The Summer Flow and Water Yield Response to Timber Harvest[1]

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Abstract: *Continuous measurement of streamflow at the Caspar Creek watersheds has led to several analyses of the effects of two harvest methods (selection and clearcut) on summer flows and annual yield. Although all Caspar Creek analyses have indicated an increase in runoff after timber removal, the magnitude and duration of the response depend on the nature and extent of the logging and site preparation, climatic conditions, as well as the definition of the hydrologic parameter at issue. Regression analysis using a calibration period of 1963 to 1971 was used to compare annual yield, summer flow volume, and minimum streamflow between the South Fork (SFC) and the North Fork (NFC) of Caspar Creek for a 35-year period. Selection/tractor logging of the SFC increased annual yield by a maximum of 2,053 $m^3ha^{-1}yr^{-1}$ during the seventh water year after harvest began. Increased yields were observed beginning the second post-harvest year and averaged 15 percent or 932 $m^3ha^{-1}yr^{-1}$. Following clearcut logging 50 percent of the NFC watershed, annual yield increased by as much as 1,032 $m^3ha^{-1}yr^{-1}$ 8 years after logging and averaged 15 percent or 608 $m^3ha^{-1}yr^{-1}$ beginning in the second postharvest year. Streamflow changes due to logging are most evident during the long, dry summer season typical of northwestern California. During this prolonged recession, zones of deep perennial saturation maintain streamflow (baseflow). Statistically significant summer flow enhancements were evident on the SFC for 7 years after logging. Subsequently, SFC summer yields fell at or below pretreatment predictions. Although summer flow increases amounted to relatively minor changes in minimum discharge averaging only 0.25 L $s^{-1}km^{-2}$ on SFC and 0.40 L $s^{-1}km^{-2}$ on NFC, these enhancements are quite substantial in comparison to pretreatment summer low flows. Minimum discharge increases averaged 38 percent after the SFC selection logging and 148 percent after the NFC harvest and site preparation. NFC flow enhancements persist through hydrologic year 1997 with no recovery trend, as yet.*

After logging, reduced interception and evapotranspiration allow for additional water to be stored in the soil and routed to streams as summer baseflow. At Caspar Creek, enhanced soil moisture in the rooting zone followed timber harvest in the NFC clearcut units. Previously intermittent stream reaches and soil pipes became perennial. The larger increases in minimum flows observed on the NFC are probably to be due to wetter soils in the clearcut units where little vegetation exists to use this enhanced moisture. On the selectively cut SFC, mature residual forest vegetation more readily exploited this additional soil moisture. Fog plays an important role in the regional ecology by moderating evapotranspiration. However, Caspar Creek data indicate that any possible postlogging loss of fog drip did not result in a net reduction in streamflow. Moisture savings due to reduced evapotranspiration appear to override any fog precipitation losses at this site.

Forest vegetation has a major influence on the hydrology of a basin. The alteration and removal of forest vegetation continues to be a controversial issue among land managers and public and private interest groups. In the Pacific Northwest, where wet winters are followed by long, dry summers, the effects of timber harvest operations on summer streamflow and soil moisture conditions during the growing season are of significant concern. Rural residents of forested watersheds often rely on springs and small creeks for year-round water supply. Fish and other stream fauna require adequate summer flows to prosper in the limited rearing habitat summer streams provide. Terrestrial species are also quite dependent on riparian areas and perennial streams.

The impacts of timber harvest on water yields and summer flows have been evaluated for several watersheds between northern California and British Columbia. Almost all report enhanced summer flows and annual yields after logging. Reduced evapotranspiration (water use by plants) is the most obvious effect of the removal of forest vegetation. Canopy interception is also reduced, allowing more direct delivery of precipitation to the forest floor. Infiltration and percolation (water movement into and drainage through the soil, respectively) may be impeded by soil disturbance and compaction associated with logging.

The magnitude, timing, and duration of these postlogging increases vary according to several important site factors. Increases in streamflow have been shown to be proportional to the amount of cover removed (Hibbert 1967). Clearcutting yields larger increases than partial cutting (Rothacher 1971). Vigorous growth by the residual understory vegetation or rapid regrowth of the overstory may quickly counter postharvest streamflow enhancements, particularly in wetter regions. The magnitude of the streamflow response to cutting also relates to mean annual precipitation. Wetter regions generally experience the greatest effects.

The dominant explanation of streamflow increases due to logging is that when trees are harvested, transpiration and interception are reduced; thus soils receive more water during the rainy season and retain more moisture through the growing season and thereby sustain higher baseflows. Even when the winter rains return, the wetter soils in the logged area require less precipitation to recharge sufficiently for storm runoff to occur, thus enhancing streamflow relative to unlogged conditions. The greatest relative increases in streamflow are observed in the summer and fall seasons.

An intriguing contradiction to this explanation was observed after logging within the Bull Run Municipal Watershed near Portland, Oregon. Here, a small decrease in annual yield was detected and the number of summer low-flow days actually increased, suggesting reduced summer streamflow (Harr 1982). Harr hypothesized that the reduced summer flow was due to reduced interception of fog precipitation after forest canopy removal. Although summer flow increases were later reported at

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Bull Run about 5 years after harvest (Ingwersen 1985), the initial anomaly observed by Harr (1982) has led to renewed interest in investigating the role of fog precipitation in the Pacific Northwest and how it might be affected by timber harvest operations.

The 35-year record of streamflow at Caspar Creek has made possible an analysis of the effects of timber harvest operations in the south coastal portion of the Pacific Northwest. This report compares the effects of selection cutting and tractor yarding on the South Fork (SFC) streamflow with those of clearcutting and cable yarding on the North Fork (NFC) streamflow. The magnitude and duration of annual yield and summer low flow changes, and variations in summer pipeflow and soil moisture levels are reported.

Methods

Instrumentation

The weirs, constructed in 1962 on the North Fork and South Fork of Caspar Creek, provide the longest continuous record of streamflow for this area. This annual discharge record is complete except for those years when the weir ponds were drained so that the debris basin could be cleaned out (Henry, these proceedings). Additional monitoring of summer flows at the gaging stations on the 13 sub-basins of the North Fork was implemented between 1988 and 1994 (Preface, fig. 2, these proceedings). Except for the mainstem gaging sites, most of these tributary stations were intermittently dry during the summer months although shallow intergravel flow occurred at near-surface depths. To evaluate changes in baseflow, slotted PVC wells were installed in the streambed and equipped with electronic stage sensing devices recording at hourly intervals during summer periods between 1988 and 1994. Although these latter sites have not provided year-round quantifiable discharge data because of resolution and gage design limitations, relative comparisons of summer flows before and after timber harvest are possible.

In addition, soil pipe discharge data collected since 1986 at four sites provides quantifiable data on summer flow contributions from the North Fork headwaters. Soil moisture levels on a hillslope in watershed KJE (Preface, fig. 2, these proceedings) were monitored using 25 tensiometers installed at depths ranging from 30 to 150 cm. Tensiometers are commonly used in agricultural applications to determine irrigation needs. The device consists of a porous cup attached to a plastic tube leading to a vacuum gage. When the soil is unsaturated, a tension is created as the soil attempts to extract moisture through the porous cup to achieve equilibrium. Tension readings (both hourly electronic and manual) from these vacuum gages were made before and after logging at this site.

Annual Yield Analysis

Regression analysis was used to evaluate differences in annual water yield (total yearly streamflow between August 1 and July 31) before and after timber harvest activities on NFC and SFC. Initial evaluation indicated no statistically significant difference in annual yield before and after the 1967 road building on the SFC. Therefore, the calibration regression used data from 1962 to 1971 to define the pretreatment relationship between the two watersheds. To evaluate the effects of the SFC logging, prediction limits ($p < 0.05$) were calculated to determine whether the postharvest yields from 1972 to 1985 were within the range predicted by the calibration relationship. Similarly, prediction limits were calculated for NFC postharvest yields 1986 to 1997. No attempt has been made to estimate annual yield at the 13 NFC sub-basins or soil pipe sites.

Summer Low Flow Analysis

A similar regression approach was used to analyze changes in minimum summer discharge (mean daily flow) before and after timber harvest activities on NFC and SFC. Minimum discharge dates were selected as late in the low-flow season as possible, generally late August or September, to avoid the effects of small rain events or missing data due to weir maintenance activities. Discharges from both weirs on the same dates were used in this regression.

Data on minimum stage from the NFC subwatershed gages were compared to further evaluate the trends observed at the weirs. One advantage of this comparison was that it allowed the use of data from the undisturbed control tributaries HEN, IVE, and MUN. For each site, the mean annual minimum stage before and after logging was calculated. The "one-tailed" *t*-test and the non-parametric Mann-Whitney test were used to determine if the postlogging mean was greater than the predisturbance mean ($p < 0.05$).

The hillslope monitoring instrumentation in watersheds KJE and MUN (Keppeler and Brown, these proceedings) provided yet another indicator of logging impacts to the NFC baseflow process. Year-round discharge from soil pipes was monitored before and after

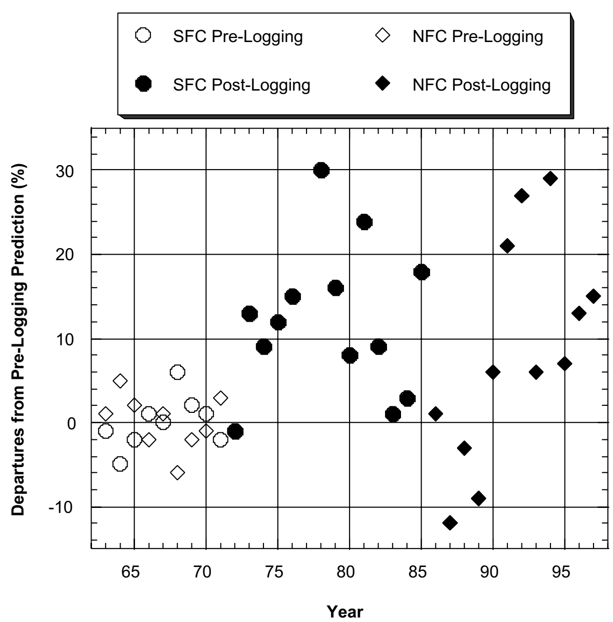

Figure 1—Annual water yield at the North (NFC) and South Fork (SFC) weirs. Departures are relative to predictions using 1963-1971 calibration regression. SFC was roaded in 1967 and logged 1971-1973. NFC was logged in 1985 and 1989-1991.

logging. Mid-summer pipeflow discharges were compared between pipe M106 (control) and K201 (logged in 1989) using regression analysis. Manual measurements of discharge during late July for years 1987 to 1989 were used to determine the calibration relationship. Postlogging measurements form 1990 to 1996 were then compared to this calibration relationship using prediction limits ($p < 0.05$).

Tensiometer data were evaluated nonstatistically to further explore the NFC response to logging. At the K2-site, soil moisture tensions were compared on July 1 before and after logging. Maximum seasonal tensions were also compared where available. Because of equipment limitations, these latter data were not always reliable.

Results

Annual Yield

Selection cutting and tractor yarding increased SFC annual yield by an average 15 percent or 932 $m^3ha^{-1}yr^{-1}$ over an 11-year period (*fig. 1*). Statistically significant ($p < 0.05$) increased yields began in 1973 (two years after logging began) and continued through 1985 (excepting 1983 and 1984). The largest increase was 2,053 $m^3ha^{-1}yr^{-1}$ (30 percent) in 1978, seven years after SFC logging began and one year after the record drought of 1977 (*table 1*).

Partial clearcut logging with mostly skyline cable yarding on the NFC resulted in a similar water yield increase (*fig. 1*). The average increase between 1990 and 1997 was 15 percent or 608 $m^3ha^{-1}yr^{-1}$. Except for 1993, these increases were statistically significant ($p < 0.05$) beginning in 1992 through 1997, the last year available for analysis. The largest absolute increase was 1,032 $m^3ha^{-1}yr^{-1}$ in 1997, but proportionately, the greatest relative increase was 29 percent in 1994 (*table 1*).

Summer Low Flows

On SFC, the minimum summer discharge (instantaneous mean

Table 1*—Annual water yield at the North Fork (NFC) and South Fork (SFC) Caspar Creek weirs and departures from predicted yields, based on 1963 to 1971 calibration regression ($r^2 = 0.99$). Mean, maximum, and minimum departures and percent change are for postlogging years (SFC: 1973-1982, NFC: 1990-1997). Bold values exceed calibration prediction limits ($p < 0.05$). No values are less than the lower prediction limit.*

Water Year	NFC $m^3ha^{-1}yr^{-1}$	SFC $m^3ha^{-1}yr^{-1}$	SFC Departure $m^3ha^{-1}yr^{-1}$	SFC Change (percent)	NFC Departure $m^3ha^{-1}yr^{-1}$	NFC Change (percent)
1963	5283	5269	-46	-1	42	1
1964	3541	3489	-190	-5	179	5
1965	7210	7008	-116	-2	132	2
1966	4943	5067	72	1	-85	-2
1967	6929	6832	-28	0	37	1
1968	3747	4093	220	6	-252	-6
1969	8184	8229	191	2	-183	-2
1970	6986	6984	71	1	-66	-1
1971	7447	7172	-174	-2	196	3
1972	3730	3826	-32	-1	13	
1973	8093	8981	1029	13	-1069	
1974	13054	13707	1099	9	-1100	
1975	7932	8722	921	12	-956	
1976	3337	4019	531	15	-584	
1977						
1978	6898	8884	2053	30	-2161	
1979	4111	4880	665	16	-719	
1980	6289	6748	489	8	-514	
1981	2754	3649	707	24	-776	
1982	9812	10455	890	9	-907	
1983	13919	13510	90	1	-27	
1984	6782	6939	217	3	-222	
1985	3646	4454	676	18	-734	
1986	6265	6193	-44		48	1
1987	3337	3883	394		-440	-12
1988	3560	3786	88		-115	-3
1989	4239	4734	399		-438	-9
1990	3903	3798	-222		216	6
1991	1754	1677	-326		307	21
1992	3227	2711	-674		688	27
1993	8267	7723	-393		434	6
1994	2827	2381	-629		637	29
1995	10238	9363	-602		672	7
1996	7676	6746	-816		876	13
1997	7833	6746	-962		1032	15
Mean	6110	6255	932	15	608	15
Maximum	13919	13707	2053	30	1032	29
Minimum	1754	1677	489	8	216	6

daily flow) increased an average of 38 percent or 0.25 L s^{-1} km^{-2} between 1972 and 1978. The maximum increase was 0.42 L s^{-1} km^{-2} in 1973, the final year of timber harvesting on this watershed. No increases were detected in 1977, the driest year of record. Summer discharge minimums returned to prelogging levels beginning in 1979 (*table 2*).

The NFC response to timber harvesting operations yielded increased minimum summer discharges, as well. *Figure 2* compares changes in minimum summer discharge levels for SFC and NFC. Even after clearcutting only 12 percent of the watershed, a 161 percent (0.30 L s^{-1} km^{-2}) increase was detected in 1986. Between 1990 and 1997, minimum summer discharge averaged 148 percent (0.40 L s^{-1} km^{-2}) greater than preharvest predictions. The minimum increase was 75 percent in 1990 and 1996. The largest relative increase was 287 percent in 1992, but the maximum absolute increase, 0.67 L s^{-1} km^{-2}, occurred in 1997 (*table 2*).

Other Summer Season Baseflow Indicators: North Fork Caspar

Additional indications of summer flow increases after the NFC logging were observed further up the watershed. Minimum summer stages in the tributary basins are shown in *figure 3*. Before logging, all of the sub-basin gaging stations were seasonally dry, with the exception of the three mainstem rated sections (ARF, FLY, and LAN) and three tributary stations (DOL, IVE, and KJE). Even with higher rainfall after the NFC logging, this pattern of no flow continued at the control gages, HEN and MUN. However, of the remaining five gaging

***Table 2**—Minimum instantaneous mean daily flow at North Fork (NFC) and South Fork (SFC) Caspar Creek weirs and departures from predicted values, based on 1963 to 1971 calibration regression ($r^2 = 0.96$). Mean, maximum, and minimum departures and percent change are for postlogging years (SFC: 1972-1978, NFC: 1990-1997). Bold values exceed calibration prediction limits ($p < 0.05$). No values are less than lower prediction limit.*

Year	NFC L s^{-1} km^{-2}	SFC L s^{-1} km^{-2}	SFC Departure L s^{-1} km^{-2}	SFC Percent Change	NFC Departure L s^{-1} km^{-2}	NFC Percent Change
1963	0.72	1.24	-0.02	-2	0.03	4
1964	0.17	0.23	-0.08	-26	0.04	27
1065	0.29	0.46	-0.05	-10	0.03	10
1966	0.22	0.30	-0.08	-20	0.04	22
1967	0.40	0.78	0.09	13	-0.05	-11
1968	0.22	0.46	0.07	19	-0.04	-17
1969	0.26	0.52	0.07	16	-0.04	-14
1970	0.16	0.29	0.02	7	-0.02	-10
1971	0.46	0.78	-0.02	-3	0.02	4
1972	0.34	0.99	0.40	69	-0.22	
1973	0.37	1.06	0.42	66	-0.23	
1974	0.43	1.10	0.35	47	-0.19	
1975	0.55					
1976	0.36	0.80	0.17	28	-0.09	
1977	0.18	0.29	-0.02	-7	0.01	
1978	0.43	0.95	0.20	26	-0.10	
1979	0.64	0.93	-0.19	-17	0.12	
1980	0.54	0.90	-0.04	-5	0.03	
1981	0.28	0.46	-0.03	-6	0.02	
1982		0.63				
1983	0.74	1.10	-0.19	-15	0.12	
1984	0.28	0.41	-0.08	-17	0.05	
1985	0.23	0.29	-0.10	-26	0.05	
1986	0.49	0.32	-0.53		0.30	161
1987	0.23	0.25	-0.14		0.08	50
1988	0.26	0.29	-0.17		0.09	52
1989	0.46	0.59	-0.22		0.13	37
1990	0.41	0.40	-0.31		0.17	75
1991	0.46	0.21	-0.59		0.33	256
1992	0.59	0.25	-0.77		0.44	287
1993	1.28	1.10	-1.12		0.66	107
1994	0.46	0.29	-0.51		0.29	166
1995	0.72	0.67	-0.58		0.34	89
1996	0.80	0.80	-0.58		0.34	75
1997	1.19	0.92	-1.15		0.67	129
Mean	0.46	0.62	0.25	38	0.40	148
Maximum	1.28	1.24	0.42	69	0.67	287
Minimum	0.16	0.21	-0.02	-7	0.17	75

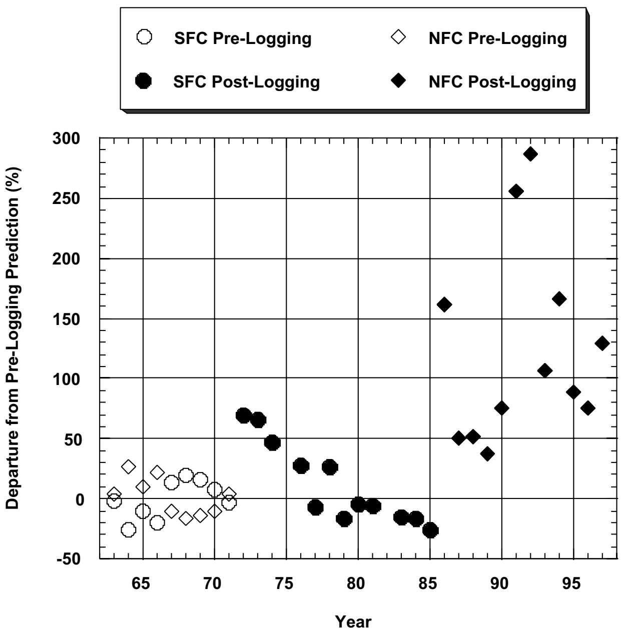

Figure 2—Minimum summer discharge at the North Fork (NFC) and South Fork (SFC) weirs. Departures are relative to predictions using 1963-1971 calibration regression. SFC was roaded in 1967 and was logged in 1971-1973. NFC was logged in 1985 and 1989-91.

sites known to cease flowing during the summer season before logging (BAN, CAR, EAG, GIB, and JOH), all had surface flow well into the summer period after logging. Instrumentation problems prevented analysis of the GIB and IVE data. For the remaining tributary sites, the mean postlogging minimum stage was greater than the predisturbance value according to both the *t*-test and the Mann-Whitney test statistics (*table 3*).

Large increases in late-July soil pipeflow from the 100 percent clearcut K2 swale were detected in 1990 to 1992, and 1994 (*fig. 4*). Increases in this mid-summer pipeflow variable averaged 179 percent or 0.45 L min^{-1}. The largest increase, 478 percent or 0.95 L min^{-1}, occurred in 1991. After 1994, K201 pipeflow fell below the calibration prediction, but this was not a statistically significant decrease (*table 4*). Because the range of the pretreatment calibration (1987-1989) only extended to about 0.3 L min^{-1}, observations during 1990, 1993, 1995, and 1996 required extrapolation of this calibration and the departures are suspect. However, it appears that summer pipeflow increases were greater the first and second year (1990 and 1991) after logging and returned to near pretreatment levels by 1993 or 1994.

After logging, tensiometer gages in watershed KJE indicated reduced tensions (higher soil moisture) on July 1. For example, at a depth of 150 cm at site C4, tensions on July 1 were 55 and 32 cb for the 2 years before logging. After logging on July 1 tensions did not

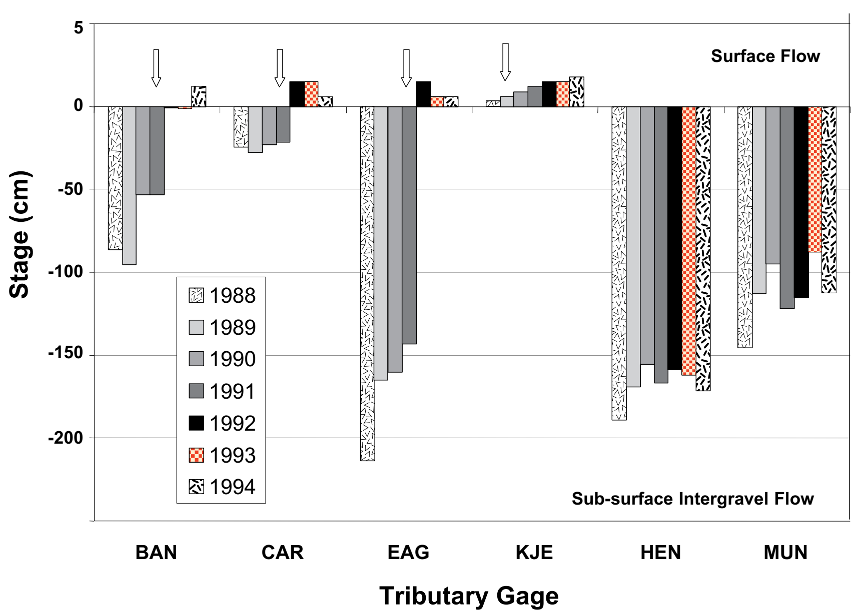

Figure 3—Minimum summer stages at clearcut tributary gages (BAN, CAR, EAG, KJE) and unlogged control gages (HEN, MUN). Positive stage values indicate surface flow persisted for the entire water year. Negative values indicate the minimum intergravel flow level measured at the instream well tube. Arrows indicate time of logging.

Table 3*—Minimum summer stages (cm) at North Fork Caspar Creek tributary gages. Positive values indicate continuous surface flow. Negative stages indicate intergravel flow level observed in well tube.*

	100 percent clearcut subwatersheds				Control subwatersheds	
Year	BAN	CAR	EAG	KJE	HEN	MUN
1988	-86.3	-24.4	-213.4	0.3	-189.0	-145.7
1989	-95.1	-27.4	-164.6	0.6	-169.2	-112.8
1990	-53.3	-22.9	-160.0	0.9	-155.4	-94.8
1991	-53.0	-21.3	-143.3	1.2	-166.7	-121.9
1992	-0.6	1.5	1.5	1.5	-158.5	-114.9
1993	-1.2	1.5	0.6	1.5	-162.2	-87.8
1994	1.2	0.6	0.6	1.8	-171.6	-112.2
Prelogging mean	-71.9	-24.0	-170.3	0.5	-171.2	-117.8
Postlogging mean	-0.2	1.2	0.9	1.4	-164.7	-106.3
Year logging completed	Winter 1991	Winter 1991	Fall 1991	Fall 1989	Not logged	Not logged

Table 4*—July pipeflow at the uncut control M106 and the logged K201 North Fork Caspar Creek sites and departures from predicted values based on 1987-1989 calibration regression ($r^2 = 0.99$). K201 was logged in 1989. Bold values exceed calibration prediction limits ($p < 0.05$). No values are below prediction limits.*

Year	M106 ($L\ min^{-1}$)	K201 ($L\ min^{-1}$)	K201 Departure ($L\ min^{-1}$)	K201 change (percent)
1987	0.150	0.185	0.009	5
1988	0.060	0.060	-0.005	-7
1989	0.250	0.295	-0.004	-1
1990	0.800	2.000	**1.022**	**104**
1991	0.170	1.160	**0.959**	**478**
1992	0.160	0.666	**0.478**	**254**
1993	1.245	1.160	-0.367	-24
1994	0.190	0.420	**0.195**	**86**
1995	0.670	0.585	-0.233	-28
1996	1.100	0.730	-0.618	-46
Mean (1990-1994)			**0.457**	**180**
Maximum			**1.022**	**478**
Minimum			**-0.618**	**-46**

exceed 10 cb. Similarly, maximum tensions at this site were 84 cb and 74 cb before logging, but never exceeded 60 cb in the postlogging monitoring period (*fig. 5*). In other words, postharvest soil moisture levels throughout the summer dry season were at or above the preharvest levels. This suggests additional soil moisture was available to support forest regrowth. Unfortunately, much of the tensiometer data was interrupted or discontinued after 1993 because of equipment problems and vandalism. It would be interesting to see if the soil moisture tensions have returned to prelogging levels as apparently the pipeflow has done.

Discussion

The Caspar Creek Response

These data clearly indicate that streamflow was enhanced after timber harvest operations in the NFC and SFC. Significant increases were detected in both summer flows and annual water yield. Previous analyses (Keppeler and Ziemer 1990, Ziemer and others 1996) have shown similar results although the stated magnitudes and duration of postlogging flow enhancement have varied according to the definitions of the streamflow variables and calibration years, and the length of the data set.

As previously noted (Henry, these proceedings) the Caspar Creek watersheds receive annual precipitation averaging 1,200 mm (45 inches). However, not all of this precipitation is routed to the channel as streamflow. Perhaps 10 to 15 percent of this precipitation is intercepted by the forest canopy and evaporated back into the atmosphere without contacting the ground. A minor amount of precipitation may percolate through the entire soil profile to bedrock fissures and into deep groundwater supplies, thus escaping our stream gaging instrumentation. Less than 50 percent of annual rainfall is measured as streamflow at the North

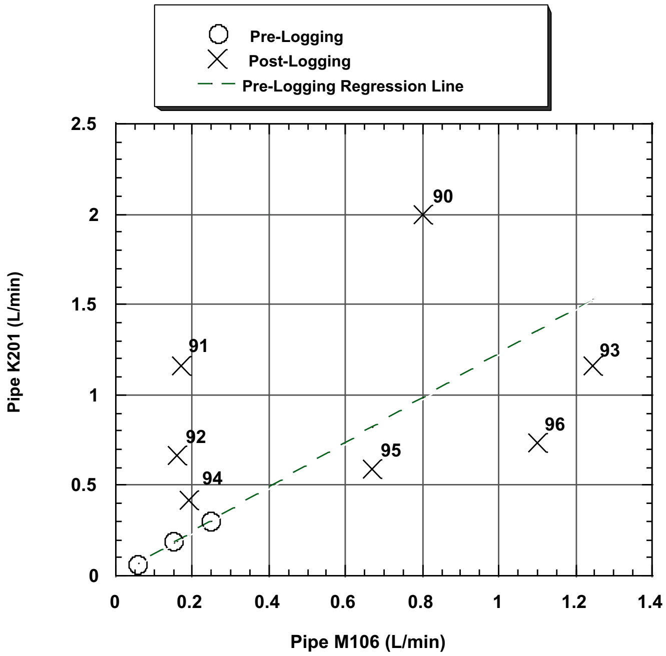

Figure 4—Summer (late July) pipeflow measured at the pipe K201 (K2-site logged 1989) and the control pipe M106 (M1-site untreated). Calibration regression (solid line) uses years 1987-1989. Dashed line is extrapolation of regression line beyond calibration data.

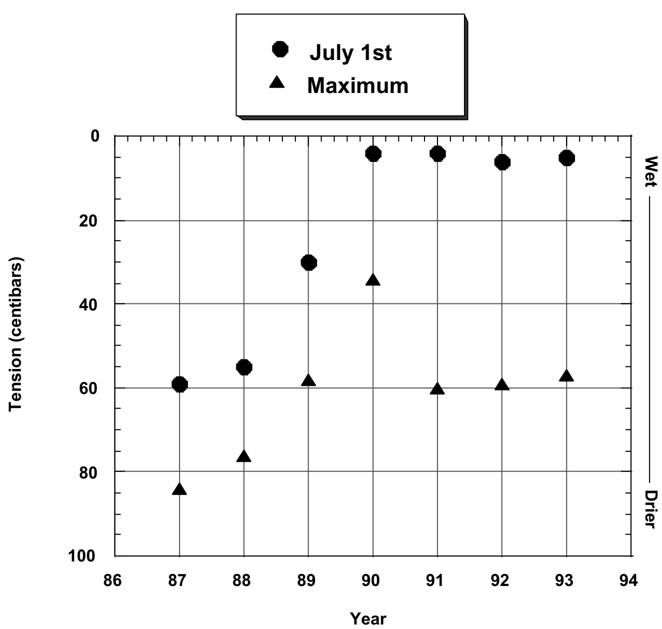

Figure 5—Soil moisture tension at 150 cm depth at the K2-site before and after the August 1989 logging.

and South Fork weirs (Ziemer 1997). Most of the remainder infiltrates into the soil where it is eventually absorbed by plant roots and transpired by forest vegetation.

It has long been acknowledged that evapotranspiration dominates the water balance over most of the landmass. Potential evapotranspiration (PET) is the return of water to the atmosphere by vegetation unrestrained by soil water limitations. Using the Thornthwaite method, Ziemer (1997) calculates annual PET at Caspar Creek to be 660 mm or about half of annual rainfall. During the months of May through September, water demand by the vegetation (or PET) far exceeds rainfall inputs; thus stored soil moisture is depleted. As soil water is depleted by subsurface drainage and plant use, actual evapotranspiration is greatly reduced. Removal of vegetation by timber harvest, forest fire, or other means will most heavily affect the evapotranspiration component of this water balance.

In light of this, the streamflow enhancements observed at Caspar Creek are not unexpected. In reviewing the results of 11 watershed studies in the Pacific Northwest, Harr (1979) reported increased annual water yields of up to 620 mm. At Caspar Creek, the increase was far more modest, averaging less than 100 mm. This is not surprising given that absolute increases due to timber harvest are largest in high rainfall areas and Caspar Creek is at the southernmost extension of this region. If we accept that the PET of the fully forested NFC watershed was 660 mm, then logging 50 percent of the timber volume could reduce plant water use by about half, at most (a savings on the order of 300 mm), under conditions where soil moisture is unlimited. However, *actual* evapotranspiration from this site is certainly limited by soil moisture levels during the dry summer months, thus lesser enhancement is expected. The average postlogging increase at Caspar Creek was less than one third of the potential amount. Cutting trees reduces, but does not eliminate transpiration. Residual and new understory vegetation in the cutblocks probably responded to increased soil moisture by increasing transpiration. Evaporation from exposed hillslope surfaces continued, and possibly increased, after logging. Also, at NFC, the riparian vegetation was mostly retained. Riparian trees and vegetation use more water than the forested hillslopes.

Harr's review also reports that summer flows elsewhere have been as much as quadrupled. After the NFC logging, minimum summer discharge almost tripled during one postlogging year, but averaged about 150 percent after clearcutting 50 percent of the watershed area. The largest increases noted in Harr's analysis occurred where complete clearcutting was done. At the fully clearcut K2-site on the NFC, the magnitude of summer pipeflow increases were similar to the maximums that Harr reports. The largest relative increases in summer minimum flows occurred after Caspar Creek's two driest rainfall years on record, 1977 and 1991.

Why were the summer flow increases larger and more persistent at NFC compared to SFC after logging? The harvest prescription appears to be the important factor. In the SFC selection cut, single trees and small groups were logged, leaving a dispersed residual timber stand and understory vegetation ready to take advantage of any soil moisture surpluses occurring after harvest. In the NFC clearcuts, soil water surpluses occurred in discrete cutblocks where only peripheral contact with residual vegetation existed. New vegetation must grow, or, in the case of redwoods and some hardwood species, resprout, and develop ample foliage to make full use of stored soil water. The postharvest site treatments may also play a part in the magnitude and duration of flow enhancements. About 20 percent of the NFC watershed area was broadcast burned after harvest. One half of the cutblocks were burned approximately one year postharvest, thus setting back the regenerating vegetation. In addition, these burned units were later treated with herbicide to control competition from brush species, also setting back the recovery of the vegetation. The YZ 1985 timber sale was precommercially thinned in 1995, once again pushing back the recovery of that portion of the NFC watershed. Additional precommercial thinning is planned for other NFC cutblocks beginning with Unit K this year (1998). Although the NFC cutblocks are now green and the regeneration appears to be growing vigorously, water use by the new vegetation appears to remain far below that of the older second-growth forest in the NFC watershed. Evapotranspiration is a function of total leaf area. Leaf area in the revegetating cutblocks remains far below that of the uncut portions of the watershed.

The Role of Fog

What is the role of fog and fog precipitation in the postlogging water balance at Caspar Creek? Literature suggests that fog plays a crucial role in the ecology of the Pacific Northwest. In this region, warm, moist air contacts cool coastal waters, lowering temperatures below the dew point and forming fog. This fog layer may travel far inland depending on the strength of the onshore breeze and local topography. The Coast Range forms a partial barrier to this marine layer, preventing penetration to inland areas except where breaks in topography occur such as along river valleys. Fog dissipates when sufficient warming of the airmass occurs to raise temperatures and re-evaporate the fog droplets. When summer fog blankets the forest, relative humidity is increased while insolation and temperature are decreased, thus reducing transpiration by the vegetation. Summer fog influences the species composition of the coastal forest. Lacking stomatal control, the coast redwood is limited to a narrow belt along the California and southern Oregon coastlines, in large part because of the prevalence of summer fog.

Fog precipitation, or fog drip, occurs when fog droplets encounter an obstruction, coalesce, and fall to the ground. This phenomenon is largely limited to exposed ridges or crests during periods of cool temperatures less than 10 °C (Freeman 1971). The redwood, Douglas-fir, and spruce forest canopy is particularly efficient at intercepting water droplets and inducing fog drip. Kittredge (1948) reported that 285 mm of fog drip was collected during one summer season under an 85-year-old spruce/hemlock stand in coastal Oregon. Azevedo and Morgan (1974) reported seasonal fog drip totaling as much as 425 mm in northern California's Eel River valley. More recently, Dawson (1996) concluded that 8 to 34 percent of the water used by the coast redwood and 6 to 100 percent of water used by understory vegetation originated as fog precipitation at his study site on a hillslope near the mouth of the Klamath River. Ingraham (1995) analyzed fog, rain, and groundwater samples from the Point Reyes Peninsula and found that the isotopic composition of groundwater reflects the contribution of fog water.

Fog drip has not been measured at Caspar Creek. However, field observations suggest that it does occur. The frequency of daytime fog can be discerned from solar pyranometer data collected at a Caspar Creek site since 1988. Summer fog within the experimental watershed area is far less frequent than in coastal Mendocino County because of the more inland location of our study site. Along the coast, 30 to 50 percent of days during June, July, and August have morning fog (Goodridge 1978). At Caspar Creek, solar radiation data collected between 1988 and 1994 indicate that only 10 to 35 percent of the June-through-August days have insolation reduced by more than about one-third because of fog or cloud cover.

Did logging reduce fog drip? The removal of the forest canopy, especially near the ridges, probably resulted in less fog interception and drip. The pipeflow swales are located near the ridge in the NFC headwaters. Here, one might expect fog drip to play a more prominent role in the water balance than in the watershed overall, but July pipeflow increased dramatically during the first few postlogging seasons, suggesting that this was not the case. July measurements for 1995 and 1996 at K201 were below the predicted levels, but this reduction was not statistically significant. At some point during postharvest recovery, one might expect that evapotranspiration rates will return to preharvest levels while the forest canopy is not yet functioning as an effective fog drip collector. This has yet to be documented and thus remains hypothetical. Because these finer nuances of postlogging recovery will be difficult to detect at the weirs before additional timber harvest commences, continued evaluation of the postlogging summer discharge trend at the pipeflow sites is warranted.

Perhaps the smaller postharvest streamflow increases observed on SFC relate, in part, to this loss of fog drip. It is quite plausible that SFC receives more fog than NFC because of its proximity to the coast, but this has not been documented. What has been documented is a measurable postharvest increase in streamflow at both the NFC and SFC weirs, as well as increased soil moisture and pipeflow in the NFC watershed. If fog drip were an important component of the hydrology of Caspar Creek, we would have seen a *decrease* in soil moisture, pipeflow, and streamflow in the cut units, not the *increase* reported here.

Ecological Ramifications

The impacts of the Caspar Creek harvest treatments on stream and riparian ecology are more difficult to discern than the physical changes. An increase in summer discharge implies that the stream is less susceptible to water temperature increases. Maximum water temperatures increased about 9 °C (from 16 °C to 25 °C) after right-of-way clearing and road-building in the SFC riparian zone (Krammes and Burns 1973). Increased summer flows did not buffer these temperature effects. On the NFC, stream temperature changes after logging were not significant (Cafferata 1990, Nakamoto, these proceedings). The use of stream-side canopy retention zones on Class I and II channels was probably far more important in preventing increases in stream temperature than the summer streamflow enhancement.

Perhaps a more important effect of enhanced summer discharges is the increase in aquatic habitat developed in the channel. Higher discharge levels increased habitat volumes, and, as witnessed at the tributary gages, lengthened the flowing channel network along logged reaches. Nakamoto (these proceedings) concludes that the amount of slow water habitat on the NFC increased after logging, but reports no corresponding increase in biomass of stream vertebrates.

In terms of both stream temperature and habitat availability, the summer flow enhancements are of greater importance than the increases in total annual water yield because it is during the summer streamflow recession that temperature and habitat carrying capacity are most critical. However, these discharge impacts are variable and relatively short-lived. Impacts of timber harvest associated with effects other than summer flow increases appear to be of greater significance to the ecology of Caspar Creek, as the other reports in these proceedings illustrate.

Conclusions

The Caspar Creek watershed studies reveal increased water yields and summer flows after timber harvesting. Increases observed at this site were more modest than those documented at other sites in the Pacific Northwest. Streamflow changes due to logging were most evident during the long, dry summer season. During this prolonged recession, zones of deep perennial saturation maintain streamflow (baseflow). After logging, reduced evapotranspiration allows for additional water to be stored and routed to streams as summer streamflow. At Caspar Creek, enhanced soil moisture in the rooting zone followed timber harvest in the North Fork clearcut units. Previously intermittent stream reaches and soil pipes became perennial. The larger increases in minimum flows observed on the North Fork are probably due to wetter soils in the clearcut units where minimal vegetation exists to use this enhanced moisture. On the South Fork, older second-growth residual forest vegetation more readily exploited this additional soil moisture.

Fog plays an important role in the regional ecology by moderating evapotranspiration. However, Caspar Creek data indicate that any possible postlogging loss of fog drip does not result in a net reduction in streamflow. Moisture savings due to reduced evapotranspiration appear to override fog precipitation losses at this site.

Continued monitoring will document the duration of summer flow increases due to the most recent North Fork logging only as long as additional harvest operations are postponed in both the North and South Fork watersheds. Fortunately, the M1 and K2 pipeflow sites provide the opportunity for continued evaluation of the effects of clearcutting on the baseflow processes without the complications caused by further harvest operations in the greater watershed area. Quantification of fog drip within the Caspar Creek watershed warrants investigation in light of the documented importance of this moisture source at some sites in the Pacific Northwest.

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