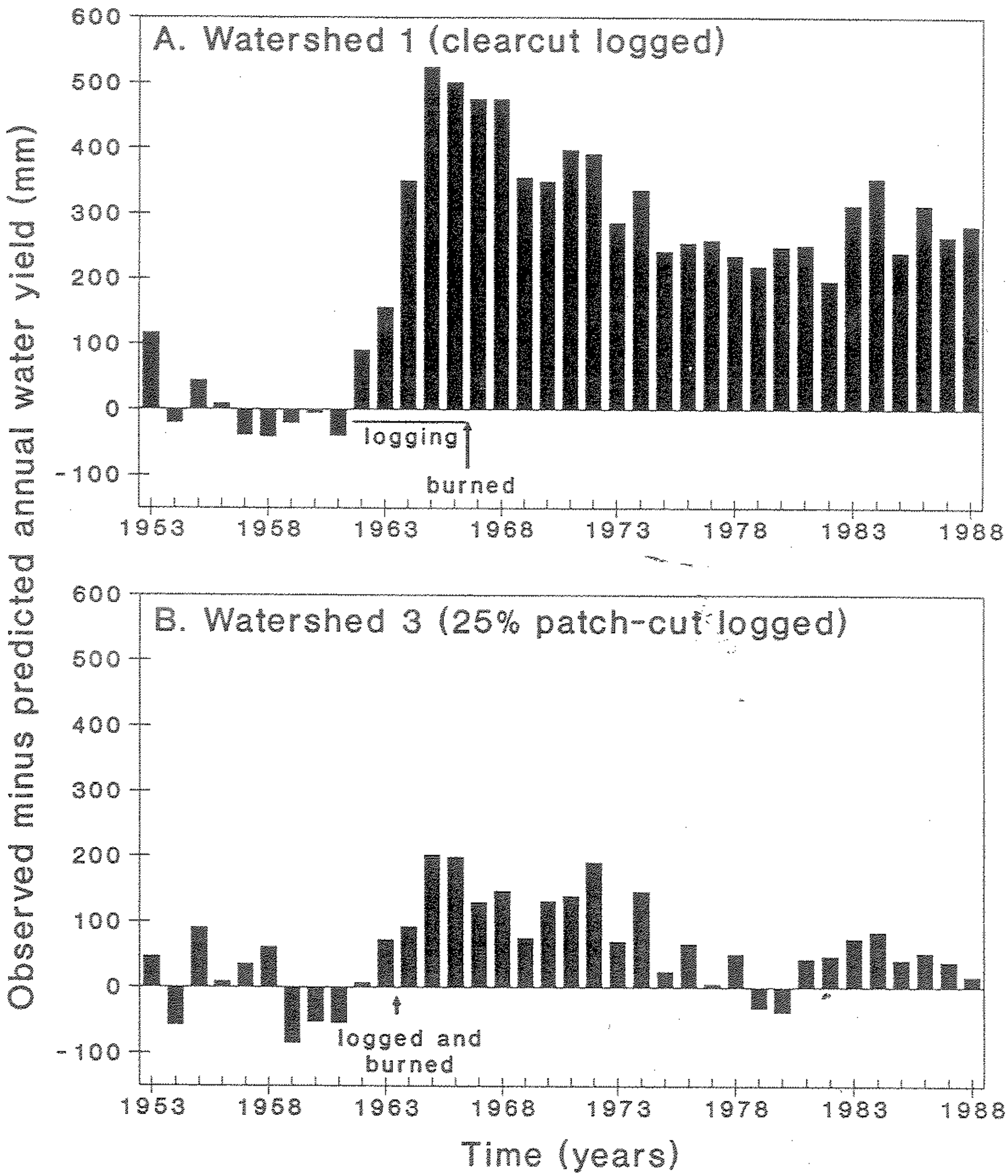

Figure 3. Differences Between Observed and Predicted Water Yield for Watershed 1 (A) and Watershed 3 (B), H. J. Andrews Experimental Forest, Western Oregon Cascades, Before and After Logging (1953-1988).

wide valley floor compared to WS 2 and 3, has well-developed riparian hardwoods. As a consequence of the narrow valley floor in WS 3, there has been little opportunity for hardwoods to establish in the riparian zone following logging. In addition, sediment deposits on which riparian hardwoods might have established have been removed from much of the valley of WS 3 by debris torrents caused by floods in December 1961, December 1964, and January 1965 (Fredriksen, 1963, 1965). Hardwoods are limited in the riparian zone of WS 2 because (1) the small amount of sediment at the channel edge prevents rooting, and (2) conifers rooted on side slopes suppress hardwood establishment along the channel (pers. comm., F. J. Swanson, Pacific Northwest Research Station, Corvallis, Oregon).

DISCUSSION

Significance of Long-Term Trends in Water Yield

Increased annual water yield has been one of the benefits generally attributed to timber harvest, and water yield did increase after logging in WS 1 and 3. Observed annual water yield from WS 1 for 1970-1988 has been 25 percent greater than predicted, after being 31 percent greater immediately following logging (1962-1969, Table 2). However, in streams of the Pacific Northwest most of the increase in annual water yield following logging occurs from October to March, when water is not in short supply (Harr, 1983). Of critical concern to instream biota is water yield in summer.

For WS 1, the period for which increased summer water yield persisted was short, especially considering the proportion of the time that it would represent (8-11 percent) during a rotation time of 70-100 years under intensive forest management. Following the period of increased water yield immediately following logging, timber harvest may actually reduce July and August streamflows for many years. So far the period of reduced yield has been 19 years, or 19-27 percent of the period of a rotation. The actual length of time for which reduced summer flows persist is not known, but they may continue for several decades, until conifers grow large enough to suppress growth of riparian hardwoods, For WS 3, the patch-cut watershed, summertime flows have generally remained at or above prelogging levels (Figure 2B).

The mechanism for different water yield responses of WS 1 and WS 3 following logging and burning is not entirely understood. Reduced evapotranspiration on hillslopes following the start of logging apparently increased delivery of water to the streams for 1962-1969 in WS 1, and for 1963-1978 in WS 3, increasing summer and annual streamflows. However, from 1970 on in WS 1, increased water use by established riparian vegetation may have been responsible for decreased streamflows. An attempt at reducing hardwoods in the riparian zone of WS 1 in 1973 was unsuccessful (pers. comm., F. J. Swanson, Pacific Northwest Research Station, Corvallis, Oregon) and no subsequent increase in water yields was observed. Higher stomatal conductance has been demonstrated in hardwoods such as quaking aspen (*Populus tremuloides* Michx.) in the Rocky Mountains than in conifers (Kaufman, 1984). Thus hardwoods are likely to use more water than conifers in summer for equivalent leaf areas.

Changes in soil moisture in WS 3 were only partly consistent with changes in streamflow. Summer soil moisture in the upper 120 cm of the profile along a transect at a logged site was greater than predicted following logging compared to a transect at an unlogged site from 1963 to 1965. From 1966 to 1980, however, soil moisture in summer was less than predicted at the logged site (Adams *et al.*, in press), even though streamflow was consistently greater than predicted in WS 3 until 1978 (Figure 2B). This suggests that water stored at depths of >120 cm was responsible for the increased streamflows during summer following logging. If changes in riparian vegetation were at least partially responsible for the reduced streamflows in WS 1, then replacement of conifers in the streamside zone with hardwoods could have important consequences for aquatic life and downstream users.

Effects on Salmonid Survival

Summer is a time of stress for juvenile salmonids rearing in streams in the Pacific Northwest. Furthermore, streamflows and water temperature can be factors limiting the survival of aquatic life in streams. Although salmonids do not use the stream in WS 1, we can infer that similar impacts of logging on streams elsewhere, such as in the Oregon Coast Range, would be detrimental. Although hardwoods such as red alder in the riparian zone may eventually shade a stream, they may also bring about detrimental changes in water quality as well as quantity. Leafdrop from hardwoods in dry conditions during late summer and early fall can contribute to low dissolved oxygen concentrations in coastal streams, which may reduce growth and survival of fish and invertebrates (Slack, 1955; Hicks, 1990). The extent of oxygen depletion was related inversely to streamflow, and was greater under red alder than under a mixed canopy of bigleaf and vine maple (Hicks, 1990).

Increased temperatures and low dissolved oxygen can have direct effects on fish, causing stress, disease, and consequent mortality. Reduced streamflow can increase the severity of changes in temperature and dissolved oxygen, and also can have direct and indirect effects on fish by reducing volume of stream habitat. Fish may die as a direct result of reduced streamflow as stretches of stream become dry. As an indirect effect, reduced flows may increase competition among fish. Riffle volumes are affected by reduced flows more than glides, and glides are affected more than pools (Hicks, 1990). Species such as age 0 steelhead (fry to fingerling-sized *Oncorhynchus mykiss*) often occupy riffles when in the same stream as pool-adapted fish such as age 0 coho salmon (*Oncorhynchus kisutch*) (Hartman, 1965; Bisson *et al.*, 1988). Thus, with reduced flows juvenile steelhead could be forced out of drying riffles and into pools, where they would face increased competition with the more aggressive coho salmon; this is likely to lower the survival of steelhead. In combination with other logging-related habitat changes, such as habitat simplification, decreases in pool habitat, increases in riffle habitat and channel widening (Lyons and Beschta, 1983; Bisson and Sedell, 1984; Tripp and Poulin, 1986; Hicks *et al.*, in press), reduced flows following forest harvest represent another factor that may seriously reduce survival of salmonids.

CONCLUSIONS

Many previous studies of changes in water yield following timber harvest have not fully considered changes in low summer flows. Analysis of logging-related water yield experiments often have looked only at annual water yields, ignoring the critical summer period when evapotranspiration is greatest and water is potentially in short supply. Furthermore, many studies have insufficient periods of record on which to draw conclusions about the long-term effects of logging on water yield (for example, Harris, 1977; Harr *et al.*, 1979; Harr, 1980).

Long-term records from WS 1 (clearcut logged) and WS 2 (unlogged control) in the H. J. Andrews Experimental Forest, spanning nine years before logging and 26 years after logging, show that the relatively large increases in water yield for August following logging were short-lived, existing for only about eight years. After this period, August water yields were less than normal for 18 of 19 years of record. We hypothesize that as a canopy of conifers closes over hardwoods in the riparian zone of WS 1 over the next few decades, the reductions in summer low flow will be eliminated and summer streamflow will return to prelogging levels, possibly 40-60 years after harvest. If the establishment of hardwoods in the riparian zone following clearcut logging has caused water yields in WS 1 to drop below predicted yields, as we suggest, then future forest harvest practices should protect conifers in the riparian zone during logging to suppress hardwood growth and thereby maintain summertime water yields. In view of the importance of the existing hydrological records from WS 1, 2, and 3 in the H. J. Andrews Experimental Forest, continued collection of hydrologic data from these watersheds is imperative.

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