Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California

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Compositional Variations with Season and Logging History in Streams of the Redwood Creek Basin, Redwood National Park, California

By WESLEY L. BRADFORD

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COMPOSITIONAL VARIATIONS WITH SEASON AND LOGGING HISTORY IN STREAMS OF THE REDWOOD CREEK BASIN, REDWOOD NATIONAL PARK, CALIFORNIA

By WESLEY L. BRADFORD

ABSTRACT

A 2-year study was made in the Redwood Creek drainage basin of Redwood National Park to determine existing chemical water-quality conditions and to identify the effects of logging on water quality in the main stem and tributaries.

Overall, the chemical water quality of the main stem and the tributaries is excellent, suitable for most beneficial uses. Dissolved-solids concentrations range from 25 milligrams per liter during the rainy season to 139 during the dry season. Water shifts from a mixed calcium-sodium bicarbonate-chloride type toward a calcium-bicarbonate type from the end of the wet season (about April) to the end of the dry season (about October). It shifts back toward a mixed calcium-sodium bicarbonate-chloride type from the end of the dry season to the end of the wet season. The pH shifts with the water type from a median value of 6.80 in the wet season to 7.37 in the dry season.

Evidence suggests that dissolved calcium and bicarbonate in stream water is produced by weathering of the Franciscan assemblage underlying the basins but that chlorides are transported inland from the ocean as dry fallout and spray and in rain. Exposure of the surface soils to the elements, either by logging or by natural causes such as sparse vegetation, seems to accelerate weathering, which leads to a calcium-bicarbonate water type. Logging accelerates weathering most in the tributary watersheds with regoliths derived from sandstone and least in those with regoliths derived from schist; however, the data suggest that the rate of weathering in a schistose watershed can increase dramatically if soil disruption is extensive.

Data collected during storms indicated that specific conductance and alkalinity were more likely to decrease at the discharge peak in logged watersheds than in forested ones. This suggests that overland flow, which contains lower concentrations of soil-derived dissolved solids than flow from other sources, is a larger component of peak flow in logged watersheds than in forested watersheds.

INTRODUCTION

BACKGROUND

The Redwood Creek drainage basin (fig. 1) is along the northern California coast where the moist, mild climate and seasonally heavy rainfall are suitable for growth of the coast redwood *(Sequoia sempervirens)* and associated vegetation. Prime examples of old-growth redwood forests are found here, particularly in Redwood National Park and neighboring State parks.

Redwood National Park was established by the U.S. Congress on October 2, 1968. The park includes downstream areas of the Redwood Creek basin and, by later acquisition, areas upslope of the park boundary. This study was completed before the later acquisitions, however. The National Park Service recognized the potential dangers to park resources from upslope logging and, soon after the creation of the park, began studies to assist in managing the park resources. On August 16, 1973, the National Park Service authorized a 3-year program of studies, and the U.S. Geological Survey began collecting data in September of that year.

Data and results of the studies have been presented in several reports. Janda and others (1975a) presented a comprehensive report on environmental conditions in the Redwood Creek drainage basin. Iwatsubo and others (1975, 1976) presented the water-quality, sediment-discharge, and biological data collected during the first 2 years of study. Janda and others (1975b), Lee and others (1975), Averett and Iwatsubo (1975), and Harden and others (1978) published interpretive reports of water and sediment discharge, rainfall-runoff relations, and aquatic biology. Results of water-quality studies were presented by Bradford and Iwatsubo (1978).

DESCRIPTION OF STUDY AREA

The Redwood Creek drainage basin consists of 725 km^2 of generally high-relief, geologically unstable terrain in California's northern Coast Ranges. Basin elevation ranges from sea level at the northern end near Orick to

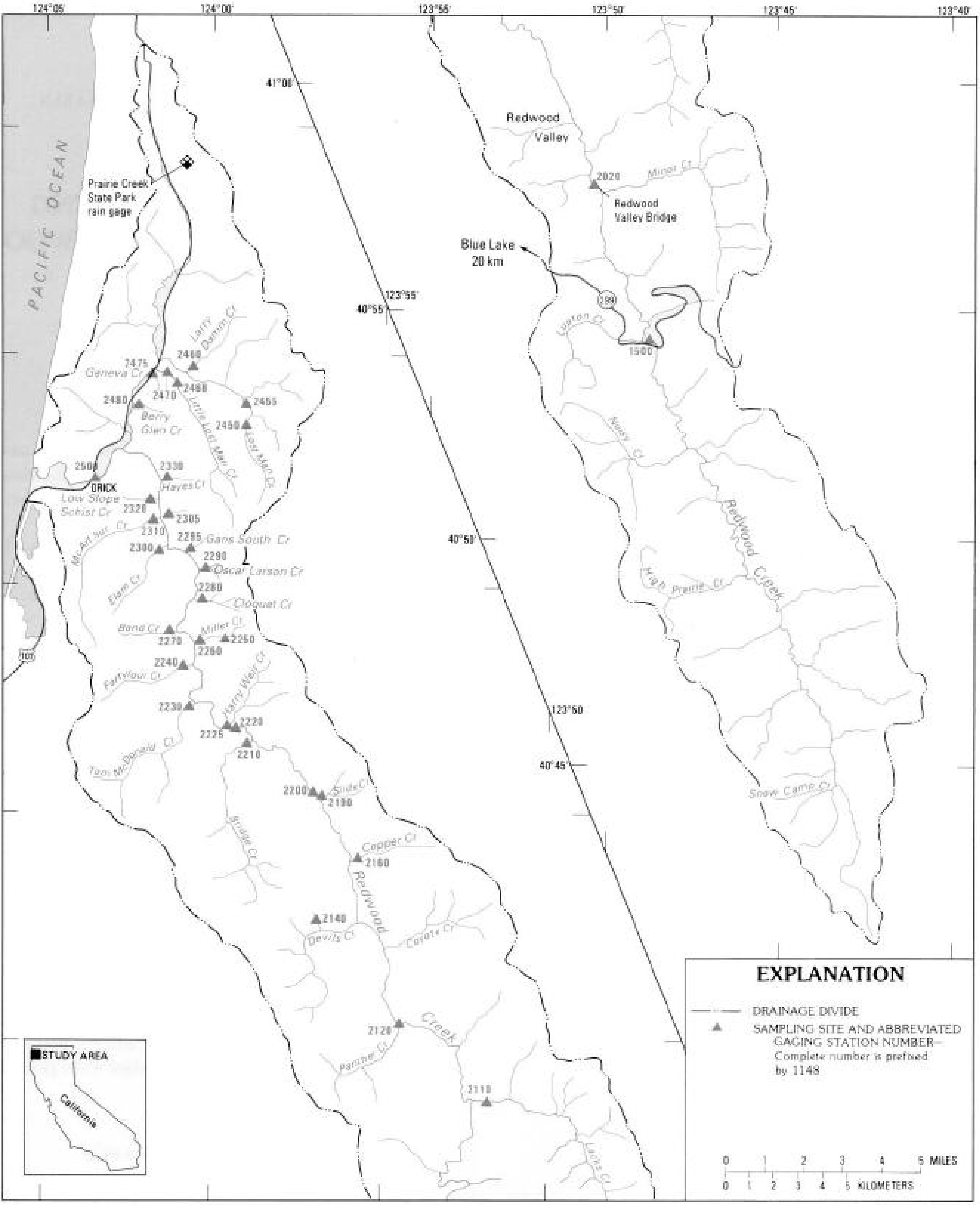

FIGURE 1. – Redwood Creek basin, showing location of sampling sites

1,600 m in the southern end. The relief, in cross sections normal to the basin axis, ranges from 600 m in the northern end of the basin to 900 m in the southern end. Hillslope gradients range from an average of 31 percent in the northern quarter to 34 percent in the southern quarter of the drainage basin. Slope gradients steepen from the drainage-basin boundary to the stream channels and in several places are nearly vertical adjacent to the streams. Flood plains along Redwood Creek are discontinuous, and most are less than 60 m wide.

The climate in the northern part of the Redwood Creek drainage basin is influenced by the ocean. It is described as coastal Mediterranean and is characterized by high winter precipitation (1,780 to 2,290 mm/yr), mild temperatures, and short, dry summers having infrequent fog. Precipitation varies widely from year to year and is greatest at highest elevations. Most precipitation occurs as rain from large storm systems generated in the Pacific Ocean. Occasionally, snow falls at higher elevations; however, accumulations usually do not exceed 0.6 m. Near the coast, some precipitation also occurs as fog drip (Janda and others, 1975a, p. 89).

Through much previous work and numerous data on California coastal streams, it is known that the seasonal pattern of streamflow follows the seasonal pattern of precipitation in a well-established sequence. As the dry season gets underway, usually in April or May, water stored in ponded areas and channels drains off. As the dry season progresses, streams are fed at a low and gradually decreasing rate by base flow made up of ground water with a long residence time in the soil and underlying materials. Soil moisture is depleted, and water levels in the ground-water reservoir decline.

When the rainy season returns, usually in October or November, precipitation first replenishes the soil moisture, and there is little runoff. At times precipitation may be intense enough to exceed the infiltration rate and cause some runoff as overland flow, which makes little contact with the soil, or quick-return flow (Jamieson and Amerman, 1969), which has short-term contact with the soil (several minutes). As the rainy season progresses, soil-moisture needs are met; infiltration gradually replenishes the ground-water reservoir, causing an increase in base flow; and the soil becomes more saturated, causing overland flow to appear more quickly in response to precipitation than earlier in the season. Also, streamflow between storms increases, owing to delayed-return flow (Kennedy and Malcolm, 1978). Delayed-return flow is water that makes contact with the soil for several hours and reemerges as surface flow (Jamieson and Amerman, 1969).

Vegetation in the Redwood Creek basin varies with slope, elevation, microclimate, and several other factors. In the lower flood plain near Orick, the vegetation is a mixture of shrubs, grasses, pasture, and trees—predominantly Sitka spruce and shore pine. Redwood and Douglas-fir dominate the upland vegetation from the shore to about 15 km inland (Janda and others, 1975a, p. 102). Farther inland, redwoods grow only in the moist flood plain, terraces, and lower slopes adjacent to streams. On higher ground, Douglas-fir, tan oak, and mandrone become more abundant; on high ground toward the southern end of the basin, Douglas-fir, white fir, incense cedar, and black oak predominate.

The Redwood Creek basin is underlain by the indurated Franciscan assemblage, which shows varying degrees of metamorphism. The eastern side of the basin consists mostly of unmetamorphosed marine sedimentary rocks, largely graywacke and sandstone with lesser amounts of mudstone and conglomerate. By contrast, rocks on the western side are finer grained and consist of small, discontinuous bodies of greenstone, bedded radiolarian chert, and thick deposits of mudstone interbedded with sandstone (Janda and others, 1975a, p. 10-11). Schists, mostly light - to medium-gray quartz-mica-feldspar and quartz-mica, crop out throughout the western half of the basin.

The regoliths (the surface mantle of unconsolidated material produced by weathering and erosion) overlying unmetamorphosed sedimentary rocks range in thickness from about 0.5 m at higher elevations to about 4 m on lower slopes. The overlying soils have high infiltration capacity, good subsurface drainage, and moderate to high erosion potential.

Logging in the late 19th and early 20th centuries was limited largely to clearing flood plains and terraces in gentle terrain to provide pasture. By 1947 less than 5 percent of the Redwood Creek basin had been logged (Janda and others, 1975a, p. 114-122). The rugged topography upslope prevented large-scale timber harvesting until the early 1950's.

Intensive logging occurred in the upper part of the Redwood Creek basin in the early 1950's and in the lower part in the late 1950's. By 1973, only about 20 percent of the basin retained old-growth redwood forest. During the 1940's, the most common logging method was selective cutting of small timber plots, but in the 1950's the clearcutting of larger blocks and yarding (gathering for loading onto trucks) the logs downhill by tractor became popular. Soil disruption resulting from extensive logging probably increased erosion (Janda and others, 1975a, p. 164) and altered the hydrology of the basin (Lee and others, 1975).

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Arcata Redwood Co., Louisiana-Pacific Corp., Miller-Rellim Redwood Co., and Simpson Timber Co. allowed field teams general access to study stations on company properties.

STUDY DESIGN

Throughout this paper reference will be made to the Redwood Creek drainage basin, which encompasses several subbasins identified by the names of the creeks tributary to the main stem. To simplify terminology, the term "drainage basin" will be used to refer only to the entire Redwood Creek basin. The term "watershed" will be used to refer to the area drained by tributaries to Redwood Creek, and the name given to the watershed will be the name of the tributary creek.

WATERSHED CLASSIFICATION

The logging and regrowth of the Redwood Creek drainage basin has produced a complex mosaic of old growth, advanced secondary growth, and cutover forest areas. Table 1 shows the codes assigned to watersheds with regard to land use and regolith composition. Sampling stations (table 2; fig. 1) were selected to provide a data set representative of this broad range of land uses. More detailed descriptions of the regolith of watersheds upstream from the sampling stations are in Iwatsubo and others (1975, 1976).

STRATEGY OF DATA COLLECTION

Major effort was devoted to obtaining an overview of water-quality conditions at several stations (table 2) during several storms. In most of these synoptic studies, field measurements were made, and one to three samples were taken for laboratory analysis. Field measurements of alkalinity, specific conductance, pH, temperature, and dissolved oxygen were made at 2- to 6-hour intervals depending on the progress of the storm. Water samples for chemical analysis were taken at various times during each storm.

During two storms, November 6 to 8, 1974, and February 5 to 9, 1975, at Harry Weir Creek and at Little Lost Man Creek at site 2, samples for laboratory analysis were collected at 1-hour or longer intervals in an intensive study of the chemograph (time series of water-quality variations during storm runoff).

To determine the seasonal variations, water-quality measurements and samples were taken at all stations at regularly scheduled intervals. These data are referred to throughout this paper as nonsynoptic data.

TABLE 1. — *Codes designating watershed types with regard to land use and regolith composition*

Code	Description
	Land use
Main stem	Main-stem stations. (Not counted as a separate land use category.)
RF…….	Regrown, forested. Watershed first logged prior to establishing park (1968) and now substantially RF type. Not being logged during this study.
VL	Virgin timber, logged. Watershed first logged since 1968; in some cases watershed was being logged during this study.
RL	Regrown, being logged. Watersheds first logged well before 1968 and being logged of second growth during this study.
VF	Virgin timber, forested. Largely virgin timber with small and variable amounts of advanced second growth.
	Regolith
St	Schist.. Watershed underlain predominantly by schist
Sn.	Sandstone.. Watershed underlain predominantly by indurated sandstone, fractured in varying degrees, and some mudstone
Mx	Mixture. Watershed underlain by a mixture of sandstone and schist or transitional rocks.

METHODS

The field measurements for alkalinity, specific conductance, pH, and dissolved oxygen and all laboratory analyses were made by methods described by Brown and others (1970) and the American Public Health Association and others (1971).

Water samples for the laboratory analyses were collected at approximately the middle centroid of flow of the stream (Guy and Norman, 1970) and were pretreated (as prescribed by Brown and others, 1970) before shipment to the U.S. Geological Survey's Central Laboratory in Salt Lake City, Utah (now known as the National Water Quality Laboratory and located in Arvada, Colo.). The samples for major constituent determinations (except carbonate and bicarbonate) were filtered through a 0.45-m pore-size membrane filter and acidified to pH <2 with nitric acid. A separate sample for carbonate and bicarbonate analysis was unfiltered and unacidified.

RESULTS AND DISCUSSION

SYNOPTIC STUDIES DURING STORMFLOW

CHEMOGRAPH SYNOPTIC STUDIES

Detailed studies of the chemograph of several chemical constituents were made at station 11482225 on Harry Weir Creek (VL (virgin timber, logged) -type water-

TABLE 2.—*Selected data for individual sampling stations*

[Codes for watershed and regolith types are defined in table 1; "(S)" in front of station numbers indicates synoptic study sites; —, no data]

Station number and name	Average stream gradient (m/km)	History of land use (percentage of area)		Virgin and advanced second growth	Watershed classification	
		Logged since establishment of Redwood National Park	Logged prior to establishment of Redwood National Park		Land use type (percent of area)	Regolith type
11481500 Redwood Creek near Blue Lake	31.3	<5	>55	40	Main stem	—
11482020 Redwood Creek at Redwood Valley Bridge, near Blue Lake	26.9	<5	>60	35	Main stem	
11482110 Lacks Creek near Orick.	57.2	10	40	50	RL	Sn
11482120 Redwood Creek above Panther Creek, near Orick	18.8	<5	>60	35	Main stem	—
11482140 High Slope Schist Creek near Orick.	293.9	—	—	100	VF	St
11482160 Copper Creek near Orick	180.1	20	30	45	VL	Sn
11482190 Slide Creek near Orick	255.9	30	40	30	VL	Sn
(8)11482200 Redwood Creek at South Park Boundary, near Orick.	18.6	<5	65	<30	Main stem	—
11482210 Bridge Creek near Orick.	60.2	21	55	24	RL	St
11482220 Redwood Creek above Harry Weir Creek, near Orick.	16.1	5	60	35	Main stem	—
11482225 Harry Weir Creek near Orick	145.1	40	—	60	VL	Mx[1]
11482230 Tom McDonald Creek near Orick	70.1	6	80	14	RL	St
11482240 Fortyfour Creek near Orick	104.5	20	75	5	RL	St
(S)11482250 Miller Creek near Orick	207.0	90	—	10	VL	Sn
(S)11482260 Miller Creek at mouth, near Orick.	200.2	77	—	23	VL	Mx[1]
11482270 Bond Creek near Orick		27	55	18	RL	St
11482280 Cloquet Creek near Orick	219.9	55	—	45	VL	Mx
11482290 Oscar Larson Creek near Orick	283.3	23	—	77	VL[2]	Mx
11482295 Gans South Creek near Orick.	271.8	—	—	100	VF	Mx
11482300 Elam Creek near Orick	89.8	40	30	30	VL	St
11482305 Gans West Creek near Orick	295.7	—	—	100	VF	Mx
11462310 McArthur Creek near Orick	47.2	30	45	25	VL	St
11482320 Low Slope Schist Creek near Orick	241.7	—	—	100	VF	St
(S)11482330 Hayes Creek near Orick.	236.8	—	4	96	VF	Sn
(S)11482450 Lost Man Creek near Orick.	103.6	—	87	13	RF	Sn
11482455 Lost Man Creek Tributary near Orick.	243.9	—		100	VF	Sn
11482460 Larry Dam Creek near Orick.	94.3	—	70	30	RF[3]	—
(S)11452468 Little Lost Man Creek at site 2, near Orick	75.4	0	6	94	VF	Sn
(S)11482470 Little Lost Man Creek near Orick	66.1	—	8	92	VF	Sn
(S)11482475 Geneva Creek near Orick.	242.4	—	100	—	RF	Sn
11482480 Berry Glen Creek near Orick.	261.2	—	100	—	RF	Mx
11482500 Redwood Creek at Orick.	13.4	10	50	40	Main stem	—

[1] Regolith type does not agree with percentage of predominant soil type of parent material.

[2] Does not fit any land use category well.

[3] Watershed is overlain by a weakly consolidated layer.

shed, Mx (mixture) -based regolith) and at station 11482468 on Little Lost Man Creek at site 2 (VF (virgin timber, forested) -type watershed, Sn (sandstone) -based regolith). This study compared and contrasted the chemical characteristics of storm-associated flow from a heavily logged watershed (Harry Weir Creek) with that from a virgin forested watershed (Little Lost Man Creek) in greater detail than was possible for all the stations combined. The two were selected for special effort because of the sharp difference between them in land use.

The first such study was made during the storm of November 6 to 8, 1974, the second storm of the rainy season. The first storm of the rainy season, which passed through the area October 27 to 29, brought 76.0 mm of rain at the Prairie Creek State Park recording gage. By November 6, discharge in the two streams had returned to levels preceding the October storm. The storm of November 6 to 8 brought 25 mm of rain in 1 day, and a hydrograph of water discharge showed an easily identifiable rise, peak, and recession in both streams. The chemograph also varied considerably with discharge (fig. 2).

The peak discharge per unit area in Harry Weir Creek is higher and occurs earlier than in Little Lost Man Creek, suggesting that a larger fraction of runoff occurs as fast overland flow in Harry Weir Creek. The difference may be due partly to differences in slope and land cover. But the storm covered a broad area and dropped comparable amounts of precipitation on both watersheds so that differences in peak discharge per unit area (almost three times larger in Harry Weir Creek) cannot be attributed to small differences in either total rainfall or short-term intensity. Likewise, the differences in

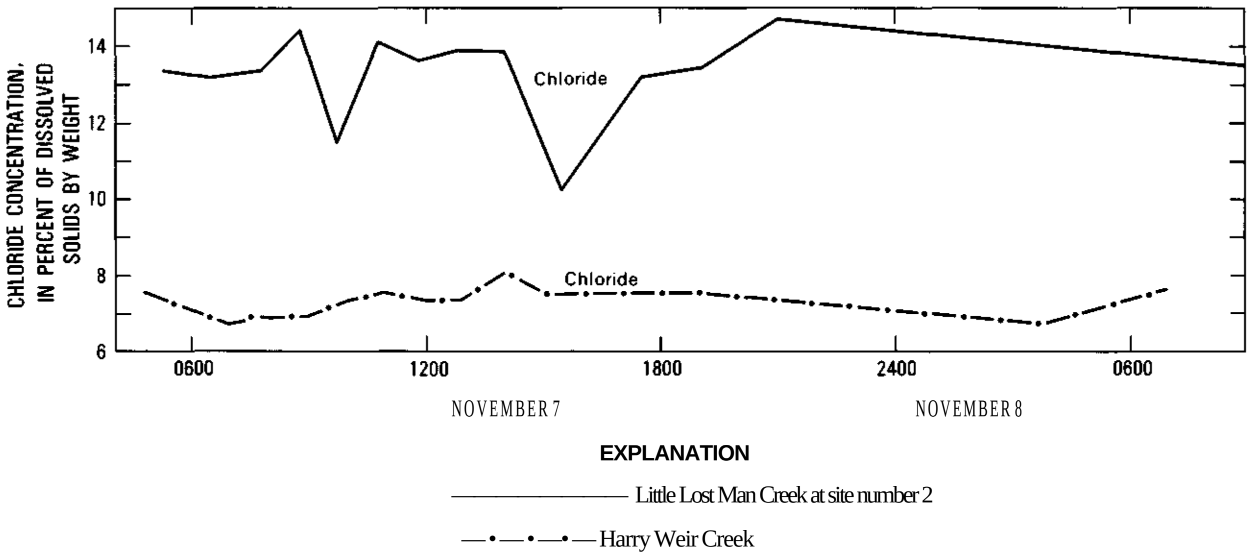


FIGURE 2.—Selected water-quality data from the synoptic study of November 6 to 8, 1974, Harry Weir Creek and Little Lost Man Creek at site 2. No data are shown for first day of the study.

timing of the two peak discharges (nearly 6 hours later in Little Lost Man Creek than in Harry Weir Creek) cannot be attributed to differences in the timing of precipitation (Janda and others, 1975b; K.M. Nolan, U.S. Geological Survey, oral commun., 1978).

The concentrations of the major constituents are higher and more variable with discharge in Harry Weir Creek than those in Little Lost Man Creek. This suggests that the rate of rock weathering to constituents soluble in water is greater in Harry Weir Creek. These soluble constituents probably were produced by weathering during the dry season and were dissolved easily in the early rains. The magnesium, sodium, and potassium lines are shown only for Little Lost Man Creek. There are slight but measurable differences between the lines for Little Lost Man Creek and Harry Weir Creek, but at the scale of figure 2, the differences cannot be resolved by eye.

The concentrations of calcium, bicarbonate, and sulfate in Harry Weir Creek all decrease steadily on the rise of the hydrograph, reach minima at or near peak discharge, and increase steadily on the recession. This suggests that, as discharge increases, an increasing fraction of that discharge comes from overland flow, which has had little contact with the soil and thus contains less dissolved solids than water from other sources. By contrast, data from Little Lost Man Creek show no discharge-related variations, suggesting that overland flow is not a major fraction of the discharge.

The concentrations of sodium and chloride are nearly equal to each other and are alike in both watersheds. Although the percentage chloride values as shown are different in the two watersheds, the chloride concentrations are approximately equal. This suggests that the source of chlorides is not rock weathering, which would have produced different concentrations in the two watersheds, as the dissolved-solids concentrations are different, but rather is sea salt either occurring as dry fallout during the summer or accompanying the rain. The latter situation probably is not the case, however, because if the chloride had been supplied at a constant concentration in rainfall, the time series of percentage chloride would have been the inverse of the time series for dissolved-solids concentration. Hence, the sodium and chloride in the runoff of the November 6 to 8,1974, storm had probably accumulated in the soil through the summer from salt spray and fog drip.

The second storm studied occurred February 5 to 9, 1975. Since October 1974, 839 mm of rainfall had been recorded. A storm of February 1 to 5 caused 89 mm of rain. Measurements were made beginning February 5 because weather forecasts predicted that a major storm would begin sometime that day. This storm did not materialize, and daily rainfalls for February 5 to 8 were 11 mm, 13 mm, a trace, and 8 mm. Finally, 26 mm of rain fell February 9. Most of the samples taken during the study were in the period February 8 to 9.

The water discharge and concentrations of major constituents (fig. 3) are shown for the period February 8-9 only. Potassium values are not shown because they are uniformly less than 1.0 mg/L and do not show variations at this scale. Magnesium and sulfate concentrations are virtually identical at both stations.

Streamflows prior to this storm were about two orders of magnitude higher than the streamflows prior to the November storm, so that the hydrograph of the storm

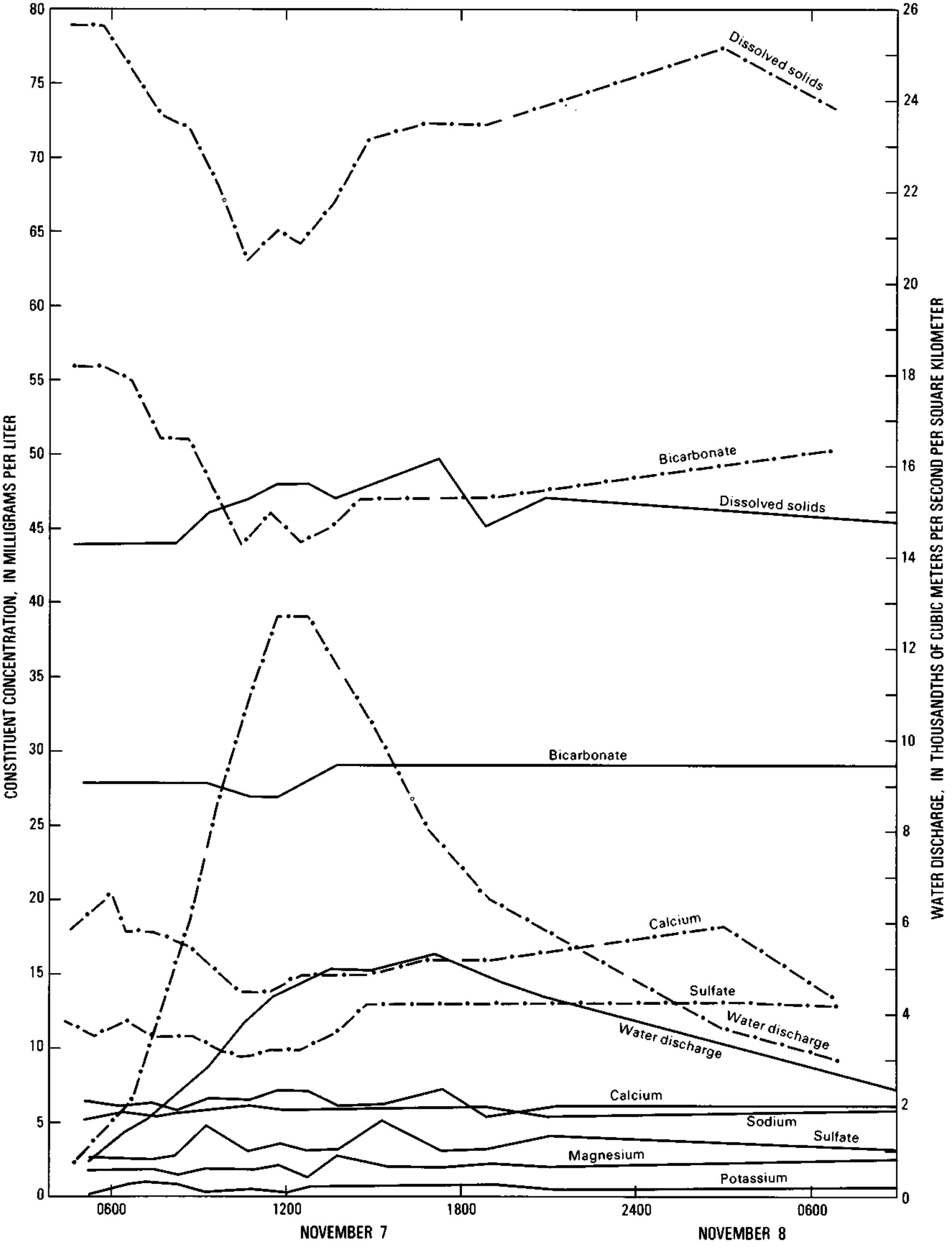


FIGURE 2.—Continued.

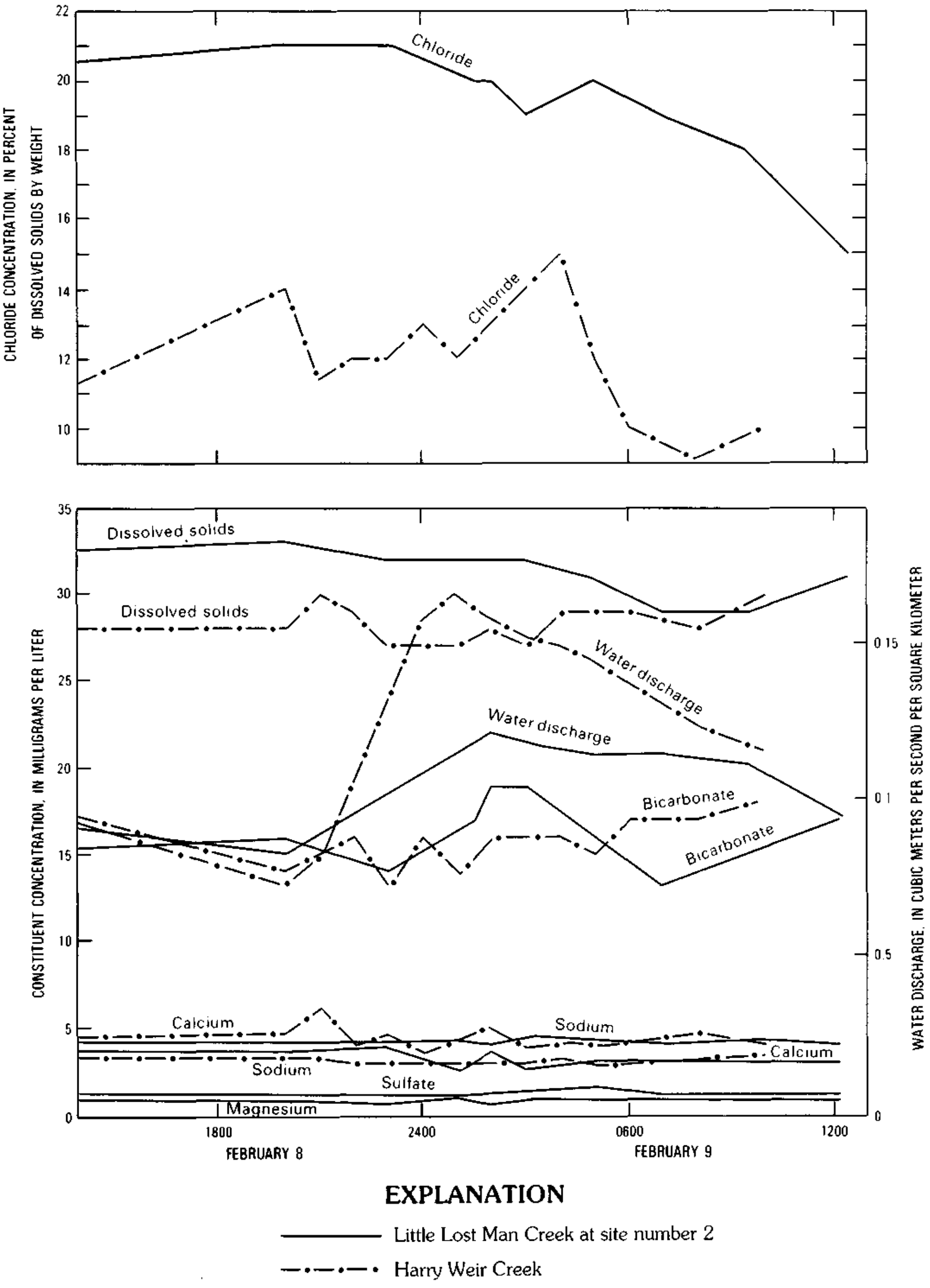


FIGURE 3.—Selected water-quality data from the synoptic study of February 5 to 9, 1975, Harry Weir Creek and Little Lost Man Creek at site 2. No data are shown for the first 3 days of the study.

discharge was superimposed on a much larger base flow in February than in November. As in the November synoptic study, the peak streamflow per unit area was greater and occurred earlier in Harry Weir Creek than in Little Lost Man Creek, suggesting that a greater fraction of the runoff in Harry Weir Creek was overland flow. Again, differences between watersheds in the peak discharge and in the time of the peak cannot be attributed to differences in total rainfall or the timing of rainfall (Janda and others, 1975b).

In the February study, the dissolved-solids concentrations in Harry Weir Creek and Little Lost Man Creek were nearly alike; in the November study, dissolved-solids concentration in Harry Weir Creek was much higher than in Little Lost Man Creek. Concentrations in both streams are substantially lower in February than in November, but more so in Harry Weir Creek. The general decrease in dissolved solids is probably due to higher discharges; that is, more water is present in both watersheds in February to dilute the soluble material available. The differences in magnitude of the decreases between Harry Weir Creek and Little Lost Man Creek suggest that in November more soluble material was available for dissolution in Harry Weir Creek. By the February storm, however, processes supplying soluble material were, apparently, operating alike in the two watersheds, as concentrations of individual constituents (except chloride) are alike.

The bicarbonate and dissolved-solids concentrations in Harry Weir Creek decreased slightly on the rise of the hydrograph (fig. 3), reached minima at or near the peak, and increased slightly on the recession, suggesting, as in the November storm, that overland flow was an important component of discharge. In Little Lost Man Creek, however, the peak bicarbonate concentration coincided with peak discharge, suggesting that much of the water constituting the peak discharge is not overland flow but is quick-return flow or water that enters the surface soil briefly and reemerges, thereby picking up more soluble salts than overland flow (Kennedy and Malcolm, 1978). This conclusion is supported by the relative shape of the two hydrographs, with Little Lost Man Creek experiencing slower rise, lower peak, and more sustained recession than Harry Weir Creek.

In Harry Weir Creek, the percentage of chloride seems to rise steadily through the discharge peak, then decreases through the recession. In Little Lost Man Creek, the percentage of chloride also decreases on the recession. In both streams, bicarbonate and dissolved-solids concentrations increase on the recession. This combination of observations suggests that, after the peak, an increasing fraction of the runoff is quick-return flow that contains higher concentrations of dissolved solids, except chloride. The chloride may be coming in primarily in rain, with little being added from the soil.

The percentage of chloride was higher in both watersheds in February than in November. In November the chloride concentrations were the same at both stations, but in February chloride was higher at Little Lost Man Creek. This suggests that chloride salts accumulated during the summer were the dominant source of chloride in November, but rainfall was the dominant source in February. The Little Lost Man Creek station may have had higher chloride concentrations in February because it is closer to the ocean and received more salt spray during the storm than did Harry Weir Creek.

From November to February, although calcium and bicarbonate continued to be important quantitatively, there was a general shift toward a sodium-chloride-type water at the expense of calcium and sulfate in Harry Weir Creek and at the expense of calcium, bicarbonate, and sulfate in Little Lost Man Creek (fig. 4). Little Lost Man Creek tended to be a more sodium-chloride-type water than Harry Weir Creek in both November and February but probably for different reasons. In November, both watersheds had accumulated roughly equal amounts of chloride salts per unit area. The first runoff of the rainy season would be expected to contain nearly equal concentrations of sodium and chloride in the two watersheds (as was seen), but because of higher concentrations of other salts, the water at Harry Weir Creek was less a sodium-chloride type than the water at Little Lost Man Creek. By February, the soluble material excess in Harry Weir Creek over that in Little Lost Man Creek that had been seen in November was gone. The processes supplying soluble solids in both watersheds were similar. But chloride in rain continued to appear in the runoff, thus causing a shift toward a sodium-chloride-type water. The chloride concentration in February was higher at Little Lost Man Creek than at Harry Weir Creek, probably because Little Lost Man Creek is closer to the ocean. Thus, in February also, Little Lost Man Creek water seems to have been a more sodium-chloride type than Harry Weir Creek water.

OTHER SYNOPTIC STUDIES

Synoptic field measurements of alkalinity, pH, temperature, dissolved oxygen, and specific conductance also were made at one station on the main stem (11482200) and at eight stations on tributaries of Redwood Creek during eight storms (table 2).

The time series of the synoptic field measurements proved to be of little value and are not presented. Other features of these data are discussed. Alkalinity and specific-conductance values occurring on the rise, peak, and recession proved to be suggestive of specific hydrologic processes. In table 3, the position of each value relative to the middle value of the measurements is shown at rise, peak, and recession. Hydrographs for the storms of February 28 to March 3, 1974, and February 5 to 9, 1975, showed poorly defined rise, peak, and recession portions at all stations and are excluded from this analysis.

Examination of the symbols (table 3) shows a preponderance of minus signs (indicating values below the middle of the three measurements) at the hydrograph peaks in all the VL-type (logged) watersheds—Harry Weir Creek, Miller Creek, and Miller Creek at mouth. Furthermore, in 18 alkalinity and in 17 specific-

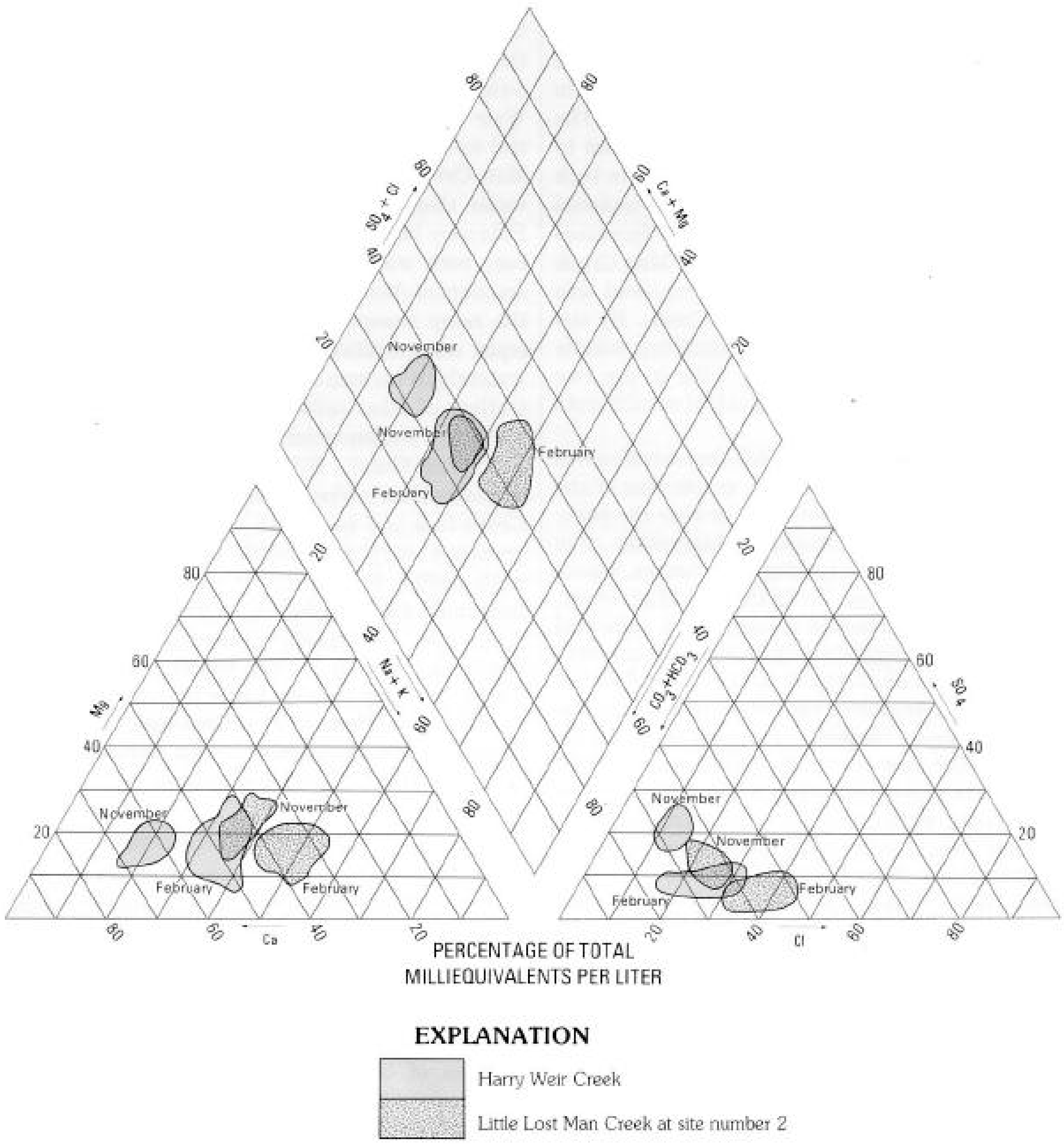


FIGURE 4.—Trilinear diagram showing major-ion composition for the chemograph synoptic studies, November 6 to 8, 1974, and February 5 to 9, 1975, Harry Weir Creek and Little Lost Man Creek at site 2. (Technique from Piper, 1944.)

conductance measurements at the peak discharge in the VL-type watersheds, no plus sign occurred. The probability of various combinations of plus and minus signs occurring at the discharge peak is given by the binomial distribution for *n* nonzero signs. From a table of the binomial distribution (Conover, 1971, table 3), one can see that, if plus and minus signs occurred with equal expectation (p=0.50) in 15 tries, between 3 and 11 plus signs would occur, with a 95 percent or greater confidence level. Since no plus signs occurred, it may be concluded that the expectation of plus and minus signs is not equal. Indeed, the lowest expectation at which at least one plus sign would occur at a 95 percent or greater confidence level is p=0.20. Considering specific conductance in VL-type watersheds, %=14, again all are minus signs. The conclusion regarding expectation is the same. By contrast, VF- and RF (regrown, forested) -type watersheds (Hayes, Lost Man, Little Lost Man, and

TABLE 3.—*Relative magnitudes of alkalinity and of specific conductance values at the beginning of the rise, at the peak, and on the recession for synoptic events that produced hydrographs with definable features*

[Symbols ("+" and "—") represent the position of each value relative to the middle value of the measurements at rise, peak, and recession. The middle is always shown with a zero. Likewise, a zero also represents two equal values. Alkalinity values are considered equal if they are within 1.5 units of each other, and specific-conductance values are considered equal if they are within 3 units of each other. Both limits are judgments based on sensitivity of the measurements. Blanks mean no data]

Station number and name	November 7-9, 1973			January 11-13, 1974			February 20-22, 1974			November 6-8, 1974			November 20-22, 1974			February 12-14, 1975		
	Rise	Peak	Recession	Rise	Peak	Recession	Rise	Peak	Recession	Rise	Peak	Recession	Rise	Peak	Recession	Rise	Peak	Recession
Alkalinity, in milligrams per liter																		
11482200 Redwood Creek at South Park Boundary, near Orick		_	+				0	_	0				+	_				
11482220 Redwood Creek above Harry Weir Creek, near Orick.										+	_	0	_	+				
11482225 Harry Weir Creek near Orick	+	0	0	+	_	0	+	_	0	+	_	0	+	_	0	_	+	
11482250 Miller Creek near Orick.	0	0	+	+	_			_	+	+	_	0	+	_	0	+	_	0
11482260 Miller Creek at mouth, near Orick	0	_	0	+	_		0	_	0	+	_	0	+	_	0	_	0	0
11482330 Hayes Creek near Orick				+	_			0	0	+	0	_	+	_	0	0	0	0
11482450 Lost Man Creek near Orick		0	0	0	0		0	0	0	+	0	_	0	+	_	0	0	0
11482470 Little Lost Man Creek near Orick, sites 1 and 2.				0	0		+	0	0	0	0	0	+	_	0	0	0	0
11482475 Geneva Creek near Orick				0	0			0	0	0	+	_	+	0	_	0	0	0
Specific conductance, in micromhos per centimeter at 25 °C																		
11482200 Redwood Creek at South Park Boundary, near Orick.	+	0	0				0	_	0				+	_				
11482220 Redwood Creek above Harry Weir Creek, near Orick.										+	_	0	+	_				
11482225 Harry Weir Creek near Orick	+	_	0	0	_	0	0	_	+	0	_	0	+	_	0	+	_	0
11482250 Miller Creek near Orick.	0	0	0	+	_		0	_	+	0	0	0	+	_	0	0	0	0
11482260 Miller Creek at mouth, near Orick	0	_	+	0	_	0	+	_	0	0	_	0	0	_	0			
11482330 Hayes Creek near Orick		0	0	0	0	0	0	_	+	0	+	_	0	_	+	_	0	+
11482450 Lost Man Creek near Orick		0	0	0	0		0	0	+	0	+	0	0	+	_	0	0	0
11482470 Little Lost Man Creek near Orick, sites 1 and 2.	+	0	0	0	0		0	0	0	0	0	0	0	0	_	0	0	0
11482475 Geneva Creek near Orick	+	0	0	0	0		0	0	0	+	_	0	+	0	0	0	0	0

Geneva Creeks) show a preponderance of zeros and small but approximately equal numbers of plus and minus signs at the peak for both alkalinity and specific conductance. This finding suggests that, in most cases, concentrations in VF- and RF-type watersheds at the peak discharge are not significantly or consistently diluted by overland flow, and the expectation of dilution occurring at the discharge peak cannot be shown to be different from $p=0.50$.

It may be concluded that peak alkalinity and specific conductance occur at peak storm discharge much less often in logged than in forested watersheds, probably because of increased occurrence of overland flow in logged watersheds.

The difference in the lag time of peak discharge between watershed types decreases from several hours in November to several minutes in February (Janda and others, 1975a, p. 6-20). This change may occur because as the soil becomes saturated it is less able to soak up new precipitation. Thus, overland flow should be more apparent in peak discharge in all watershed types late in the rainy season. In table 3, plus signs at the discharge peak occur only in VF and RF watersheds and only in the two storms studied in November 1974. This suggests that quick-return flow was a predominant part of peak discharge only in VF- and RF-type watersheds and only early in the rainy season, whereas late in the rainy season overland flow becomes important at the discharge peak in all types.

The significance of differences in water quality during storms between watersheds of different land use was evaluated by grouping the data from each synoptic study according to common land use type and calendar quarter (first quarter January through March, second quarter April through June, and so on). Calculations were made from data grouped by class interval (Sokal and Rohlf, 1969). Calculated values (table 4) are shown to one additional significant figure to avoid rounding error in subsequent statistical hypothesis testing. No mean or standard deviation is calculated for sets of less than 10 values because the sampling error of the mean and standard deviation are unduly large given only 10 values. The mean of each data set for the RF- and VL-type watersheds and the main stem was compared to the corresponding mean for the VF-type watersheds by using a student *t-test* (table 5).

Mean alkalinity and pH vary in the same direction and are mostly higher in VL-type watersheds than in

TABLE 4. —*Statistical summary of field-measurement data from synoptic studies, grouped by calendar quarter and watershed type*

[Means and standard deviations calculated from data grouped by class as follows: alkalinity, 1 mg/L; specific conductance, 5 µmho at 25 °C pH, 0.2 units; temperature, 0.5 °C; dissolved-oxygen saturation, 2 percent. Calculated values are shown to one additional significant figure to avoid rounding error in subsequent statistical hypothesis testing. —, no data]

	Fourth quarter 1973					First quarter 1974				
Watershed types[1]	Media	Range[2]	Mean	Standard deviation	Number of samples	Median	Range[2]	Mean	Standard deviation	Number of samples
Alkalinity, in milligrams per liter										
VF streams		12-15	—	—	3	14.8	7-24	14.7	2.2	49
RL streams		11-14	—	—	8	13.1	9-17	12.5	1.3	60
VL streams		11-18	13.9	1.5	23	14.9	10-21	15.1	2.4	73
Main-stream stations		27-34	—	—	3	29.5	26-32	28.9	1.6	11
Specific conductance, in micromhos at 25 °C										
VF streams		40-65	50.3	7.3	16	52.9	40-90	53.4	8.6	100
RL streams		30-55	43.1	5.4	16	42.6	20-55	41.7	5.1	94
VL streams		35-85	52.2	11.2	58	49.2	30-75	51.9	7.8	172
Main-stream stations		65-85	—	—	6	72.2	65-85	73.0	4.4	19
pH										
VF streams		6.8-7.6	—	—	3	7.00	5.8-7.8	6.92	.40	64
RL streams		5.6-7.0	6.17	.41	13	7.05	5.8-7.6	6.90	.36	71
VL streams		7.0-7.4	7.11	.11	40	7.07	6.2-7.6	7.04	.25	97
Main-stream stations		6.2-8.2	—	—	3	6.90	6.8-7.0	—	—	8
Temperature, in degrees Celsius										
VF streams		11.0-12.0	11.1	.2	18	8.3	6.5-9.5	7.9	.6	103
RF streams		11.0-13.5	11.7	.4	29	7.5	5.0-10.0	7.3	1.0	98
VL streams		11.5-13.0	12.0	.2	56	8.0	6.0-9.5	7.7	.7	159
Main-stream stations		12.0-13.0	—	—	6	7.6	6.0-8.5	7.2	.7	19
Dissolved oxygen, in percent saturation										
VF streams		88-102	95.9	3.3	16	97.0	84-104	95.8	3.9	57
RF streams		88-102	95.6	2.9	16	96.2	84-104	95.1	4.0	50
VL streams		98-102	99.4	1.2	17	98.3	92-104	97.9	2.1	73
Main-stream stations		96-100	—	—	3	97.5	92-100	—	—	9

	Fourth quarter 1974					First quarter 1975				
Stream/station description	Median	Range[2]	Mean	Standard deviation	Number of samples	Median	Range[2]	Mean	Standard deviation	Number of samples
Alkalinity, in milligrams per liter										
VF streams	24.2	20-38	26.9	5.4	67	12.7	9-17	13.0	1.3	57
RF streams	24.8	11-41	25.0	9.6	50	12.4	9-14	11.7	1.2	52
VL streams	31.4	17-52	32.5	8.1	62	14.3	10-18	13.7	1.4	65
Main-stream stations	70.0	54-94	72.1	10.7	12	26.9	13-47	28.0	7.1	10
Specific conductance, in micromhos at 25 °C										
VF streams	78.2	60-200	102.6	38.2	103	72.7	30-90	61.2	18.9	156
RL streams	93.8	60-150	87.4	16.8	81	41.2	30-65	42.6	6.8	152
VL streams	89.9	60-150	100.1	22.6	105	45.8	30-90	47.2	7.2	131
Main-stream stations	243.0	210-300	245.2	19.5	22	69.9	60-85	70.0	6.1	47
pH										
VF streams	7.38	6.4-3.6	7.36	.43	74	7.01	6.4-7.6	7.05	.23	125
RL streams	6.82	6.2-7.2	6.62	.20	50	7.19	6.4-7.6	7.06	.22	81
VL streams	7.48	6.8-8.0	7.35	.21	[3]56	7.16	6.0-7.6	7.14	.27	84
Main-stream stations	7.70	7.0-8.4	7.56	.37	11	7.04	6.2-8.0	7.04	.37	18
Temperature, in degrees Celsius										
VF streams	9.7	8.0-11.5	9.32	1.0	97	9.2	7.5-10.5	9.2	.6	154
RF streams	10.1	8.0-12.0	10.1	.8	77	8.6	6.5-10.1	8.7	.9	166
VL streams	9.8	8.5-12.5	9.6	.7	108	9.6	7.5-11.1	9.1	.8	129
Main-stream stations	11.1	9.0-12.5	10.6	.9	24	8.2	6.0-10.5	7.9	.9	42
Dissolved oxygen, in percent saturation										
VF streams	93.9	84-104	93.4	3.7	311	97.5	92-102	96.5	2.4	48
RF streams	88.1	80-96	87.2	3.8	32	96.9	88-104	96.4	2.6	46
VL streams	95.2	84-100	93.5	3.2	50	97.6	84-104	96.3	3.1	48
Main-stream stations	95.0	86-100	93.2	3.7	10	99.2	90-106	98.9	3.7	19

[1] Codes for watershed types (VL, RF, and so on) are defined in table 1.

[2] The range is the low end of the lowest class to the high end of the highest class.

[3] Seven pH values taken November 6 to 8, 1974, at Miller Creek at mouth are much lower than values determined simultaneously at Miller and Harry Weir Creeks and are not included in this calculation. Instrument malfunction was suspected at Miller Creek at mouth.

TABLE 5.—*Results of comparing the means of field measurements from RF, VL, and main-stem stations with means of field measurements from VF streams*

[The student *t-test* is used to test a null hypothesis that the means being compared are equal. Rejection of the null hypothesis with level of confidence in a one-tailed test implies that the difference shown (plus or minus) is significant at that confidence level. No data in the column indicates acceptance of the null hypothesis. N means no test was performed due to insufficient sample size. Relation of subject mean to the mean for VF streams is as follows: +, greater than; —, less than; 0, no difference]

Period	Description (land use code)	Alkalinity (mg/L)		Specific conductance (µmho at 25 °C)		pH		Temperature (°C)		Dissolved oxygen (percent	
		Mean	Confidence level	Mean	Confidence level	Mean	Confidence level	Mean	Confidence level	Mean	Confidence level
Fourth quarter, 1973	RF	0	N	-	0.99	-	N	+	0.99	-	0.99
	VL	+	N	+	+		N	+	.99	+	0.99
	Main stem	+	N	+	N	-	N	+	N	+	N
First quarter, 1974	RF	-	0.99	-	.99	+		-	.99	-	
	VL	+		-			0.95	-	.95	+	.99
	Main stem	+	.99	+	.99	-	N	-	.99	0	N
Fourth quarter, 1974	RF	-		-	.99	0	.99	+ +	.99	-	.99
	VL	+	.99	-				+	.95	0	
	Main stem	+	.99	-	.99	+		+	.99	0	
First quarter, 1975	RF	-		-	.99	0		-	.99	0	
	VL	+	.99	-	.99		.95	0		-	
	Main stem	+	.99	+	.99	0		-	.99	+	.95

[1] Codes are defined in table 1.

VF-type watersheds. Alkalinity and pH tend to be lower in RF-type watersheds than in VF-type watersheds. This difference may be due to different regoliths rather than different land uses, but lack of data prevents further analysis.

Mean temperatures in RF- and VL-type streams and in the main stem are significantly higher than in the VF-type streams in the fourth quarter of each year but are significantly lower in the first quarter of each year (table 5). This finding suggests a buffering of the VF-type streams against extremes of heat and cold. The amount of solar energy reaching the soil surface and the amount of energy radiating back to space would be expected to be greater in logged than in forested watersheds. Hence, streams draining logged watersheds should be warmer in summer and colder in winter than streams draining forested watersheds.

There is clear evidence that the main stem has significantly higher alkalinity and specific-conductance values than the VF-type streams, suggesting that the major dissolved-solids inputs to Redwood Creek occur upstream of the park.

Mean specific-conductance values are always significantly lower in RF-type streams than in the VF streams and are generally lower in the VL-type streams than in the VF-type streams. Lower mean values in VL-type streams may be due to a greater fraction of the runoff in these streams being from overland flow. Lower mean values in RF-type streams suggest a lower rate of regolith weathering than in VF-type streams.

Dissolved-oxygen saturation values show no pattern between watershed types.

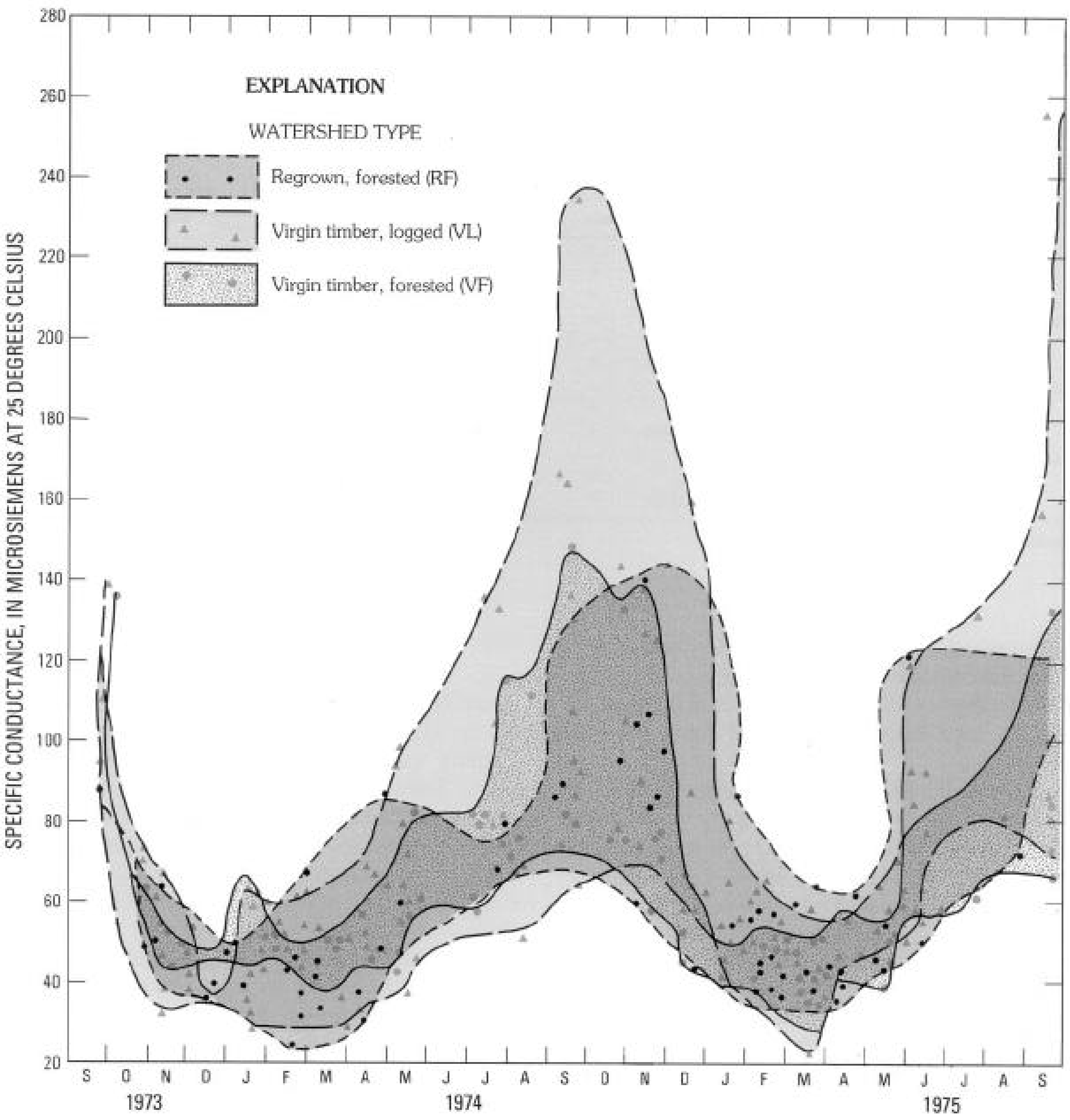
SEASONAL VARIATIONS

Specific conductance, temperature, and alkalinity vary greatly with season. Because specific-conductance and alkalinity variations tend to be alike, alkalinity is not shown. Data used in this analysis consist of all the regularly gathered data from each station plus medians derived for the sites in each synoptic study.

Envelopes enclosing the range of values overlap considerably for VF- and RF-type watersheds (fig. 5); the envelope in VL-type watersheds has a greater range, and the values tend to be higher during the summer dry season. This difference between VL and the other types of watersheds suggests that logging accelerates normal weathering processes or initiates new processes altogether, leading to greater ranges of observed values at low flow. But the effect is apparently not uniform among VL-type watersheds; otherwise, the lower limit of the VL-type envelope would have shifted upward as did the upper limit in the dry season.

Temperatures vary too little between tributaries to be shown in this manner.

The time series of measurements at the main-stem stations above and below Harry Weir Creek, which approximately separates water of upstream origin from water affected by inpark tributary inflow, shows a different pattern (fig. 6). Water from upstream and water within the park are alike during the rainy months when specific conductance and temperature are both at minimum values, but water in the two areas differs considerably during the dry season. Main-stem water above the park is warmer and has a higher specific



conductance than main-stem water within the park, indicating that the main-stem water is diluted and cooled as it passes through the park, presumably from tributary inflow, influences of the marine climate, and shading.

Higher specific-conductance values upstream during the dry season suggest that the drainage basin upstream of the park is weathering faster than tributary watersheds within the park. Faster weathering may be partly related to slight differences in regoliths or to the intensity of logging activity (the drainage basin upstream of station 11482220 was 65 percent cutover as of 1973; table 2). It may also be related to exposure of the soil to the elements. According to Janda and others (1975a), vegetation in the upper basin grades upstream to prairie and sparse Douglas-fir, in contrast to the downstream part, which, in its pristine state, is covered by dense stands of redwood, Douglas-fir, and heavy undergrowth.

Differences related to regolith can be seen in the VL-type watersheds (fig. 7). During the dry season, streams with St-type regoliths seem to have the lowest specific-conductance values; streams with Sn-type regoliths have the highest values, and the Mx-type

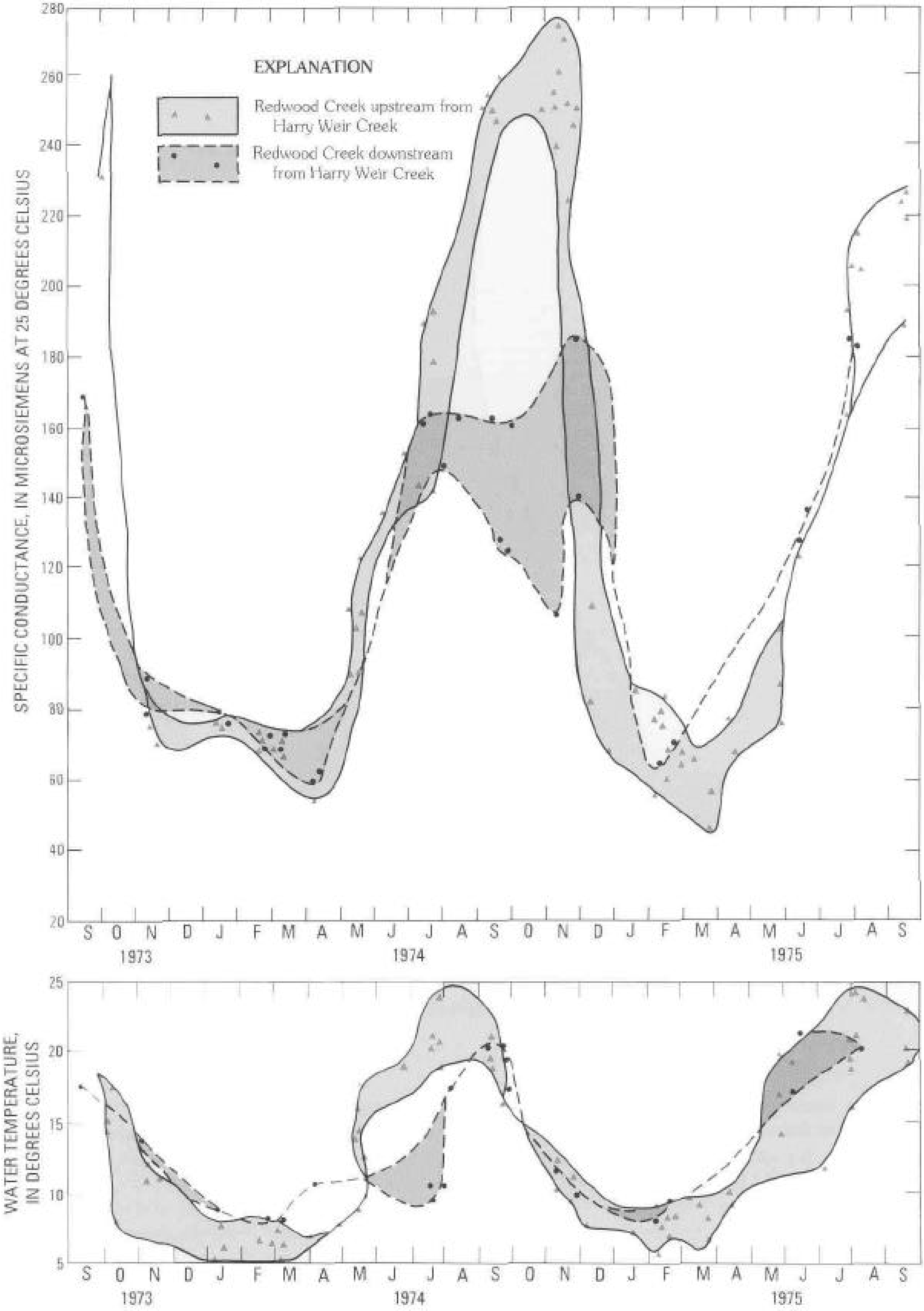


Figure 6. – Specific-conductance and water-temperature values for main-stem stations.

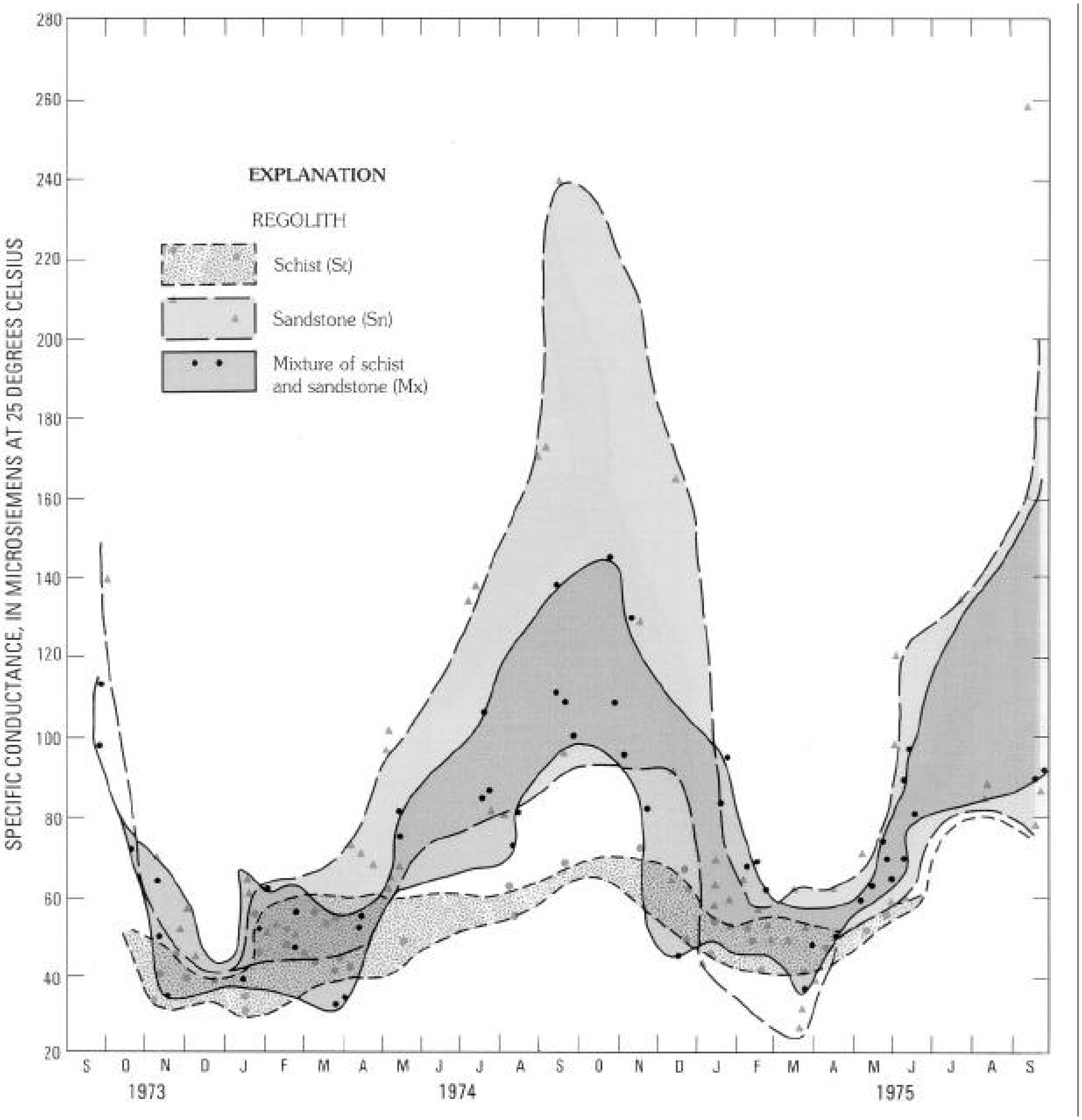


FIGURE 7.—Specific-conductance values for VL-type watersheds underlain by St-, Sn-, and Mx-based regoliths.

regoliths fall in between. This arrangement suggests that the sandstone-based (Sn) watersheds, when disturbed by logging, are more susceptible to weathering than are the schistose (St) watersheds. An examination of the data used in preparing figure 5 shows that the lower limit of specific conductance in VL-type watersheds during the dry season is defined by watersheds having a schistose regolith.

No differences in values related to regolith differences were found in the VF-type watersheds.

To examine further the characteristics of streams draining schistose regoliths, all data from St-based regoliths were analyzed in a similar manner (fig. 8). Envelopes enclosing data from VF-, VL-, and RL- (regrown, being logged) type watersheds generally overlap except for Bridge Creek (RL-type), which has much higher values of specific conductance than all other St-type streams. The Bridge Creek watershed is one of the steepest and most susceptible to erosion and landslumping in the Redwood Creek drainage basin.

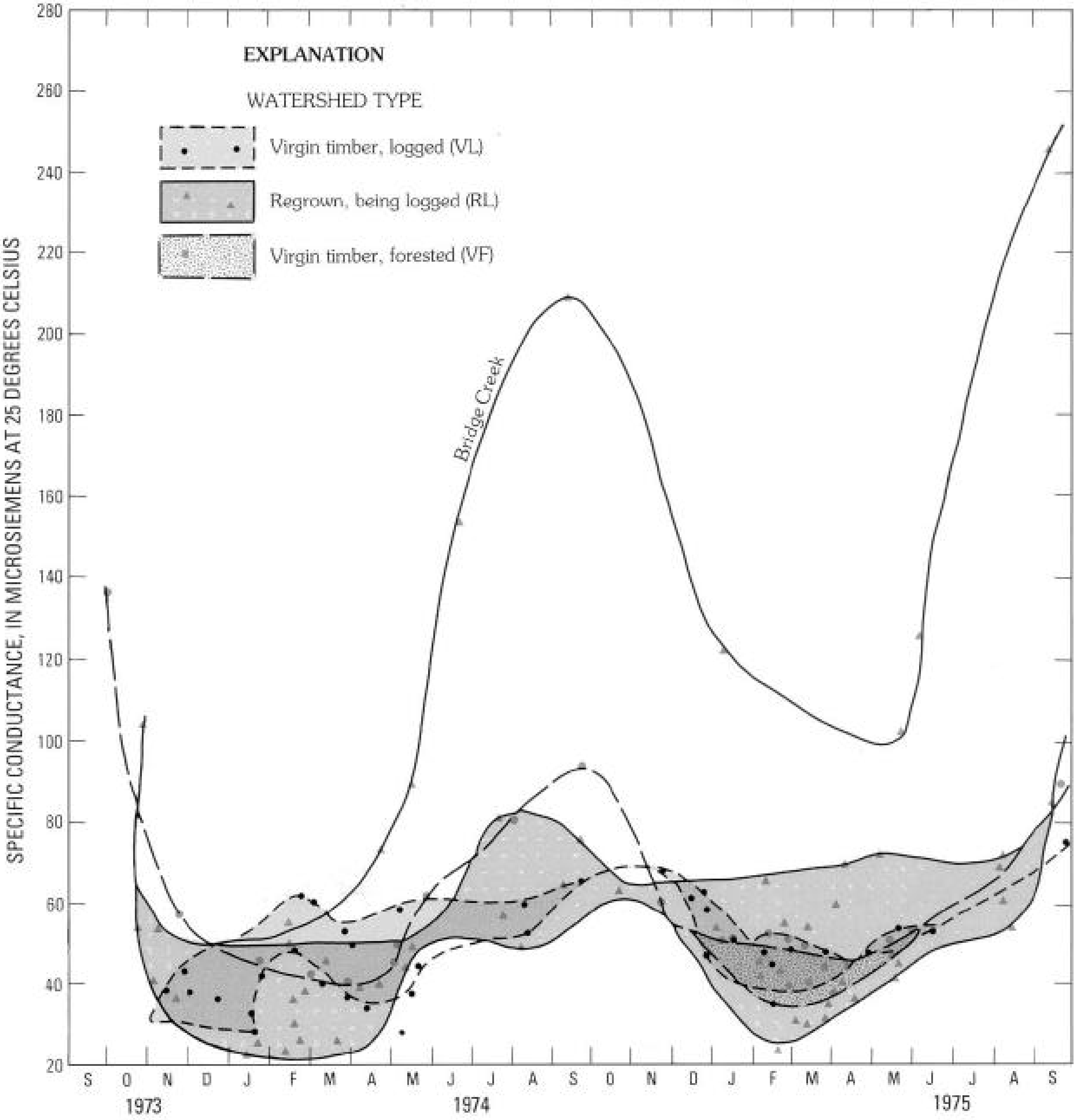


FIGURE 8.—Specific-conductance values for St-based regoliths in VL-, RL-, and VF-type watersheds.

Furthermore, it was logged intensively during this study. Because of the steepness of the slopes, logging caused considerably greater disruption of the surface soils there than in any other logged watershed (Deborah Harden, U.S. Geological Survey, oral commun., 1976). Perhaps intensive surface disruption has exposed deeper, less weathered soils to the elements, resulting in a greater rate of leaching of carbonate rocks.

In an analysis of water-type variations, preliminary evaluation indicated no differences between data sets collected in the first and fourth calendar quarters of both years. Data from these quarters were combined into one set representative of water quality during the rainy season. No regolith-related compositional differences could be found in the rainy-season data, but land-use-related differences are apparent (fig. 9).

The main-stem water is a calcium-bicarbonate type; water from unlogged areas (VF- and RF-type) is mixed sodium-calcium bicarbonate-chloride type. Water types from logged areas (VL-type) lie in between. The progression of water type from sodium chloride to calcium bicarbonate corresponds to increasing exposure of the

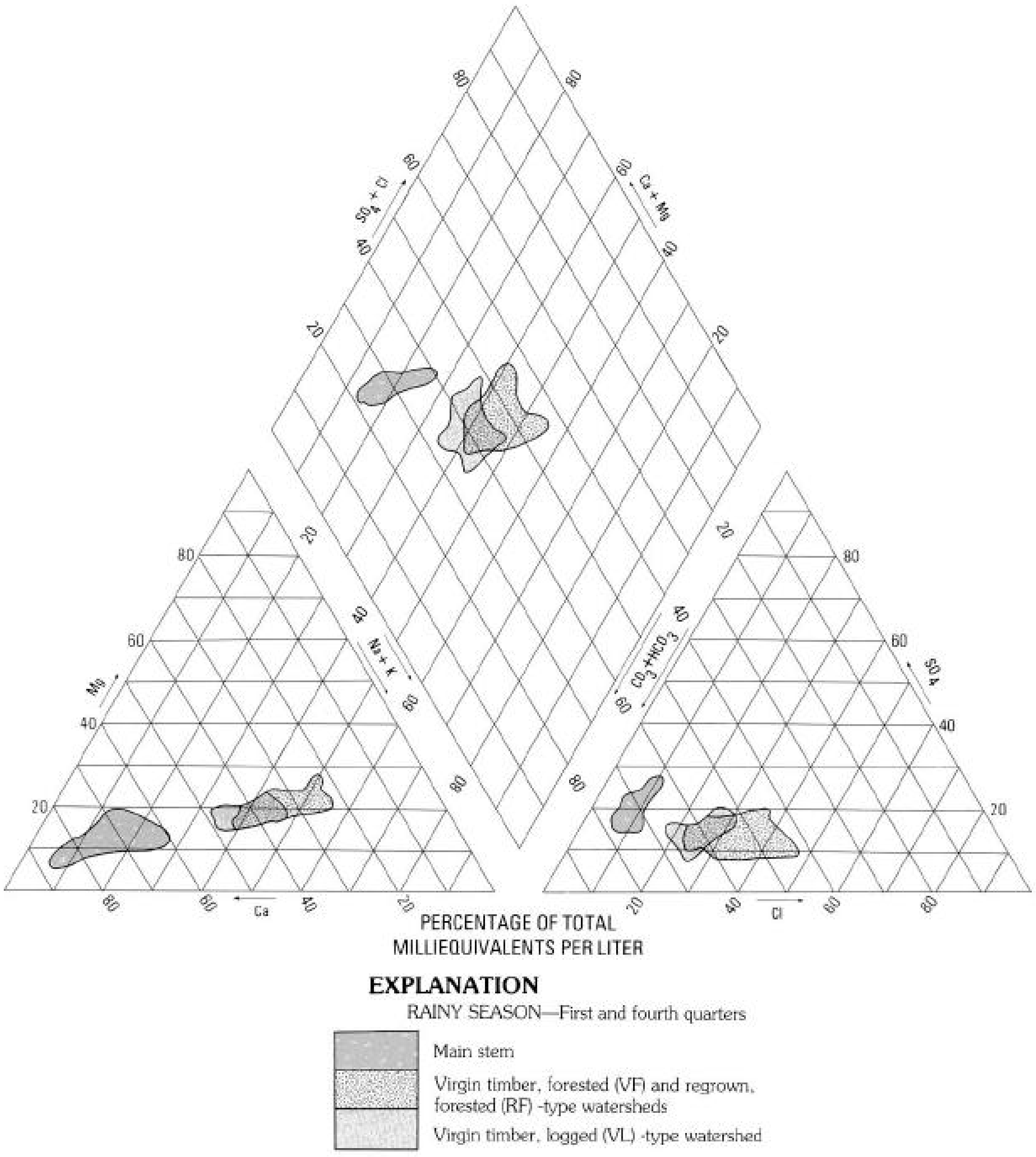


FIGURE 9.—Trilinear diagram showing major-ion composition in the fourth and first quarters, based on the nonsynoptic data, for VF-, RF-, and VL-type watersheds and main stem. (Technique from Piper, 1944.)

soil, either from logging activity or natural differences in vegetation.

Analysis of data from the second and third calendar quarters suggested that there are no compositional differences between sets from VF- and RF-type watersheds and no pattern of compositional differences due to differences in regolith in the combined VF- and RF-type sets. Differences attributable to regolith were observed in VL-type watersheds only.

Water from VF- and RF-type watersheds shifts from the second to the third quarter toward a calcium-bicarbonate type (fig. 10). Coincidentally, main-stem water, which is a single definable type in the second quarter, shifts to two types observable at South Park

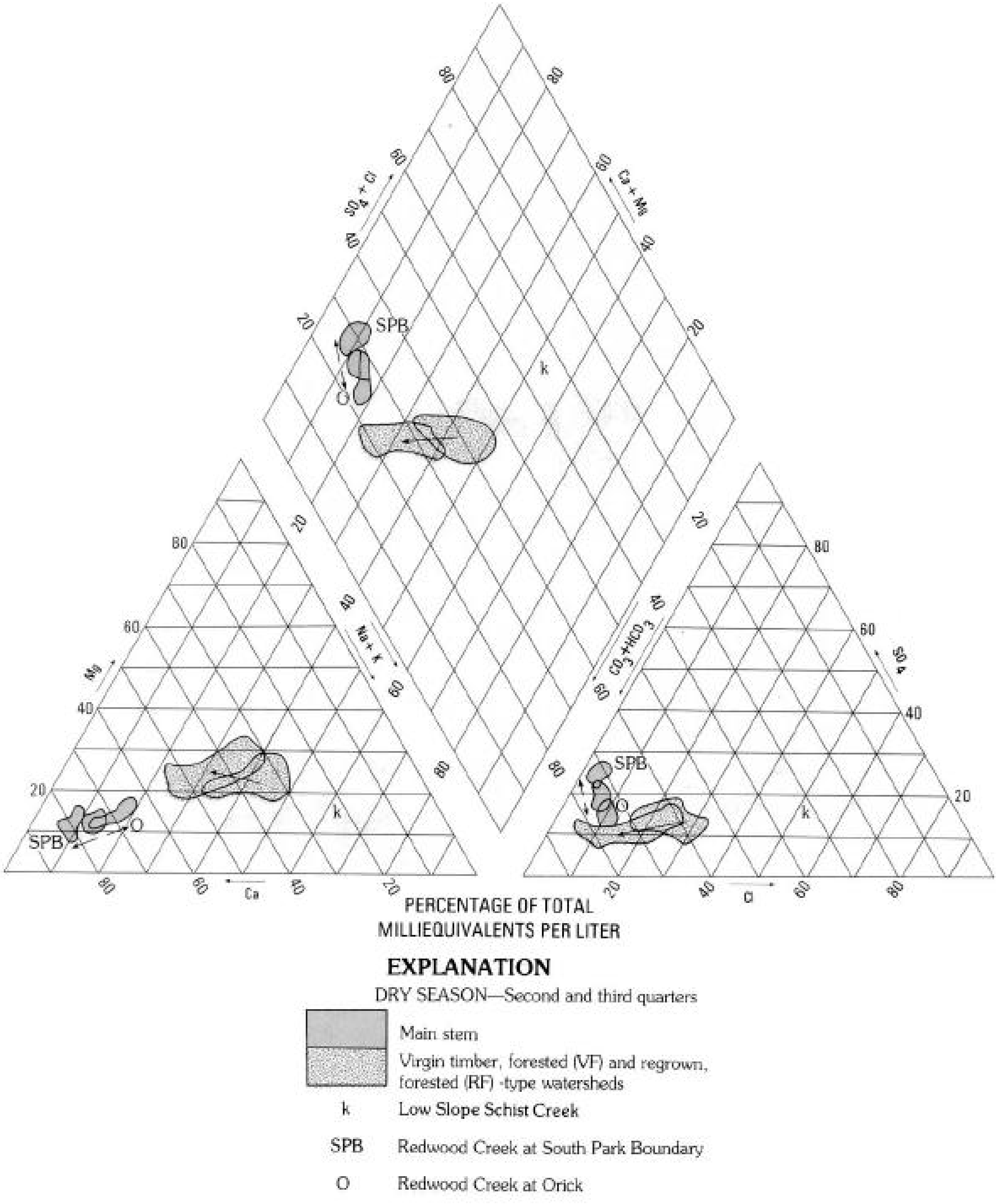


FIGURE 10. —Trilinear diagram showing major-ion composition in the second and third quarters, based on the regular data, for VF-and RF-type watersheds and main stem. Arrows indicate shifts in water types from the second to the third quarter. (Technique from Piper, 1944.)

Boundary (11482200) and at Orick (11482500). The water type at Orick shifts toward that of the park tributaries, indicating the effect of tributary inflow on main-stem water composition. Low Slope Schist Creek (VF-type, St-type watershed) stands out in figure 10 as a sodium-chloride-type water, suggesting very low weathering activity on the regolith of that watershed.

Compositional differences, apparently related to regolith differences, also exist between logged (VL- and RL-type) watersheds (fig. 11). This difference is most

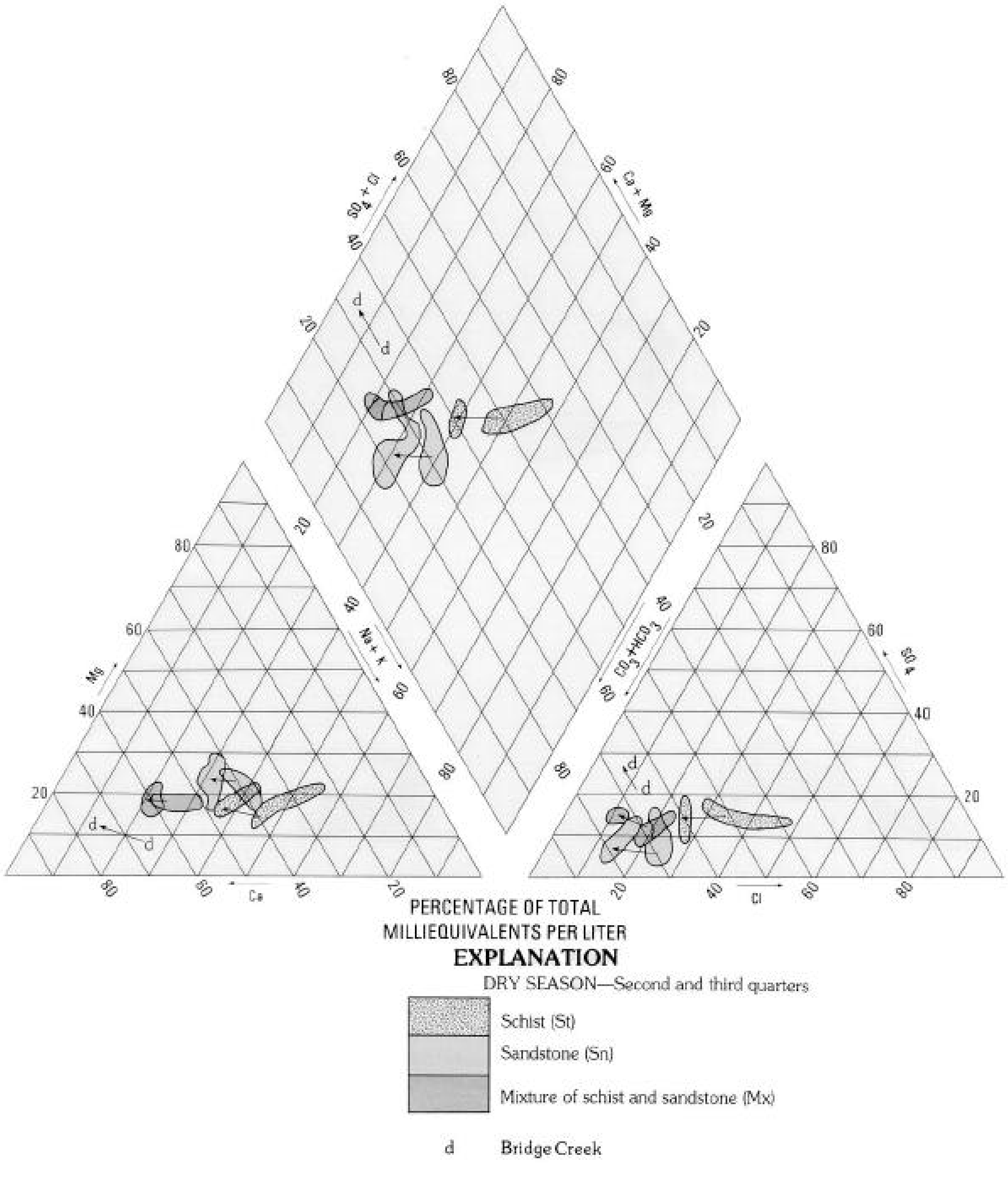


FIGURE 11.—Trilinear diagram showing major-ion composition in the second and third quarters, based on the regular data, for VL-and RL-type watersheds (St-, Sn-, and Mx-based regoliths). Arrows indicate shifts in water types from the second to the third quarter. (Technique from Piper, 1944.)

pronounced during the second quarter of the year. In the second quarter, St-type watersheds have a mixed sodium-chloride-bicarbonate-type water; Sn-type watersheds have a calcium-sodium-bicarbonate type. From the second to the third quarters, however, the water types in both St- and Sn-type watersheds shift toward calcium bicarbonate. Again, Bridge Creek (RL-type, St-type watershed) is unique among the St-type watersheds in having a calcium-bicarbonate-type water (see fig. 8).

In the second and third quarters, there is little difference in water type between the combined VF- and RF-type watersheds and the VL-type watersheds, as can be seen by comparing figures 10 and 11. If the schistose (St-type) watersheds are excluded from the set of VL-type watersheds, however, there is a tendency for the remaining VL-type watersheds to have water higher in calcium and bicarbonate than the water of the VF- and RF-type watersheds.

The weight of evidence suggests that schistose regoliths are generally more resistant to weathering than the other regolith types, which results in lower specific conductances and a more sodium-chloride-type water. But in cases of severe disruption (like Bridge Creek), the schistose watersheds can weather very rapidly, and this weathering results in high specific conductances and a calcium-bicarbonate-type water—the same characteristics seen in water from nonschistose watersheds that have been logged.

Data on pH and dissolved oxygen had no regular predictable dependence on time, so that handling the data by time series methods yielded little information. Changes with season and differences attributable to the land-use- or regolith-related watershed types were determined by statistical analysis of the grouped data.

No systematic variations in dissolved oxygen were observed either between calendar quarters or between the land-use- and regolith-related watershed types. Since physical turbulence is high in all streams studied, dissolved oxygen concentrations were all near saturation.

The mean pH of all streams studied appears to increase from 6.69 in the first quarter to 7.36 in the third and then decrease in the fourth quarter. The only systematic difference between land-use-related watershed types observed by a grouping analysis was that pH values for main-stem stations tended to be higher than those in tributary streams. Neither land use nor regolith type seemed to affect pH systematically between tributaries.

SUMMARY

HYDROLOGIC EFFECTS OF LOGGING

Overland flow makes only short-term contact with the soil before entering the stream. Thus it presumably contains fewer dissolved solids than the other components of stormflow. Dissolved-solids concentration or specific conductance and alkalinity decreased at peak storm discharge a significant number of times in the VL-type watersheds but only occasionally in the VF-type watersheds. This finding suggests that overland flow is an important part of peak discharge only in the watersheds that have been recently logged and is responsible for diluting the dissolved-solids concentrations. A statistical analysis suggests that peak specific conductances and alkalinities coincide with peak storm discharge with expectations of 50 percent in forested watersheds but at best only 20 percent in logged watersheds. Dilution at the peak occurs both early and late in the rainy season, suggesting that overland flow is an important part of the peak discharge in VL-type watersheds throughout the rainy season. Overland flow becomes more important in VF- and RF-type watersheds as the rainy season progresses but never occurs as frequently in them as in VL-type watersheds.

SYSTEMATIC VARIATIONS IN MAJOR-ION COMPOSITION WITH TIME

The most important changes in chemical composition with time are a regular shift in water type from season to season and accompanying changes in dissolved-solids concentrations. At the end of the dry season, streams tend to peak in specific conductance (hence, dissolved-solids concentration) and to be a calcium-bicarbonate type. As the rainy season progresses, the water type shifts steadily toward sodium chloride, and the specific conductance decreases, reaching a minimum in late March or early April. The change in water type through the rainy season is particularly evident from the chemograph data (fig. 4). Through the dry season, the water type shifts steadily back to calcium bicarbonate. This pattern is observed to about the same degree in all watersheds studied, although some distinction is evident between the land-use-related watershed types.

The probable mechanism for the changes in water type and dissolved-solids concentration is as follows. The first rains enter the soil and dissolve the soluble materials accumulated during the dry season, both products of weathering and salt spray from the ocean. A large part of this water probably percolates to the ground-water reservoir and later appears as base flow. The remainder of the water runs off, probably as quick-return and delayed-return flow. This process is repeated with each rain. As the soil becomes saturated and the water table rises, less water percolates and more appears as overland and quick-return flows. Repeated rains also leach the soils of soluble materials. Runoff from the early rains tends, therefore, to be of the same type and dissolved-solids concentration as the base flow except where the overland flow component is large. But as the rainy season progresses, available soluble materials decrease relative to the volume of runoff. Hence, runoff from rains later in the season contains less calcium and bicarbonate derived from the weathering of the Franciscan-based soils.

At the end of the rainy season, the water stored in the soil appears as base flow. Early in the dry season, the base flow consists largely of the water from the most recent rains. As the dry season progresses, and the water table falls, an increasing fraction of the base flow consists of water percolated to the water table at various times in the rainy season just concluded.

Because chloride salts are not produced in significant concentrations by the weathering of most rocks, the ocean is probably the source of those salts in runoff water. The chemograph studies suggested that chloride enters runoff water by different mechanisms early and late in the rainy season. Chloride concentrations were equal in both Harry Weir and Little Lost Man Creeks in November, and the time series of chloride concentrations were identical to the time series of other constituents. This similarity suggests that the predominant source of chlorides was the soil. Chloride salts were probably accumulated as dry fallout during the summer.

In February, the chloride concentration was higher in Little Lost Man Creek than in Harry Weir Creek and tended to remain constant through the discharge hydrographs of both streams. This observation suggests that late in the rainy season the predominant source of chloride was the rain itself. The chloride concentration was higher in Little Lost Man Creek probably because that creek is closer to the ocean than Harry Weir Creek and received more sea spray in the precipitation. The water type shifts toward sodium chloride as the rainy season progresses because other salts are derived from the soil and become scarce relative to the volume of runoff, whereas the chloride salts come with the rain.

VARIATIONS IN PHYSICAL CONDITIONS AND MAJOR-ION COMPOSITION BETWEEN LAND-USE-RELATED AND REGOLITH-RELATED WATERSHED TYPES

Stream temperatures are more variable in watersheds having more soil surface or stream surface exposed to the open sky. Mean temperatures in RF- and VL-type streams and in the main stem during stormflows are higher than mean temperatures in the VF-type streams in the fourth quarter and lower than in the VF-type streams in the first quarter (table 5). This pattern suggests that exposure of the soil leads to higher water temperatures in autumn and lower temperatures in winter during stormflow. This pattern is not seen in the data collected between storms in the dry season.

During the summer months, the main stem is significantly warmer above Harry Weir Creek than below it. This difference may be due to the greater exposure of the main stem above Harry Weir Creek, together with the cooling effect of water entering the main stem below Harry Weir Creek from tributaries in the park.

During low flow, watersheds having more exposure to weathering (VL- and RL-type) tend to have water with higher dissolved-solids (as indicated by specific conductance) concentrations than the forested (VF- and RF-type) watersheds. Also, the main stem above Harry Weir Creek has higher dissolved-solids concentrations at low flow than the main stem below Harry Weir Creek. The drainage basin above Harry Weir Creek is highly exposed both because of heavy logging and because the natural vegetation is sparser than in the drainage basin below the creek. Within the group of logged watersheds (VL), streams from the schistose regoliths (St) have the lowest dissolved-solids concentrations, and streams from the sandstone-based regoliths (Sn) have the highest concentrations. Within the group of schistose (St) watersheds, no differences in dissolved solids were discernible between watershed types, except that Bridge Creek, the watershed in the study area perhaps most heavily scarred by the various activities accompanying logging, has the highest dissolved-solids concentrations of any stream studied. Other factors not investigated here may contribute to high dissolved-solids concentrations in Bridge Creek. Thus, a firm cause-and-effect relationship cannot be established without further study.

Differences in water types also can be seen between land-use-related and regolith-related watershed types. During the rainy season, water types from the forested watersheds, logged watersheds, and the main stem form a regular progression from a mixed calcium-sodium bicarbonate-chloride type to a calcium-bicarbonate type. This progression corresponds to increasing exposure of the watershed to weathering due either to logging or to natural differences in vegetative cover. During the dry season, water from the group of VL- and RL-type watersheds (excluding the schistose watersheds) tends to be a more calcium-bicarbonate type than water from the VF- and RF-type watersheds.

The schistose (St-type) watersheds provide less consistent results. Generally, the water in this group of streams is a mixed calcium-sodium-bicarbonate-chloride type, regardless of the land-use-related watershed type, but Low-Slope Schist Creek (VF-type) has a distinctive sodium-chloride-bicarbonate-type water. In contrast, Bridge Creek (RL-type) has a calcium-bicarbonate-type water.

The results discussed above suggest that exposure of the land surface increases the rate of chemical weathering of the native regolith. The sandstone-based regoliths generally are most susceptible, and the schistose regoliths generally least susceptible to accelerated weathering, but extensive soil disruption in the schistose watersheds, as in Bridge Creek, may overwhelm the apparent natural resistance of the schistose regolith to weathering.

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