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Influence of Partial Harvesting on Stream Temperatures, Chemistry, and Turbidity in Forests on the Western Olympic Peninsula, Washington

Abstract

Stream temperatures, chemistry and turbidity were monitored in two partially harvested (7–33%) watersheds, Rock and Tower creeks, and an uncut old-growth watershed, West Twin Creek in the Hoh River Valley on the Olympic Peninsula, Washington. Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) was replanted in the harvested areas and red alder (*Alnus rubra* Bong.), a nitrogen fixer, dominated the riparian areas in the sampling sites on Rock and Tower creeks. We collected grab stream water samples monthly, from May 1996 to June 1998 and analyzed them for pH, electrical conductivity, total N and P, and major cations and anions. Stream temperatures were monitored continuously and turbidity was monitored monthly from May 1997 to June 1998. Partial harvesting had little influence on stream temperature, chemistry and turbidity 11–15 years after harvesting. Stream temperatures were more seasonally variable in the harvested streams compared to the unharvested old-growth site with an average summertime maximum elevated by 3.5°C. Maximum stream temperatures did not exceed 16°C in any stream and therefore salmonid species are not likely to be affected. There were significant differences in concentrations of some cations, anions and EC between the old-growth and the partially harvested watershed streams, but in most cases concentrations were actually higher in the unharvested watershed. Nitrate concentrations and stream turbidity were not significantly higher in the harvested watersheds.

Introduction

Forest management practices can alter the temperature, turbidity, and chemistry, of streams (Beschta and Taylor 1988, Binkley and Brown 1993). For example, removal of streamside vegetation increases the amount of solar radiation reaching the stream and elevates temperatures, which may be slow to recover even with regrowth of vegetation (Hostetler 1991). Although increased solar radiation may result in an increase in stream productivity, increases in temperature may negatively affect temperature sensitive species, particularly salmon (McCullough 1999). Harvesting can also result in increased siltation and stream turbidity (Binkley and Brown 1993) which may deplete salmon habitat. In addition, forest removal can result in increases of stream nitrate levels due to increased soil nitrification, although concentrations generally stay below drinking water standards (Binkley and Brown 1993). Recently, partial harvesting, has become a component of ecosystem management (Franklin 1992). Therefore, it is important to investigate the influence of partial harvesting on key environmental variables that affect stream health.

In the Pacific Northwest disturbed riparian areas are generally recolonized by red alder (*Alnus rubra* Bong.), a deciduous tree with a symbiotic bacteria in root nodules capable of fixing nitrogen. Wigington et al. (1998) hypothesized that the variability of nitrate concentrations and other chemical constituents found in 48 coastal Oregon streams was directly related to the red alder vegetation. However, the regrowth of red alder along the stream channel does not immediately result in increased nitrogen inputs to a stream, since it takes time for nitrogen-fixing bacteria to establish (Van Miegroet et al. 1992). It is important to determine if the legacy of forest harvest in the Pacific Northwest has resulted in shifts in stream chemistry, turbidity and temperature that negatively influence stream health.

Although the influence of harvesting on Pacific Northwest streams has been studied (Feller and Kimmins 1984, Beschta and Taylor 1988, Binkley and Brown 1993), few studies reporting changes in stream temperature, nitrate concentrations and turbidity after harvesting have been conducted in coastal streams, particularly on the western Olympic Peninsula of Washington. Some studies have been conducted in coastal Oregon (Miller and Newton 1983). We have been studying stream chemistry in a small old-growth forested watershed in the Hoh River valley (West

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Twin Creek) for more than 15 years (Edmonds et al. 1998) and in 1996 we initiated a study to compare data from this watershed with data from two adjacent partially harvested watersheds, Rock and Tower creeks, where the riparian zones are now dominated by red alder. The chemistry of these streams was monitored before harvesting (Larson 1979). Our objective was to determine if there were differences in stream temperature, chemistry and turbidity in the two partially harvested watersheds relative to the adjacent pristine old-growth watershed 10–15 years after harvesting.

Study Sites

West Twin Creek Watershed

The 58 ha West Twin Creek watershed is located in the Hoh River Valley on the western side of Olympic National Park (Figure 1), approximately 32 km inland from the ocean, and is described in detail in Edmonds et al. (1998). West Twin Creek is a first order stream. Stream width varies from 1–2 m and the average channel slope is 25.6 percent (Table 1). Elevations in the watershed range from 240 to 800 m, sampling was done at 240 m, just above the weir. Mean January and July air temperatures are 4 and 16°C, respectively at the Hoh Ranger Station. Soil temperatures never fall below 0°C and rarely exceed 20°C. Annual rainfall averaged 3333 mm from 1985 to 1994 and is strongly seasonal with most falling from October to May (Edmonds et al. 1998). Snow rarely falls in the lower elevations, but a weak snowpack may develop above 600 m. Annual discharge from the watershed from 1985 to 1994 ranged from 54 to 89% of precipitation. Soils are

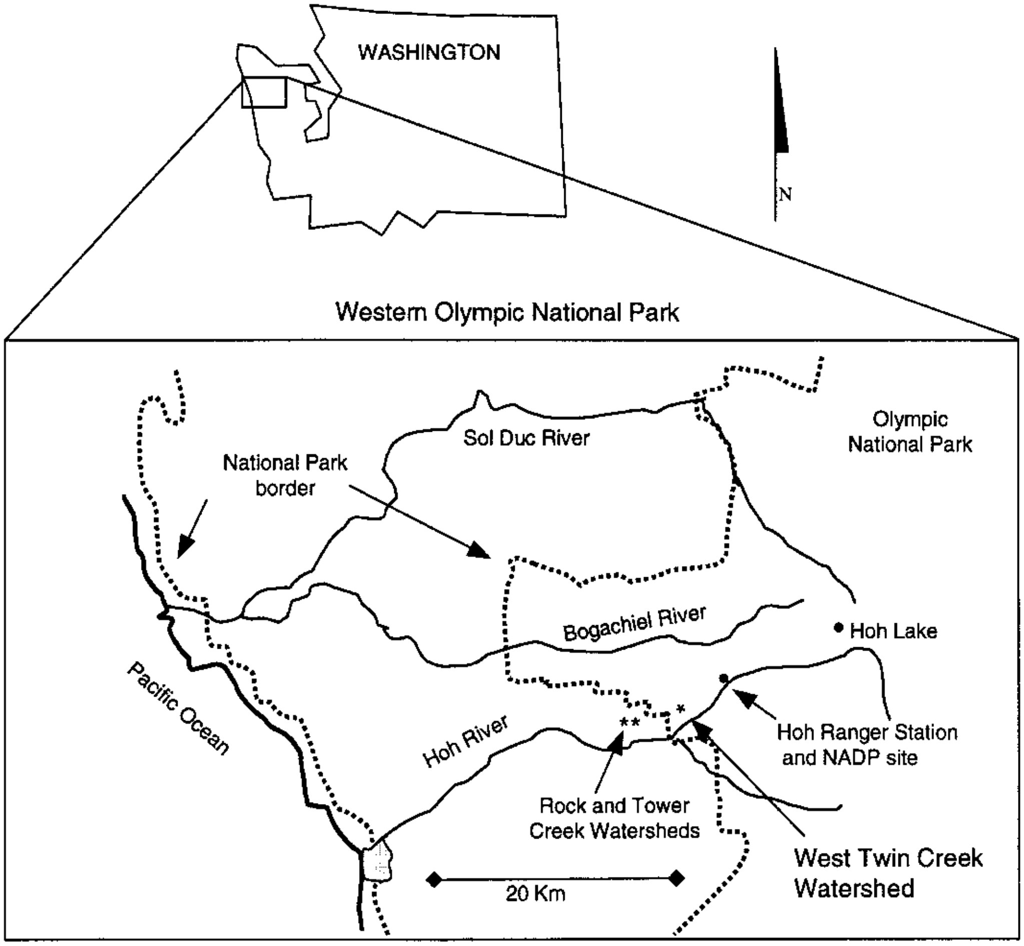

Figure 1. Location of the West Twin, Rock and Tower Creek watersheds in western Olympic National Park, Washington.

inceptisols, and forest floor depth ranges from 5 to 10 cm (Edmonds et al. 1998). The watershed encompasses two vegetation zones identified by Franklin and Dyrness (1973). The lower watershed is in the western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) zone, while the upper watershed is in the Pacific silver fir (*Abies amabilis* (Dougl.) Forb.) zone. The main tree species in the watershed are Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock, western red cedar (*Thuja plicata* Don.) and Pacific silver fir. The forest is uneven-aged with oldest trees more than 600 years.

Rock and Tower Creeks

Rock (235 ha) and Tower (263 ha) Creek watersheds are located on Washington State Department of Natural Resources lands just outside of the Olympic National Park (Figure 1) and are 24 and 26 km inland from the ocean. Both streams are slightly wider than West Twin Creek (3–4 m) at the sampling sites just above the weirs, and are higher order streams. However, all 3 watersheds extended over similar elevations, with the Rock and Tower watersheds ranging from 170 to 825 m and from 230 to 900 m, respectively (Table 1) from the weirs to the upper boundaries. Average channel slopes are 21.7 and 21.3 percent for Rock and Tower creeks, respectively. All sampling was done at the lower limit of the elevation range just above the weirs. The climate in the watersheds is similar to that in the West Twin Creek watershed and annual discharge from 1975 through 1977 ranged from 86 to 91% of precipitation (Larson 1979). Soils are inceptisols (Larson 1979).

Both watersheds originally contained old-growth forest similar to that in the West Twin Creek watershed (Larson 1979). In 1981, a small portion, 7%, of the Rock Creek watershed was logged while 33% of Tower Creek watershed was logged from 1985 to 1987. Logging did extend to the stream channel, including the area adjacent to our stream sampling. Both sites were replanted with Douglas-fir and there is natural regeneration of western hemlock. Red alder dominates the riparian zones. Anadromous fish are not present above the weirs in any of the watersheds.

Methods

Stream temperatures

Stream temperatures were monitored using Optic Stowaway® temperature dataloggers starting on 25 June 1996 in Rock and Tower creeks, and on 10 July 1996 in West Twin Creek. Monitoring continued through 15 June 1998. Daily maximum, minimum and average temperatures were determined.

Stream chemistry

Concentrations of cations, anions, and total N and P, Electrical Conductivity (EC), and pH were determined from grab samples collected from the three creeks once every four weeks from 15 May 1996 through 4 June 1998. Samples were placed in a cooler for transportation back to the laboratory, and analyzed at the Analytical Services Laboratory at the College of Forest Resources, University of Washington. Electrical conductivity, pH and alkalinity (reported as HCO_3) were determined on unfiltered samples. EC was determined with a YSI Model 31 Conductivity Bridge (Yellow Springs Instrument Co., Yellow Springs, OH 45387) and corrected to 25°C. pH was determined with a Radiometer PHM85 pH meter (Radiometer, Copenhagen, Denmark). Alkalinity was determined by titration to an end point of pH 5.

TABLE 1. Watershed characteristics.

Watershed	% Harvested	Elevation Gradient (m)	Average Channel Slope, S_c (%)[1]	Catchment Length (km)	Aspect (degrees)	Distance from Ocean (km)
Rock	7	170-825	21.7	2.5	200	24
Tower	33	230-900	21.3	2.2	215	26
West Twin	0	200-800	25.6	0.9	145	32

[1] S_c=(elevation at source - elevation at mouth)/stream length (values were estimated from USGS topographic map, scale 1:64,000 enlarged by 400%).

Remaining sample material was filtered through Whatman GF/A filters and stored at 4°C and analyzed within a month after arrival at the lab.

Solutions were analyzed for Ca, Mg, K, and Na, using Inductively Coupled Plasma atomic emission spectrometry. Ammonium was determined with a Technicon Autoanalyzer II (Technicon, Tarrytown, NY 10591). Sulfate, Cl, NO_3 and PO_4 were determined with a Dionex 2100 Ion Chromatograph (AS4A and AG4A columns) (Dionex, Sunnyvale, CA 94088). Macro Kjeldahl digests were done on all samples having sufficient volume and those digests were analyzed for total N and P using a Technicon Autoanalyzer II.

Turbidity

Turbidity in the three creeks was determined using a HF Scientific, Inc. Model DRT-15CE portable turbidity meter. Samples were taken every four weeks from May 1997 to June 1998 at the same time that samples were taken for stream chemistry. Turbidity was recorded in nephelometric turbidity units (NTUs). Except for the samples taken on 17 December 1997 and on 14 January 1998 stream samples were taken in midstream and turbidity recorded after approximately 40–60 seconds. On 17 December 1997 and 14 January 1998 three samples were taken across the stream and turbidity was read after 30, 35 and 40 seconds and the average was calculated.

Statistical analyses

Differences in average concentrations of elements and turbidity in the three streams were detected using one-way ANOVA with a Post Hoc Tukey HSD test ($p = 0.05$), using SPSS® software.

Results and Discussion

Stream temperatures

Daily average and maximum temperatures for the three streams over the period from 15 May 1996 to 15 June 1998 are shown in Figures 2A and 2B, respectively. Some data are missing in summer 1997 because the data loggers malfunctioned in Rock and Tower creeks. Daily average temperatures in West Twin Creek were lower in summer and higher in winter than those in Rock and Tower creeks (Figure 2A). Rock and Tower creeks were similar. The range was less variable in West Twin Creek (5.4–11.4°C) than in Rock and Tower creeks (1.9–15.1°C).

Daily maximum stream temperatures (Figure 2B) had similar patterns to the average stream temperatures with greater seasonal fluctuations in Rock and Tower creeks than West Twin Creek. Maximum temperatures in the summer were higher in Rock and Tower creeks (15.4°C) than West Twin Creek (12.1°C) and lower in winter (3.7 and 6.0°C, respectively). Minimum temperatures were also more extreme in harvested watershed creeks with the lowest minimum temperature in Rock Creek, 1.2°C compared to 5.5°C in West Twin Creek.

Higher stream temperatures and greater fluctuations in Rock and Tower creeks compared to West Twin Creek could be due to harvesting activities. In Oregon, Hall and Fredriksen (1988) found summer daily average stream temperatures to be 2.5 to 3°C higher in watersheds with 25 percent harvested area than control watershed streams. With 66 percent overstory removal in British Columbia, Feller (1981) found a 5°C increase in summer average daily stream temperatures. These increases are similar to the increases we found in summer (Figure 2A). In Salmon Creek watershed, Oregon, Beschta and Taylor (1988) found increased maximum and minimum stream temperatures over a 30-year period due to the cumulative effects of forest harvesting. This included disturbance of regrowing streamside vegetation during peak flow events which prolonged recovery of riparian shade. In another Oregon watershed, Streamboat basin, extensive logging has been conducted since 1955, which did not include leaving riparian buffer strips until the early 1970s (Hostetler 1991). Stream temperatures have only gradually recovered in the basin and summer high temperatures remained near the upper tolerance level for steelhead in some streams (Hostetler 1991). In our study, the maximum temperatures were not above water quality standards, however, some differences were observed 11–15 years after harvest. Rock and Tower creeks are larger creeks than West Twin Creek and should be more buffered against stream temperature changes than smaller streams. Therefore the increases are due to some other factor, perhaps differences in riparian zone shade.

Although shade is a factor, stream gradient and the elevation at which monitoring occurs may also influence stream temperatures. In a model

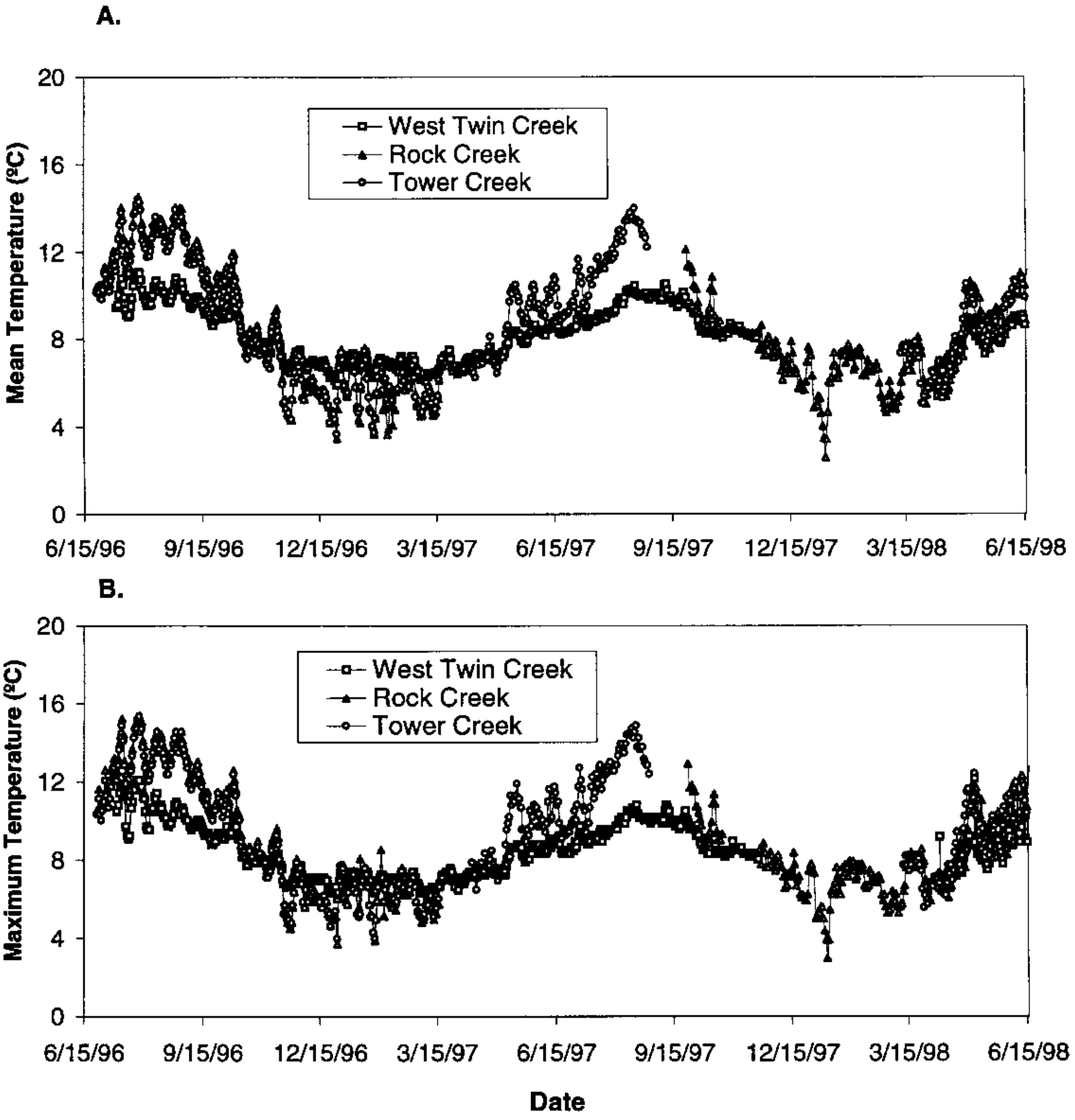

Figure 2. A. Mean daily, and B. maximum daily stream temperatures in West Twin, Rock and Tower Creeks from June 1996 to June 1998.

developed by C. Earle, Beak Consultants Inc. (unpublished), using data from 92 streams in Washington State, shade had little influence on stream temperatures at elevations below 447 m. All streams monitored below this elevation were likely to exceed 16°C, the Washington State water quality upper limit for salmonids, regardless of the amount of shade. When gradient was included in the analysis the model suggested that steep gradient streams would have a buffered stream temperature regardless of shade. All of our monitoring was done between 170–244 m. West Twin Creek had the steepest stream gradient and shortest catchment length among the watersheds (Table 1). However, from the data available to us we cannot determine if the differences in stream gradient and catchment length in our study influenced the buffering of stream water temperatures.

Stream Chemistry

pH, Alkalinity, Electrical Conductivity, Total N and Total P

There were no seasonal patterns or significant differences in pH amongst the streams and pH was > 6.5 except for the two drops seen in West Twin Creek (Figure 3A). The low pH values in West Twin Creek occurred in spring of both 1996 and 1997 and have corresponding dips in alkalinity (Figure 3B). Rainfall measured at the Hoh Ranger Station nearby the watersheds and streamflow from West Twin Creek are presented in Figure 4A and B (streamflow was not measured in the harvested creeks). The sampling dates when large decreases in pH were detected were preceded by large rain events of 191 and 202 mm in one day (only 7 out of 2291 days measured have exceeded 178 mm of rain). Streamflow data were unavailable for the first large rain event but the later event resulted in a quick response in streamflow (Figure 4B). Whitfield et al. (1993) demonstrated that storm events in a coastal British Columbia forested watershed resulted in rapid and significant decreases in alkalinity that took days to recover. Although in that study pH decreased only slightly the authors hypothesized that a larger storm could consume all of the alkalinity and pH would then decrease significantly (Whitfield et al. 1993). A large storm event may cause dilution of base flow, dominated by base cations, and an increase in subsurface flow, dominated by organic acids and nitrate, resulting in a dramatic change in stream chemistry (Whitfield et al. 1993). From autumn of 1993 through 1995, the pH of West Twin Creek was lower than the long-term average due to acidic inputs (Edmonds et al. 1998). This may have lowered the buffering capacity of the stream. The reason we do not see pH and alkalinity drops in the harvested streams may be due to: (1) lack of a thick organic layer, and (2) soil disturbance after harvesting providing more buffering capacity deeper in the soil profile. More extensive sampling of storm events and soils are needed to ascertain this.

There appeared to be little long-term influence of harvesting on stream pH, alkalinity, EC, and total N and P concentrations. Total N and P concentrations were not different among streams and were generally low ranging between 0–0.62 and 0–0.72 mg L^{-1} for N and P, respectively. Electrical conductivity was slightly higher ($p<0.0001$) in West Twin Creek (Figure 3C) than Rock or Tower creeks. The typical seasonal pattern that we have observed in the past in West Twin Creek (Edmonds and Blew 1997), i.e., high EC during low summer flow reaching a peak in September before the start of the rainy season and low values in winter, were observed in all three streams.

Cations

Calcium (Figure 5A) and Mg (Figure 5B) concentrations were consistently higher ($p<0.0001$) in West Twin Creek (averaging 777 µeq L^{-1} and 164 µeq L^{-1}, respectively) than in harvested streams (averaging 639 µeq L^{-1} and 125 µeq L^{-1}, respectively). Potassium (Figure 5C) and Na (Figure 5D) concentrations were not significantly different among streams (averaging 40 µeq L^{-1} and 161 µeq L^{-1}, respectively), however, there was a Na peak in August of 1996 in the harvested streams that was not in West Twin Creek. Sodium, Ca and Mg all varied seasonally, that is, highest values occurred in summer and fall and lowest values occurred in winter (Edmonds and Blew, 1997). Cations tend to concentrate when flows are low and are diluted when flows are high and rock contact time is shorter. The weathering of minerals, including calcite, albite, vermiculite, and kaolinite, is likely the main source of these cations (Larson, 1979). However, a large source of Na input to coastal streams is from precipitation, due to oceanic aerosols and particles. In fact Na was found to be the dominant cation in precipitation at these sites (Blew and Edmonds, 1995). The Na peak observed in August 1996 in the harvested streams may have been due to inputs from the ocean, although no unusual precipitation events occurred during that month (Figure 4A). The reason for the lack of this peak in the old-growth site is not clear; however, it may be due to the difference in distance from the ocean and watershed aspect (Table 1). It has been shown that the concentration of Na and Cl in precipitation can decrease with distance from the ocean with the largest changes occurring within 10–40 km (McColl, 1982, Blew and Edmonds, 1995). Wigington et al. (1998) also showed that Cl concentration in stream waters decreased at similar distances from the ocean. Unlike the higher concentrations of Mg and Ca found in West Twin Creek Na concentrations were not different in comparison to the harvested streams

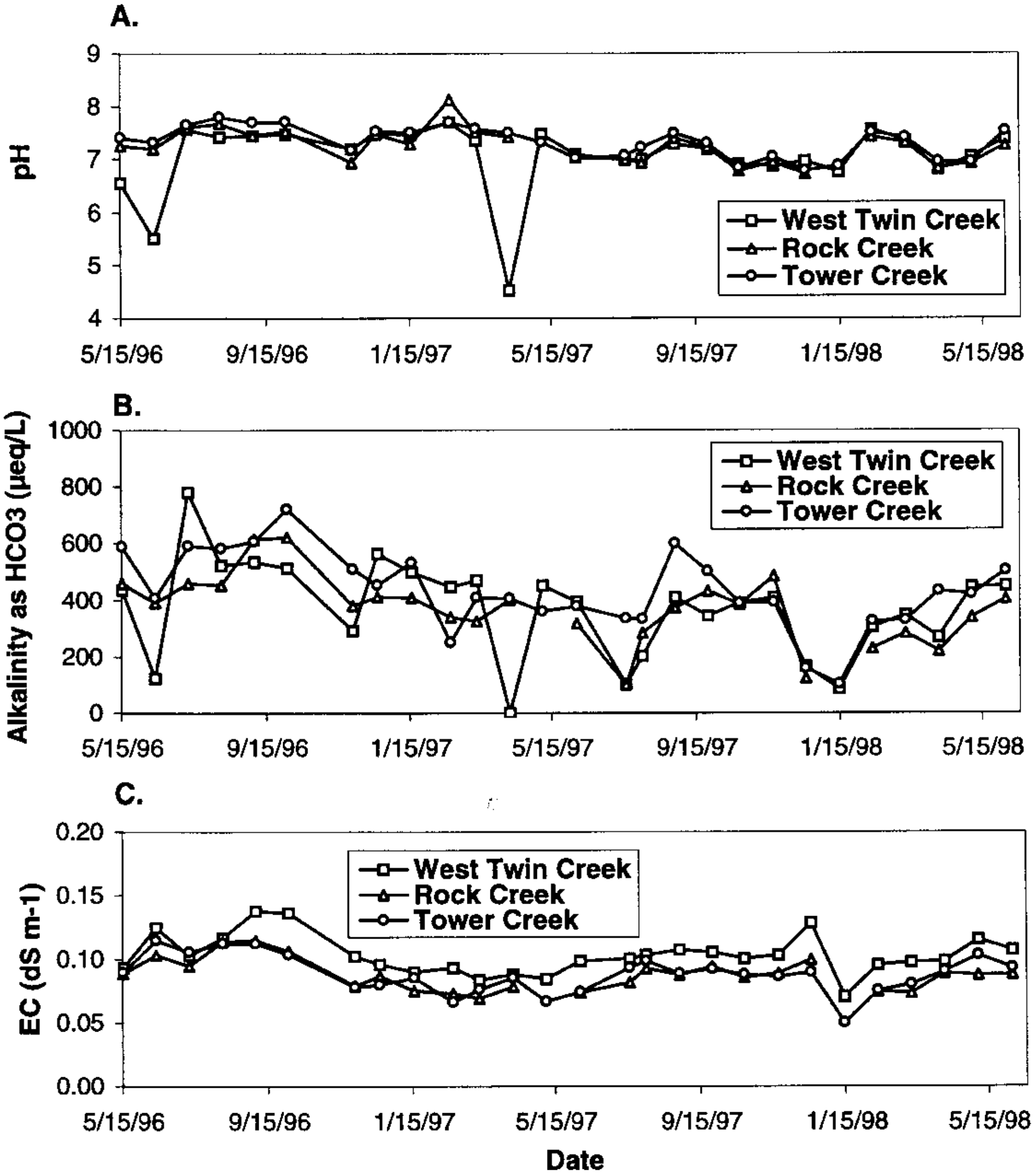

Figure 3. A. pH, B. alkalinity, and C. electrical conductivity (EC) in West Twin, Rock and Tower creeks from May 1996 to June 1998. Average EC was significantly higher in West Twin Creek than Rock and Tower creeks ($P < 0.001$). No significant differences for pH and alkalinity.

(Figure 5D) while Cl concentrations were lower (Figure 6B). The ratio of Na to Cl is also higher in West Twin Creek than the harvested streams (2.4 and 1.7, respectively), suggesting that the watersheds are influenced differently by sea salt inputs. Excess Na concentrations in precipitation, from 1984–1999 (Edmonds, unpublished data), show that it is not unusual to have oceanic influenced inputs in the summer, perhaps due to marine fog. Canopy cover is also a factor in how Na and Cl enter the watersheds. Salts can concentrate on leaves and needles during the summer

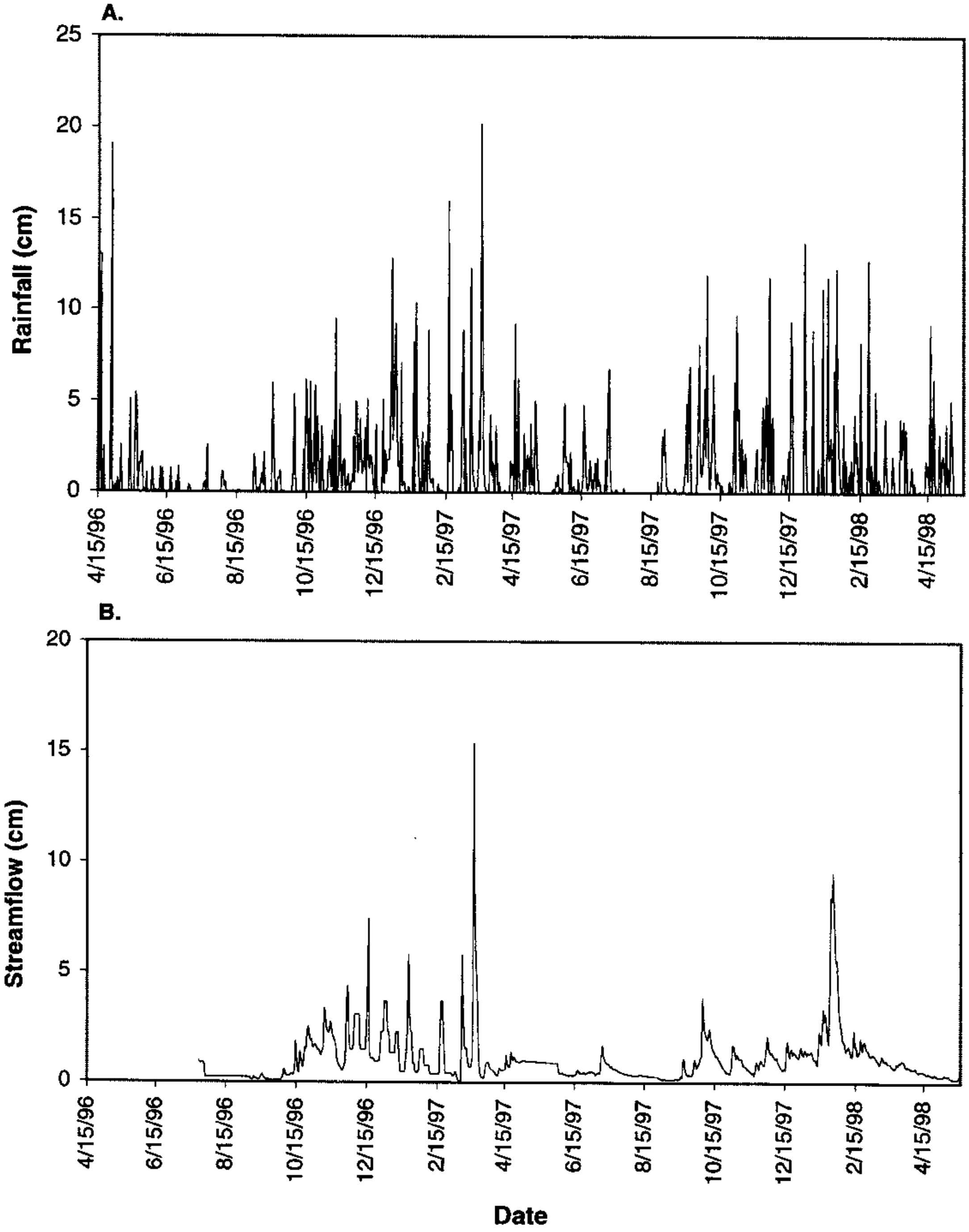

Figure 4. A. Daily rainfall (cm) from the Hoh Ranger Station and B. Daily streamflow (cm) at West Twin Creek weir.

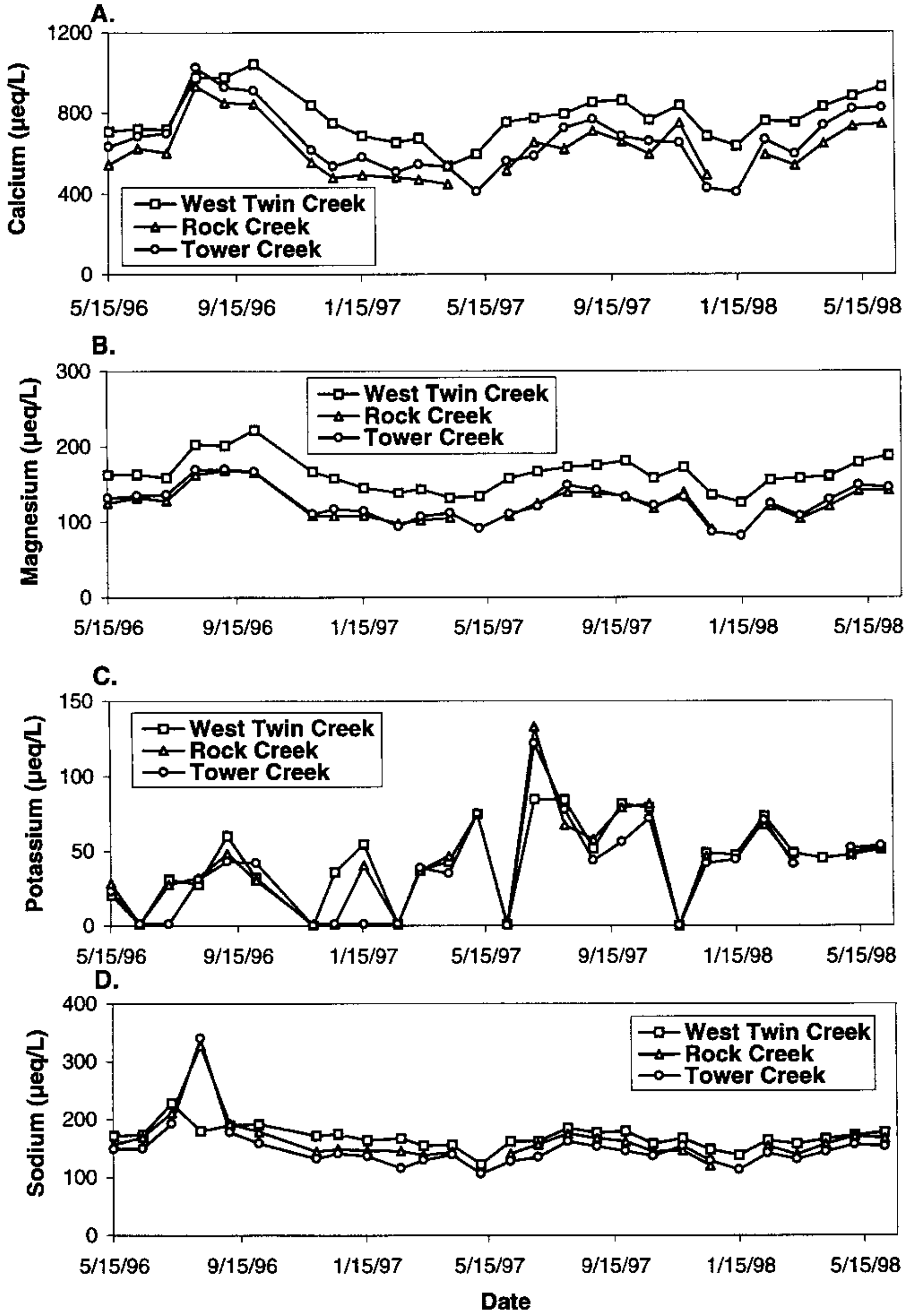

Figure 5. Concentrations (µeq L^{-1}) of A. calcium, B. magnesium, C. potassium, and D. sodium in West Twin, Rock and Tower Creeks from May 1996 to June 1998. Average concentrations of calcium and magnesium were significantly higher in West Twin Creek than Rock and Tower creeks ($P < 0.0001$). No significant differences for potassium and sodium.

time resulting in input pulses with the onset of rain. The harvested streams have red alder that hang over the stream channel, while the old-growth channel has a less dense and higher canopy.

Ammonium concentrations in all streams were low and often below detection averaging 0.9, 1.0, and 0.6 µeq L^{-1} for Rock, Tower and West Twin creek respectively. The concentrations of cations we observed were similar to those observed by Wigington et al. (1998) in coastal streams in Oregon, although our Ca, K and Na concentrations were slightly higher.

The lower cation concentrations observed in the harvested watersheds are probably due to more runoff. Harvesting can decrease the amount of evapotranspiration, and hence increase runoff, due to lower leaf area (Swift and Swank 1981) and this effect can be larger in wetter areas (Bosch and Hewlett 1982). Thinning has also been noted to decrease evapotranspiration (Aussenac et al. 1982). Evapotranspiration is low in the old growth site, averaging 22% of precipitation from 1985–1994 (Edmonds et al. 1998), and may be even less in the harvested watersheds. However, it is unlikely that differences in evapotranspiration alone could account for the differences in cation concentration. Differences in soil weathering rates may also contribute to the differences in concentrations we observed. Our results could indicate that the soil in old-growth sites are weathering faster than the disturbed sites. It may be that the amount of organic acids is higher in the old-growth soils and this may enhance weathering rates during base flow. Viers et al. (1993) found that organic acids increased weathering and solutes leaving tropical forest catchments. The underlying mineral soils and bedrock are similar in all three watersheds (Larson 1979, Edmonds et al. 1991), therefore differences in organic horizons in the watersheds may be a reasonable explanation.

Anions

There were few differences in NO_3 concentrations among the streams except during the summer of 1996 (Figure 6A). All three streams had increased NO_3 concentrations in July 1996. Concentrations in West Twin Creek then fell while they increased to a maximum concentration of 60 µeq L^{-1} in Rock and Tower creeks in August 1996. In the past we have observed peaks in NO_3 concentrations in West Twin Creek in the late summer or fall when the rainy season begins and vegetation demands are decreased (Edmonds and Blew 1997). Although the summer of 1996 was relatively dry it was not without summer rainstorms that could have mobilized the nitrate to the stream. The prolonged NO_3 pulse in the disturbed watershed may have been due to red alder in the riparian zone. Stottlemyer (1992) related elevated stream nitrate concentrations to the presence of alder vegetation in the riparian area of a stream in Alaska. Wigington et al. (1998) suggested that the high nitrate concentrations in autumn from 48 streams in Oregon were mainly due to red alder. They found concentrations NO_3 concentrations ranging from 28 to 94 µeq L^{-1} in coastal streams. The maximum concentration we found in Rock and Tower creeks was 60 µeq L^{-1}.

A seasonal NO_3 peak was not observed in any of the three streams in 1997. This also was observed in a nearby Queets tributary (Bechtold et al. 1999). We hypothesize that the pattern observed in 1997 was due to excess rains during an El Niño that kept soils moist throughout the summer (Figure 4A), not allowing the buildup of nitrate. Others have found that stream NO_3 concentrations vary seasonally and often peak with increasing flows during spring snowmelt (Foster et al. 1989, Arheimer et al. 1996). High stream NO_3 concentrations were observed at a site in Wales after a warm and dry period followed by increased rain (Roberts et al. 1984). These studies and our results emphasize the influence of the hydrologic cycles on nitrate leaching.

There were no significant difference in alkalinity (Figure 3B), Cl (Figure 6B), and PO4 (data not shown) among the three streams and concentrations were similar to those found by Wigington et al. (1998) in coastal streams in Oregon. However, alkalinity did decrease significantly in West Twin Creek when pH decreased in the spring of 1996 and 1997, as discussed earlier. Sulfate and silica concentrations were significantly higher ($p<0.0001$) in West Twin Creek than Tower and Rock creeks (Figure 6C and 6D), however, seasonal patterns were similar between streams. For sulfate the highest concentrations were observed in the summer. Sulfate is present in the bedrock material of this area and the major source to these streams is weathering (Larson 1979). Silica

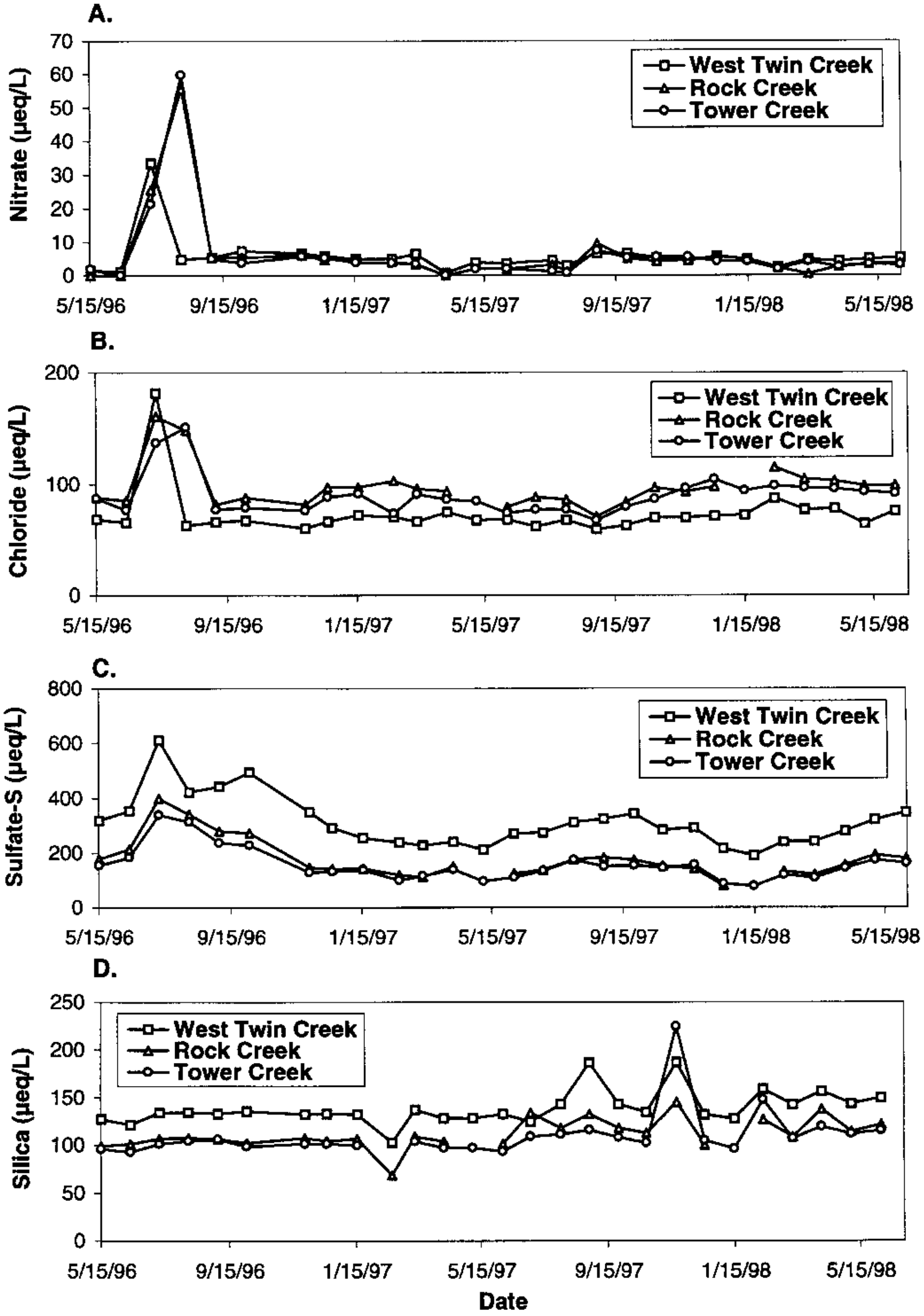

Figure 6. Concentrations (μeq L^{-1}) of A. nitrate, B. chloride, C. sulfates, and D. silica in West Twin, Rock and Tower Creeks from May 1996 to June 1998. Average concentrations of sulfates and silica were significantly higher in West Twin Creek than Rock and Tower creeks ($P < 0.001$). No significant differences for nitrate and chloride.

concentrations did not have a seasonal pattern. Similar to the cation concentrations the difference observed in sulfate and silica are likely due to differences in runoff and weathering.

Stream turbidity

Concentrations of suspended sediments can increase after forest harvesting and road construction, but not always (Binkley and Brown 1993). Turbidity data for Rock, Tower and West Twin creeks are shown in Figure 7. Turbidity was low and not significant among the streams, averaging 1.06, 0.89 and 0.83 NTU for Rock, Tower and West Twin creeks, respectively, which is typical for Northwest streams (Binkley and Brown 1993). In the winter of 1997–1998 turbidity in all three streams increased, with maximum values of, 3.63, 4.37 and 4.63 NTU for Rock, Tower and West Twin creeks, respectively. This was likely due to storm events and higher flows. In a study in California by Bolda and Meyers (1997) turbidity increased during storm events. Although there were no increases due to disturbance, variability was greater in disturbed watersheds. In addition, suspended sediments were significantly higher in one year. The discrepancy between turbidity and suspended sediment measurements was due to larger soil particles derived from the sandy loam soil increasing the mass but not the refractive properties of the samples (Bolda and Meyers 1997). Fowler et al. (1988) found an increase in turbidity and suspended sediment immediately after road construction in harvested areas, but little after that.

Conclusions

Partial harvesting of 7–33% of the land area in the Rock and Tower creek watersheds resulted in only small influences on stream temperature, chemistry and turbidity 11–15 years after harvesting. This suggests that partial harvesting may be a successful aspect of ecosystem management with respect to streams. Maximum stream temperatures increased by only about 3°C in the harvested streams compared to the unharvested old-growth site and were more seasonally variable. Stream temperatures did not exceed 16°C in any stream and therefore salmonid species are not likely to be affected; there were no salmonids in our streams. There were some significant differences in concentrations of some cations, anions and EC between

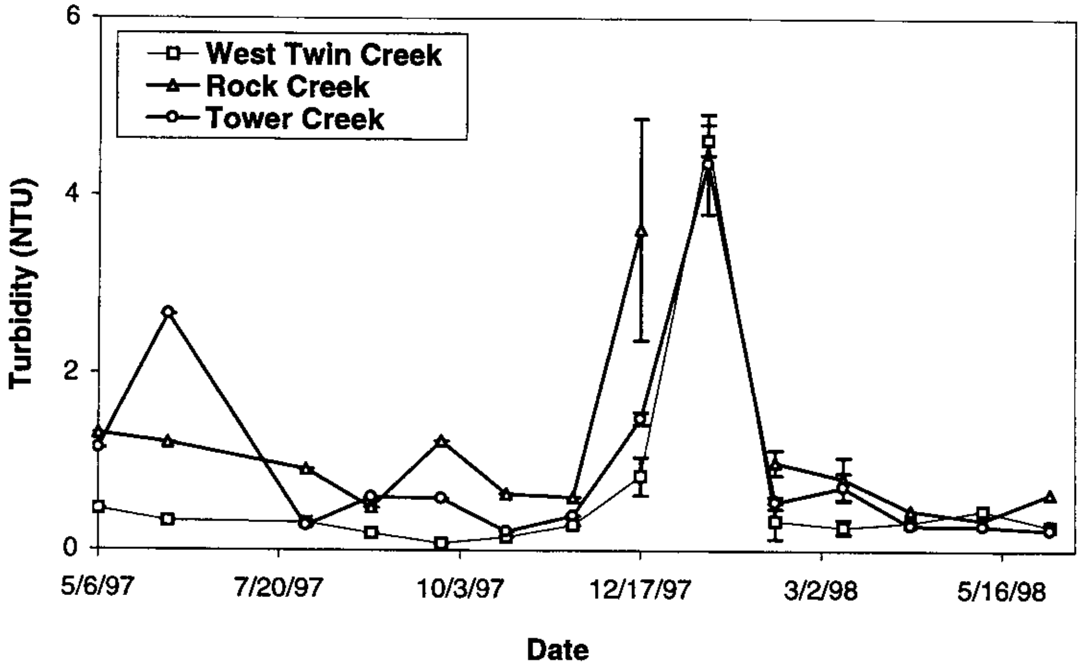

Figure 7. Turbidity in West Twin, Rock and Tower creeks from May 1997 to June 1998. Error bars are standard deviations. Average turbidity was not significantly different among watersheds ($P < 0.001$).

the old-growth and the partially harvested watershed streams, but in most cases concentrations were actually higher in the unharvested watershed. Average nitrate concentrations were not significantly different among watersheds, although the highest nitrate concentrations were observed in the harvested watersheds. Red alder in riparian areas may be contributing to the higher nitrate in the disturbed watershed streams. Stream turbidity was not significantly higher in the harvested watersheds. However, our study did not address the effects of logging that can occur within the first few years post harvest such as increased siltation and nitrate pulses that have been documented at other sites (Binkley and Brown 1993).

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