EFFECTS OF COAL MINE DRAINAGE ON THE WATER QUALITY OF SMALL RECEIVING STREAMS IN WASHINGTON, 1975-77

By Frank A. Packard, Earl L. Skinner, and Luis A. Fuste'

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DONALD PAUL HODEL, Secretary

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Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
1201 Pacific Avenue - Suite 600
Tacoma, Washington 98402-4384

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CONVERSION FACTORS, INCH-POUND TO METRIC

Multiply inch-pound units	By	To obtain SI units
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
ton, short	0.9072	megagram (Mg)
degree Celsius (C^o)	$^oF = 9/5^oC + 32$	degree Fahrenheit (^oF)

EFFECTS OF COAL MINE DRAINAGE ON THE WATER QUALITY OF SMALL RECEIVING STREAMS IN WASHINGTON, 1975-77

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ABSTRACT

Drainage from abandoned coal mines in western and central Washington has minimal environmental impact. Water-quality data from 51 abandoned coal mines representing 11 major coal-bearing areas indicate that less than 1 percent of the mine drainage has a pH of 4.5 or less. Fifty percent of the drainage has a pH 7.0 and greater, and about 96 percent has a pH 6.0 and greater. Less than 2 percent is acidifed to a pH 5.6, a point where water and free atmospheric carbon dioxide are in equilibrium. The area where pH 5.6 or less is most likely to occur is in the Centralia-Chehalis mine district.

Water-quality characteristics of mine drainage that will have the most significant environmental impact are suspended sediment and turbidity. A hydraulic mining test arranged near Wilkeson Creek indicated that large increases in suspended sediment and turbidity, accompanied by slight increases in temperature, are associated with hydraulic mining.

Results from a detailed study of a typical coal mine drainage site on Wilkeson Creek show that the mine drainage had some detrimental effects on the quality of Wilkeson Creek from a point where the drainage enters to where the two waters become completely mixed. Iron, as ferric hydroxide, precipitated and deposited along the stream channel. Hardness, alkalinity, sulfate, and dissolved solids increased; dissolved oxygen and pH decreased slightly.

No difference in diversity of benthic organisms was found when all months of data were compared. Significant differences in diversity were found during low streamflow months in a zone from the point where the mine drainage enters to about 50 feet downstream when diversity was compared to a control site on the receiving stream above the effects of the mine drainage. Within the 50-foot zone, ostracods were more abundant than at the control site but mayflies, stoneflies, and caddisflies were less abundant than at the control site. Correlations with water-quality measurements show that these faunal changes are closely associated with iron and sulfate.

Gallop and Loretta Creeks, two small stream basins that are undeveloped but considered likely to undergo underground coal-mine development in the near future, were found to be comparable with Wilkeson Creek in another area above the point where that stream receives mine drainage. It was determined that Gallop Creek is more likely to have increased acidity due to mining activity than Loretta Creek, but both were less likely to have net acidity than drainage from the Centralia mines or streams that drain the Centralia-Chehalis coal district. This assessment was confirmed by soxhlet extracting and chemically analyzing coal from mines in the three basins and comparing those data with data for the drainage from mines in the basins.

INTRODUCTION

Lower Tertiary formations in western and central Washington contain estimated coal deposit reserves of about 6.2 billion tons of low-sulfur coal (Beikman and others, 1961). The general location of these coal reserves is shown in figure 1. Many of these deposits occur in the form of thin beds which have been faulted and folded and which now occupy areas of high relief. Strip mining is economical in areas such as the Centralia-Chehalis and Kelso-Castle Rock coal-bearing areas, where folding is gentle and overburden ratios are low. In other coal areas where the coal is more deeply buried, the coal is more likely to be removed by underground mining.

The effects of underground mining must be considered with respect to environmental concerns. The approach used in the study was to appraise such effects by applying information gathered at existing or abandoned mines to future prospective mines. The abandoned underground mines of the State were located by using the mine map files of the Washington Department of Natural Resources.

Objectives

The objectives of this report are: (1) to characterize the water quality of drainage from abandoned underground coal mines in the 11 major coal-bearing areas of the State; (2) to identify the physical, chemical, and biological effects of the water quality on a stream receiving drainage from an abandoned underground coal mining area; (3) to identify the baseline water-quality conditions of the surface water at two prospective underground coal-mining areas; and (4) to propose a scheme for monitoring the water-quality effects of underground mining at the sites selected in objective 3, on the basis of information from the first three objectives.

Previous Studies

In the Wilkeson mine drainage study area, the geology has been described by Daniels (1914), Beikman and others (1961), the U. S. Bonneville Power Administration (1963), and Livingston (1974). Several miscellaneous discharge measurements were made by the U. S. Geological Survey at a gaging station on Wilkeson Creek from July to October 1949 and in August 1951.

In the Gallop Creek baseline area, discussions of the geology of local coal deposits have been published by Woodruff (1914), Beikman and others (1961), Moen (1969), Livingston (1974), and most recently by VonHeeder (1975). The Washington Department of Fisheries (DOF) has gathered spawning data on anadromous fish along the lowest 1/3 mile of Gallop Creek since 1941. In the Loretta Creek baseline area, geologic reports have been published by Jenkins (1924), Beikman and others (1961), and Livingston (1974).

Additional information on underground mines is available from Evans (1912), Saunders (1914), Jenkins (1924), Warren (1945), Snavely and others (1958), Roberts (1958), Gower and Wanek (1963), Livingston (1966, 1971), and Vine (1969).

Acknowledgments

The authors wish to acknowledge several persons, corporations, organizations, and agencies that provided valuable assistance to this study. We appreciate the assistance and advice of Ellis VonHeeder of the Washington Department of Natural Resources; George Savannik of the U.S. Bureau of Mines; Gary Dahl of Burlington Northern; Don Hume and Assoc.; Albert Finachau of Transcontinental Log and Export Co.; Kirk Fox, Chris Palzer of Takahashi Exports; Joel Douglas of Glacier Lands Co.; Roger Hickey and Roger Paul of WIDCO; the Black Prince Coal Co.; the Palmer Coking Coal Co.; and John Cheung and Scott Veenhuizer of Flow Research. Susan Hahn, U.S. Geological Survey, Menlo Park, California; Dr. Stanford Smith, Central Washington State University, Ellensburg, Washington; Dr. Gerald Kraft, Western Washington State University, Bellingham, Washington; and Dr. John J. Lattin, Oregon State University, Corvalis, Oregon, provided much needed help in verifying biologic identifications.

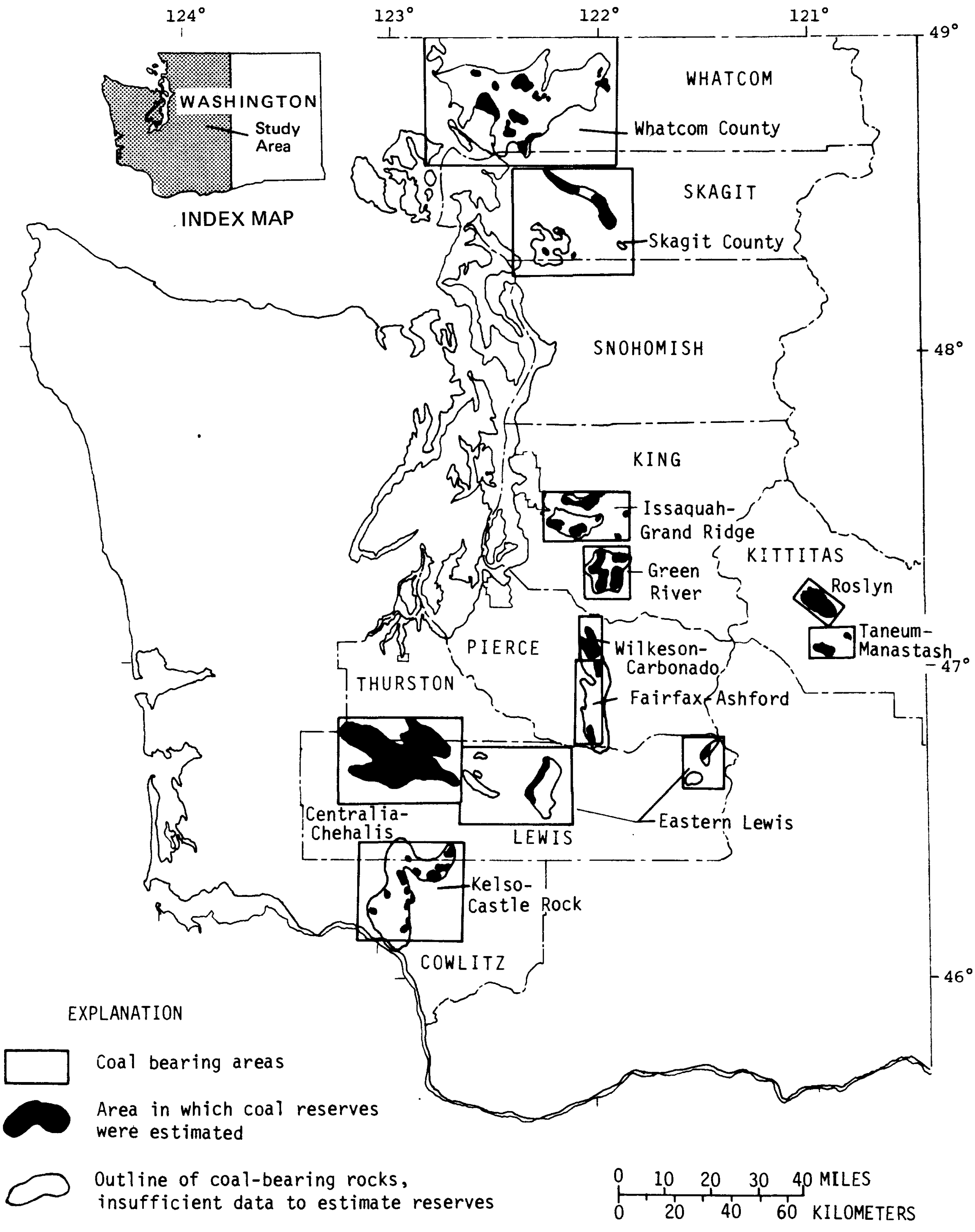


FIGURE 1.--Major coal-bearing areas in western and central Washington.

GENERAL GEOCHEMICAL EFFECTS OF COAL MINE DRAINAGE

Two problems generally associated with coal mine drainage are dissolved chemical and suspended solid loads imposed on the receiving stream (U. S. Department of Interior, 1969). The dissolved constituents that most directly affect stream biota and water use are related directly to the amount of sulfur contained in the coal being mined in the drainage basin (Caruccio and others, 1977). When chemically reduced sulfur contained as pyrite in sedimentary deposits is exposed to oxygenated water, the potential exists for the water to become acidic. Some species of sulfur in coal-rich deposits can be reduced to produce hydrogen sulfide. At pH levels below 4.5, most of this pyrite oxidation is bacterially mediated, and therefore is an efficient energy source for further microbial growth (Walsh and Mitchell, 1979). Depending upon mine practices, stratigraphy, and ground-water hydrology, low pH and acidic coal-mine drainage have the capacity to produce high concentrations of dissolved trace metals and increased concentrations of iron, sulfates, aluminum, manganese, dissolved solids, and hardness in receiving streams (Wentz, 1974). Iron in mine effluent commonly precipitates to form deposits that can coat stream substrates and reduce niche habitats for benthic invertebrate communities (Koryak and others, 1972). Reduced habitat commonly leads to a reduction in fish populations. Other dissolved and suspended solids can restrict use of the water for domestic and industrial purposes. The generally accepted stochiometric equations which describe the chemical reactions taking place in the iron pyrite oxidation are given by Hollyday and McKenzie (1973) and Scott and Hayes (1975).

Unlike coal seams in the northern Appalachian region and other regions where high-sulfur coal deposits are found, the sulfur content of Washington coal is low and the typical mine drainage is classified as alkaline. Alkaline mine drainage is described as having pH near neutral (pH 7.0 ± 0.5), high sulfates, low concentrations of aluminum, significant concentrations of calcium, magnesium, and manganese, and moderate concentrations of iron. Such drainage may result when only a few acid-producing minerals are associated with a mineral body, or when the acid mine drainage is neutralized by carbonate minerals (Scott and Hayes, 1975).

COAL MINE DRAINAGE IN WASHINGTON

The coal-mining areas of the State are characterized as having many variations in geology, coal deposits and geochemical processes that are occuring within the individual mines, mining areas and in the water draining from the mines. The chemistry of the water draining from coal mines in Washington is a reflection of these variables. Mine water drainage was sampled from several coal areas for the purpose of characterizing water quality of the mine drainage in the State. Many of the mines visited were not draining, probably due to lowered water tables resulting from the drought of 1976-77.

Water Quality

Of the 247 abandoned underground coal mines estimated to exist in the State (Scott and Hayes, 1975), 137 were investigated to determine if they had visible drainage. Of these, 51 mines, representing 9 of the 11 known coal areas, had drainage. Specific conductance, pH, dissolved oxygen, and temperature were measured in the field at each of the 51 mine drainage sites, and samples were collected for analysis of acidity and iron. Each of the coal-bearing areas, except the Taneum-Manastash and the Wilkeson-Carbonado areas, were sampled for a more complete chemical analyses in the laboratory (Fuste' and others, 1983).

Cumulative probability distribution curves were prepared for pH, sulfur, alkalinity, and acidity (figs. 2a, 2b). Sulfur content analyses were taken from proximate analyses described in Beikman and others (1961). Eighty percent of the coal seams examined have less than 1 percent sulfur, and less than 5 percent of the coal seams have sulfur content greater than 2.2 percent. All coal in Washington is classified as low sulfur, having a statewide median of 0.65 percent sulfur (Beikman and others, 1961). The Centralia-Chehalis coal area has the highest sulfur content of all the coal-bearing areas in the State (1.12 percent, based on an area weighted average) and pyrite is more common than in other coal areas. Coal having high sulfur content and more extensive pyrite deposits is most likely to produce acid in quantities that at times might exceed the neutralizing capacity of the alkalinity (carbonates).

The pH of the mine drainage samples ranged from 5.6 to 8.5. Most of the low pH readings recorded were from mines in the Centralia-Chehalis coal area in western Lewis County, southwestern Washington. The cumulative probability distribution for pH (see fig. 2a) shows that the probability of pH of mine drainage water occurring below 5.6, the theoretical pH of water in natural equilibrium with carbon dioxide (Hem, 1970), is less than 2 percent.

The cumulative probability distribution of acidity and alkalinity reveals that concentrations of alkalinity are two to four times greater than concentrations of acidity 95 percent of the time (see fig. 2b). This indicates that alkalinity is available in excess of what is required to neutralize any acidity produced by pyrite oxidation, and that acid mine drainage is unlikely to occur in Washington.

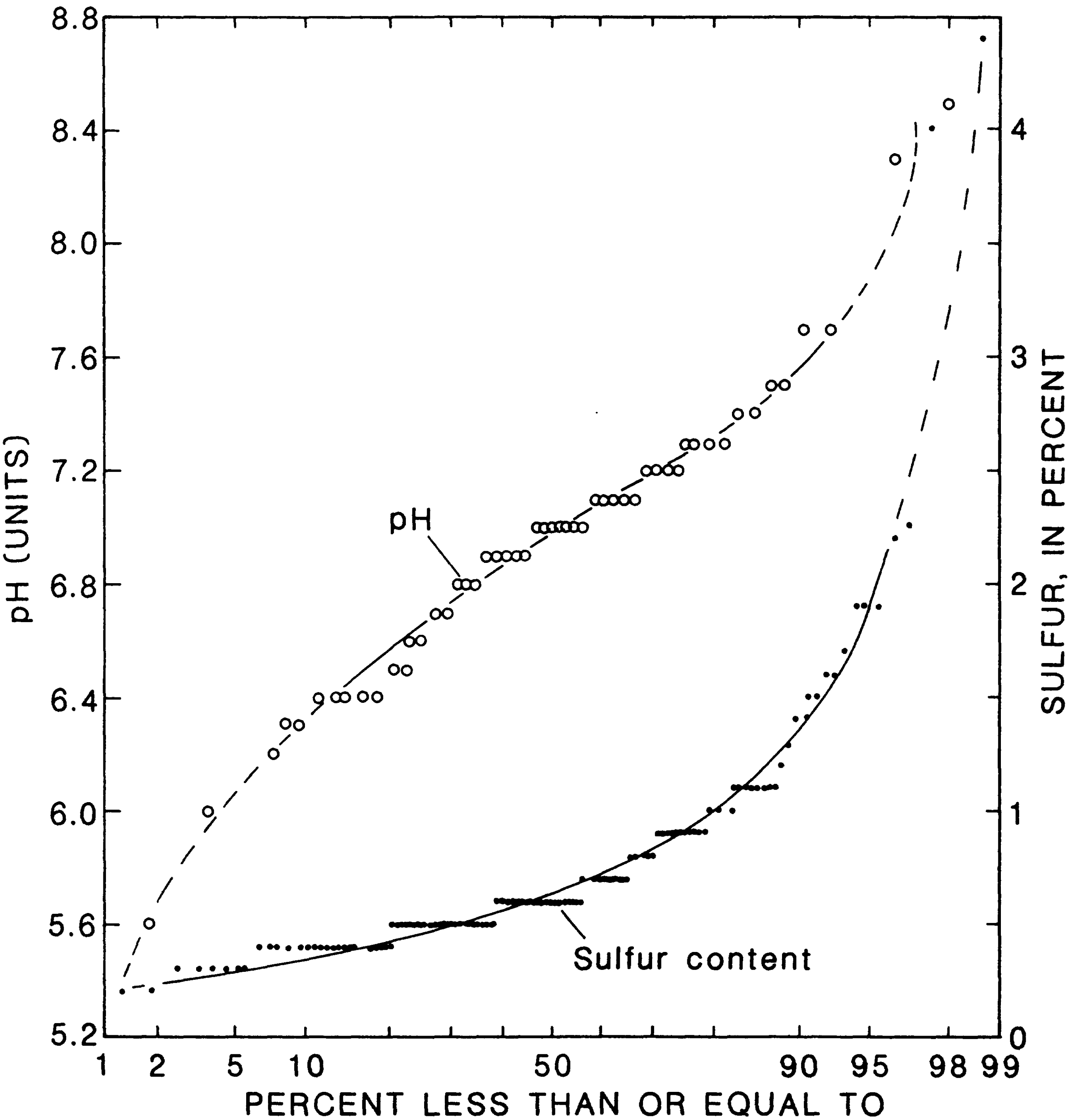


FIGURE 2a.--Cumulative probability distributions of pH in coal mine drainages and sulfur content of coal seams in Washington.

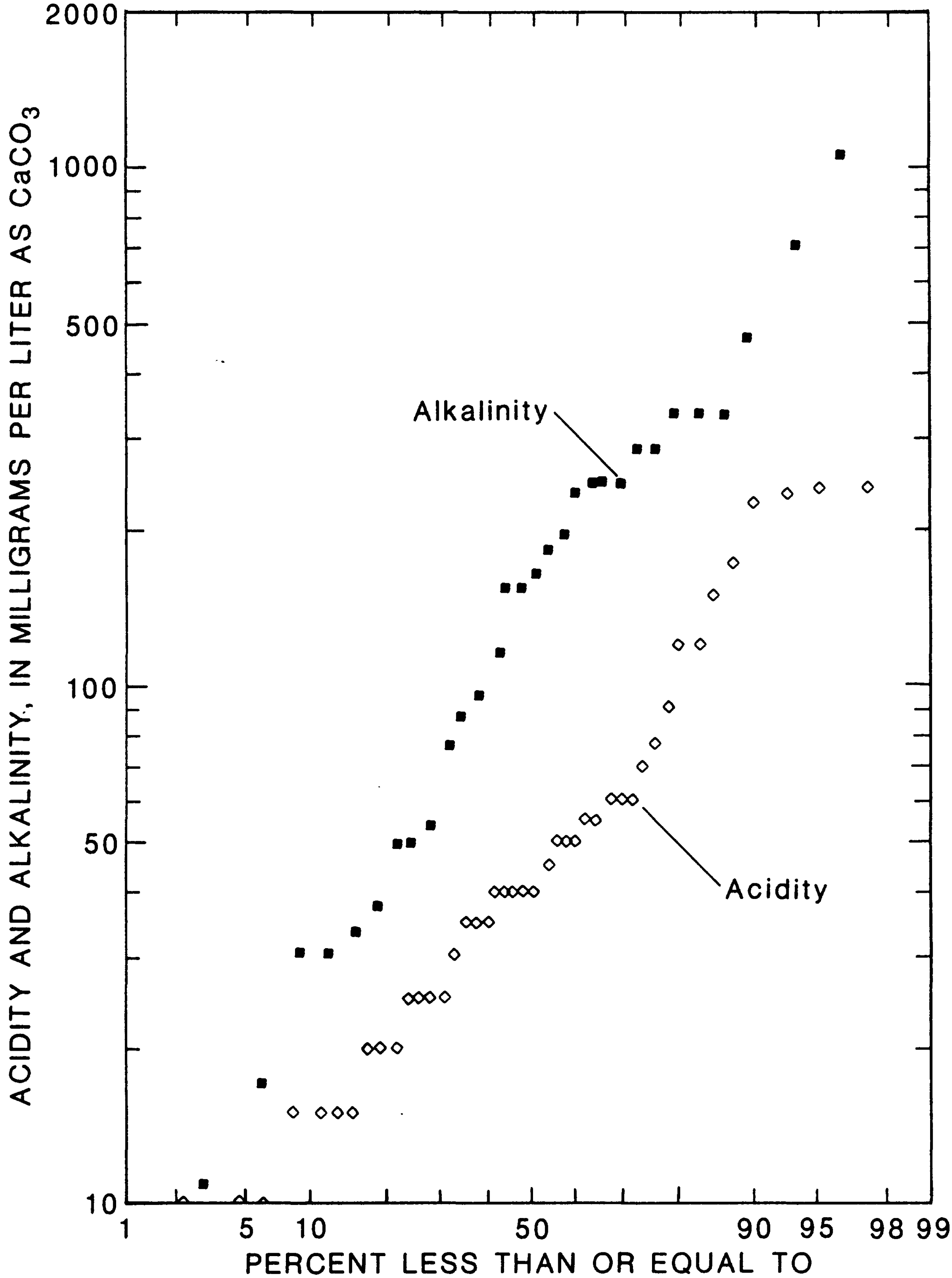


FIGURE 2b.--Cumulative probability distributions of acidity and alkalinity in coal mine drainages in Washington.

Relatively complete analyses, including trace metals, are available for 16 mine drainages. Copper and lead were the only trace metals that had concentrations considered to be analogous, and even these were small. Low pH is a causative factor in the occurrence of high trace metal concentrations (Wentz, 1974). Because mine drainage in Washington is considered to be alkaline, significant concentrations of trace metals in the mine drainage are not expected.

Correlation of Water-Quality Characteristics and Coal Mine Drainage

A Spearman correlation test (Conover, 1971) was performed for 10 water-quality characteristics and a matrix chart was constructed (table 1). The sulfur content of local coals and the number of years elapsed since each mine was opened were included in the test. Only coal sulfur content greater than 0.6 percent was used as a characteristic because sulfur in that range is thought to represent pyrite as a source of sulfur, whereas coal with a sulfur content less than 0.6 percent is probably organically bound. Only those correlations with $P \leq 0.10$ are considered as significant.

Sulfur content of coal or the number of years since a mine became active could not be correlated with any of the other eight characteristics tested. This is due in part to the continual neutralizing effects between the acids formed by the pyritic sulfur and the alkalinity (carbonates) in the soil and rocks surrounding the coal seams and mine discharges.

Dissolved oxygen (DO) has positive correlation to net acidity but a negative correlation (inverse relationship) to alkalinity and specific conductance, and no correlation to pH. The positive correlation of dissolved oxygen and net acidity is expected in alkaline water where alkalinity exceeds potential acidity, and therefore, net acidity probably does not exist in the mine discharges. Conversely, when acid is being formed causing a decrease in alkalinity, dissolved oxygen would be expected to increase. Such a condition is shown by the inverse relationship between alkalinity and dissolved oxygen correlation in the matrix (table 1). Dissolved oxygen and pH are expected to correlate in natural water due to plant photosynthesis and respiration. These processes take up carbon dioxide and expel oxygen to the water by photosynthesis during the day, then take up oxygen and expel carbon dioxide by respiration during the night. Because this fluctuation involves carbon dioxide, pH should fluctuate in response to excesses and deficiencies in carbon dioxide. In the mine drainages, this does not occur. The matrix chart shows no correlation between dissolved oxygen and pH because the chemical oxidation of pyritic materials rather than free carbon dioxide is the factor controlling pH.

All other characteristics correlated as expected for both natural water and water affected by alkaline mine drainage. These correlations generally involved increasing mineralization due to sulfate, iron, and alkalinity with a commensurate increase in specific conductance.

TABLE 1.--Spearman correlation matrix for paired, water-quality characteristics and coal mine drainage ($P \leq 0.10$)

[The correlation coefficient is listed along with the number of data points available for the calculation; net acidity equals acidity as $CaCO_3$ minus alkalinity expressed as milligrams per liter; X means no significant correlation was found at $P \leq 0.10$]

	1	2	3	4	5	6	7	8	9	10
1. Coal sulfur content (> 0.6 pct)	1.0 24	X	X	X	X	X	X	X	X	X
2. Number of years since mine became active		1.0 34	X	X	X	X	X	X	X	X
3. Dissolved-oxygen			1.0 35	-0.41 35	X	-0.33 34	0.50 21	-0.43 22	X	X
4. Specific conductance				1.0 43	X	0.75 37	-0.45 23	0.63 25	0.58 22	X
5. pH					1.0 43	-0.50 37	-0.66 23	0.61 25	X	X
6. Acidity						1.0 37	X	X	0.61 20	X
7. Net acidity							1.0 23	-0.91 23	X	0.46 20
8. Alkalinity								1.0 25	X	-0.36 22
9. Sulfate									1.0 22	X
10. Total iron										1.0 36

Impact of Borehole Hydraulic Mining on Water Quality

Borehole hydraulic mining of coal can have a significant impact on the quality of the water used in the mining operation. The U.S. Bureau of Mines, in 1976, sponsored a research effort to conduct borehole hydraulic mining tests in a coal deposit in southwestern Washington near the mouth of Gale Creek, a tributary to Wilkeson Creek. This site is about 2 miles southeast of Wilkeson and about 1 mile southeast of the mine-drainage study site at the Skookum mine. This type of coal mining utilizes a high pressure jetting tool which forces water into the coal seam to fracture it into small particles. The coal seam is accessed by way of a borehole. The cavity formed as the coal is fractured serves as a mixing chamber to form a slurry of coal and water that is forced to the surface through a pipe in the jetting tool (fig. 3).

Water used in the borehole hydraulic test was taken from Gale Creek upstream from the influence of the test site. After the coal-water slurry was brought to the surface it was diverted into the open settling tank No. 1, then pumped into the second open settling tank, No. 2, and finally pumped through pipes where a flocculent was added, then into the final settling pond where it was allowed to overflow back to Gale Creek. Samples were collected from Gale Creek above the mining site and both No. 1 and No. 2 settling tanks and analyzed for selected water-quality constituents and characteristics. Results of the analyses are published in Fuste' and others (1983).

Following is a tabulation of selected data collected on June 29, 1976, from Gale Creek upstream from the mining operation before it was used in the process and from settling tanks No. 1 and No. 2 after the water was used in the jetting-slurry operation.

	Gale Creek water		
	Upstream water unaffected by mining	Slurry effluent Tank No. 1	Slurry effluent Tank No. 2
Suspended sediment, in milligrams per liter	10	8,340	9,590
Turbidity, in nephelometric turbidity units	7	540	480
pH (units)	7.1	7.9	7.8
Dissolved solids, in milligrams per liter	50.0	86	76
Temperature, degrees Celsius	11.4	15.0	15.0
Dissolved lead, in micrograms per liter	1	2	2
Dissolved manganese, in micrograms per liter	30	30	20
Dissolved nickel, in micrograms per liter	2	6	--
Total iron, in micrograms per liter	1,600	130,000	29,000

The large increases in suspended sediment and turbidity measured at the settling tanks are due to fine particles of coal, rock fragments, and soil in suspension. Efficient flocculation techniques are required to prevent this suspended mixture from reaching the streams. Dissolved solids increased, as did total iron concentration. The increase in total iron concentration was associated with suspended particles such as small particles of pyrite ore or iron compounds, sorbed onto the particles. The increase in dissolved solids resulted from increases in sodium and bicarbonate.

The pH of the water changed to a more alkaline (basic) character than it was before it went through the process, but it was still within the ranges (6.5 to 8.5) required by Washington State Department of Ecology for stream fauna. Temperature of the slurries in tanks No. 1 and 2 showed about a $3.5^{\circ}C$ increase over the stream water. This increase was due to the fact that water used in the process was recycled.

The types of problems encountered during this borehole hydraulic test are thought to be indicative of what might happen in underground mining in other areas of the State. Suspended sediment, turbidity, and iron associated with the sediment may be the most significant impacts this mining practice has on the quality of the process water. Temperature increase may be the next most significant impact. This research effort addressed the impact a borehole hydraulic mining process would have on the process water; it did not address the effects that such an operation would have on a stream receiving the final effluent. No measurements were made downstream from where final settling pond water discharges into the stream and no assessment was made of the impact on the water chemistry of Gale Creek.

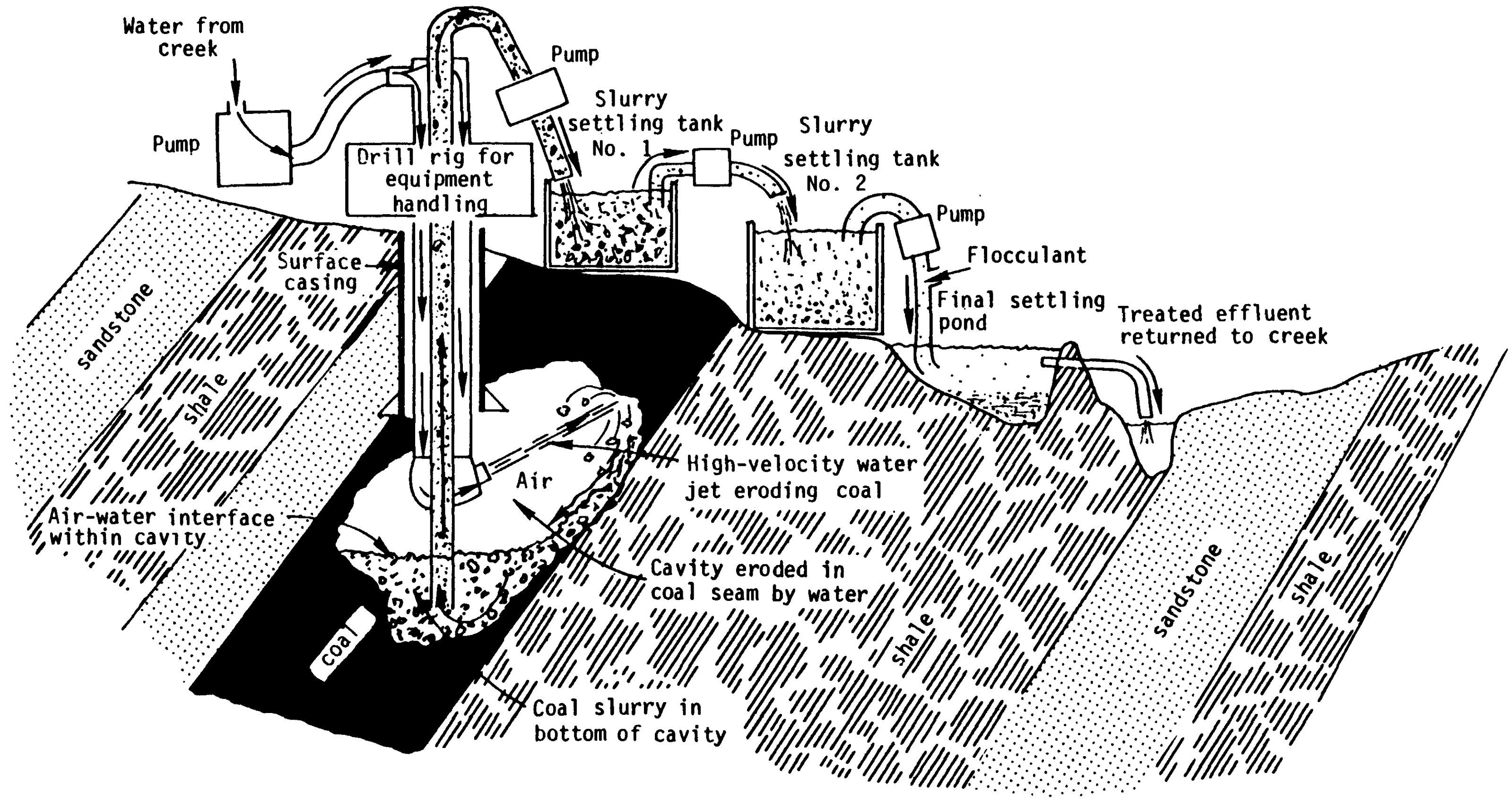


FIGURE 3.--Diagrammatic cross section showing borehole hydraulic coal-mining process.

EFFECTS OF COAL MINE DRAINAGE ON A RECEIVING STREAM

A study of the effects that coal mine drainage has on a receiving stream requires the careful selection of a study area and monitoring sites, determination of the physiographic and hydrologic features and climatic characteristics of the study area, and an assessment of the water quality of the mine drainage and receiving stream. The selection of study areas and monitoring sites should follow established criteria so that the area and sites are characteristically representative of the problems to be studied.

Study Area and Station Selections

A study area was selected on the basis of several criteria. These criteria included morphologic and biologic similarity to baseline streams, the ratio of the quantity of mine drainage to the receiving stream discharge, accessibility to the study site, and the similarity of mine effluent chemistry to the average coal mine drainage in other areas of the State. On the basis of these criteria, the Skookum mine drainage and Wilkeson Creek in the Wilkeson Creek basin were chosen (fig. 4).

The two principal coal seams of the area are Wilkeson Nos. 2 and 3 (Daniels, 1914). These seams, along with several other seams, were mined through the Skookum slope portal and the Fanhouse portal (fig. 4). These mines were worked principally in the early 1900's. The mines were reopened in the 1950's, but were abandoned in 1963. The geology of these coal seams is described in detail by Arndt and Kent (1980). They stated that the sulfur content of the Nos. 2 and 3 coal seams averages 0.6 and 0.4 percent, respectively, but ranges from 0.5 to 1.1 percent in several other seams.

During this study the dilution ratio of the combined mine drainage from the Skookum mine area to the measured discharge for Wilkeson Creek ranged from approximately 1:10 during the lowest measured flow (11 ft^3/s) to 1:100 during the highest measured flow (120 ft^3/s).

The stream stations and mine-site stations that were sampled in the Wilkeson Creek study area are shown in figure 4. The control station was located about 1,500 feet upstream from Skookum mine drainage above the influences of the mine and other tailings drainage. Two other stations were located on Wilkeson Creek near the point where drainage from the Skookum mine area enters Wilkeson Creek. One station was located near the right bank, just above the point where the combined Skookum Creek mine area drainage enters Wilkeson Creek. The other station was located on the left side of Wilkeson Creek about 20 feet downstream from the point where Skookum drainage enters. A fourth station was located about 3,000 feet downstream from the point where the combined Skookum mine drainage enters Wilkeson Creek and where the mine drainage and Wilkeson Creek are thoroughly mixed. Combined drainage from all portals in the Skookum mine area was sampled just before it entered Wilkeson Creek. The station on Wilkeson Creek just above the combined Skookum drainage point of entry receives ephemeral drainage from another abandoned mine located upstream from the station. Mine tailings are scattered along both banks of Wilkeson Creek between the upper and lower stations. The other stations shown on figure 4 as sampling stations Nos. 1 through 7 were sites that refer to off-stream sampling points within the Skookum Mine area.

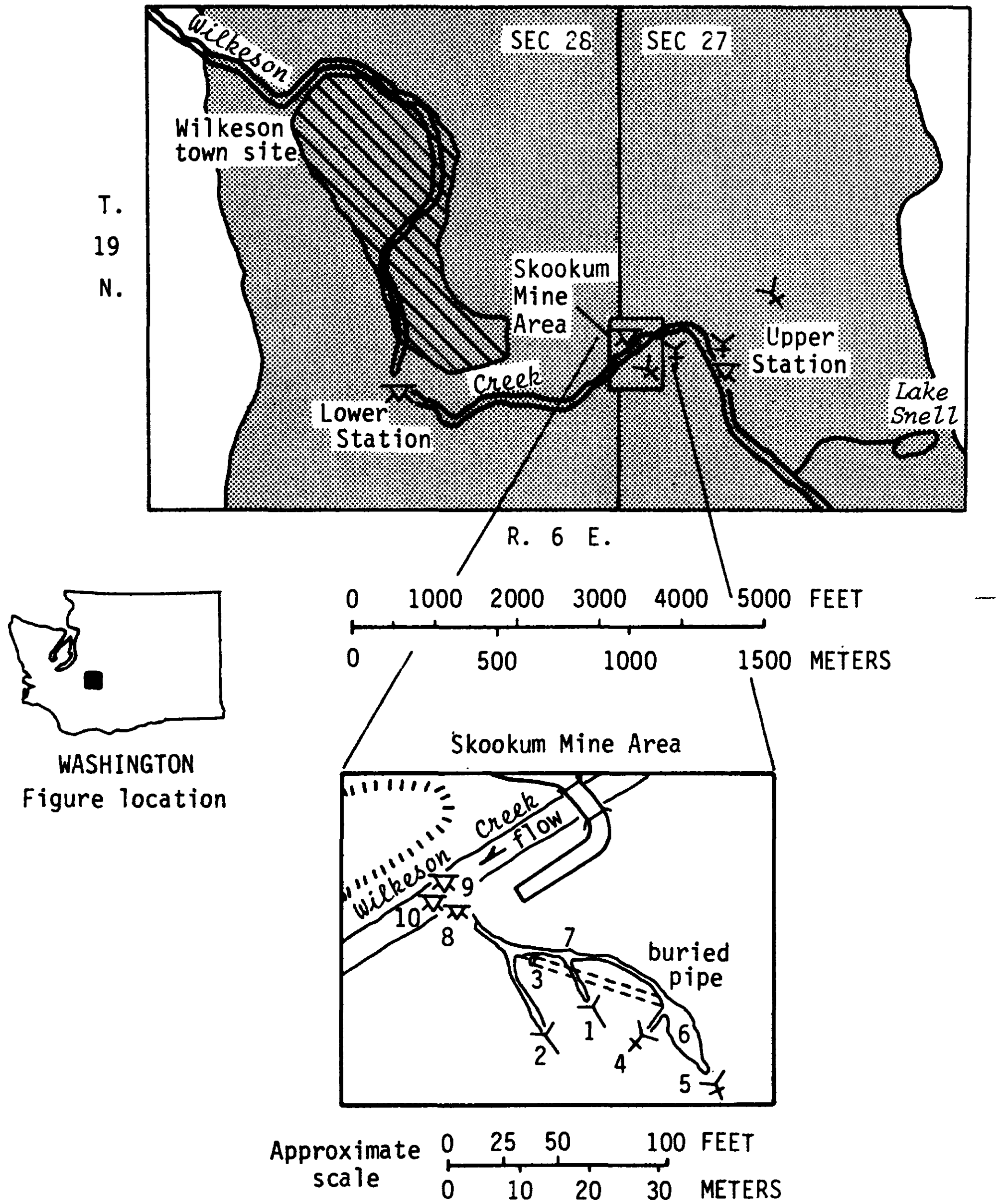
Physiographic, Hydrologic, and Climatic Characteristics

Physiographic and Hydrologic Features

The physiographic and hydrologic features of the Wilkeson Creek basin above the lower station have been summarized for use in characterizing the mine drainage area (table 2). Differences in altitude between sampling stations are negligible because the lower station is only 55 feet lower than the upper station. All sampling stations are located in riffle reaches of the pool-riffle stream.

Climate

Precipitation during the sampling period between September 1976 and February 1977 was well below the average for the 30-year period of record (fig. 5). The cumulative rainfall for the study period ranged from 1 inch below the long-term cumulative mean in November 1976 to about 9.5 inches below by May 1977 (fig. 5). This drought period had an influence on the streamflow and most likely the water quality regimen in Wilkeson Creek. The comparison between stations on Wilkeson Creek is valid because all stations were equally affected during the study period. Air temperature was near normal compared to the long term mean value. The only significant departure from normal during the study period was that the temperature was about 1°C cooler than normal in August 1976 and January 1977 and about 2°C and 1°C warmer in February and April 1977, respectively.



Index to Skookum Mine Drainage and Wilkeson Creek Sampling Stations

1. Skookum slope portal
2. Fanhouse portal
3. Lower end of buried pipe
4. Collapsed tunnel
5. Collapsed tunnel
6. Drainage pool at head of buried pipe
7. Small pool along Skookum drainage
8. Combined effluent (sample point #8)
9. Station just above the mine drainage
10. Station just below the mine drainage

EXPLANATION

- Sampling station
- Mine portal
- Collapsed portal
- tailings pile
- Boundary of area for which measured and inferred coal data are sufficient to estimate reserves (Beikman and others, 1961)
- Bridge

FIGURE 4.--Wilkeson Creek study area, Washington, with detailed inset map of sampling stations.

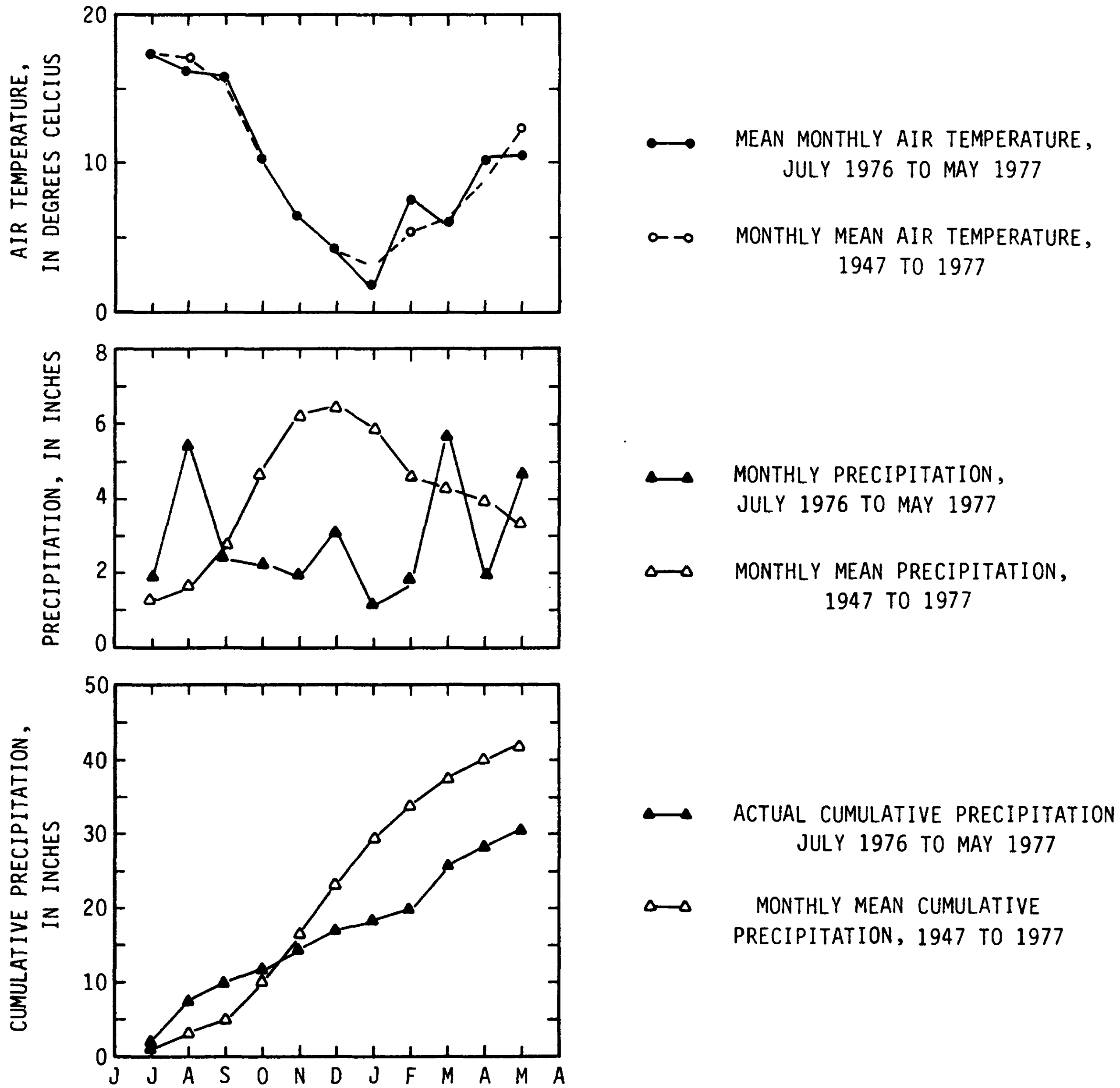


FIGURE 5.--Comparison of air temperature and monthly precipitation with the respective long-term records in the Wilkeson Creek study area, Washington.

TABLE 2.--Physiographic and hydrologic features of the Wilkeson Creek sampling stations

Basin station	Upper station	Left and right bank stations - combined Skookum area discharge point	Lower station
Location	SW 1/4 SW 1/4 sec. 27, T.19N., R.6E, approx. 600 feet upstream from sharp bend in channel.	NW 1/4 SW 1/4 sec. 27, T.19N., R.6E., approx. 150 feet downstream from wooden bridge to Skookum slope portal.	SW 1/4 SE 1/4 sec. 28, T.19N., R.6E., approx. 200 feet downstream from concrete bridge (Highway 165).
Approx. stream reach slope	0.014 foot/foot	0.014 foot/foot	0.014 foot/foot
Stream order	5	5	5
Stream morphology	Riffle-pool station is in riffle.	Riffle-pool station is in riffle.	Riffle-pool station is is in riffle.
Average measured depth	0.86 foot	1.00 foot	0.90 foot
Average velocity	0.82 foot per second	---	0.90 foot per second
Approx. altitude above sea level	860 feet	835 feet	805 feet
Drainage area above station	22.5 square miles	22.9 square miles	23.5 square miles

Quality of Skookum Mine Drainage

The water quality of the combined Skookum mine drainage (see sample point No. 8, fig. 4) was compared with the water quality data collected from mine drainages statewide (see table 3). Median values for the water-quality characteristics that commonly are affected by mine drainages were about the same for the combined Skookum drainage as for mine drainage statewide except for iron, which was almost four times greater in the combined Skookum drainage than the mine drainage statewide. The water quality of anaerobic drainage from the Skookum slope portal and aerobic drainage from the Fanhouse portal were more of a contrast. This is evidenced by the differences in water chemistry and biological characteristics of the drainages from the two portals. The drainage from both the Skookum slope portal and the Fanhouse portal combine before flowing into Wilkeson Creek.

Water Chemistry

The water chemistry of drainages from the Skookum Slope portal and Fanhouse portal, both of which are within the Skookum mine area, and of the combined drainage from the entire mine area are presented in table 4. On July 21, 1976, unaerated water discharging from the Skookum slope portal had no dissolved oxygen (DO), high specific conductance (983 uS/cm), high alkalinity (480 mg/L), high dissolved sulfide (13 mg/L) and low iron (30 ug/L). In contrast, the Fanhouse portal, which drains an aerated system of tunnels, was discharging water with moderate concentrations of dissolved oxygen (60 percent saturation), lower specific conductance (353 uS/cm), moderate alkalinity (160 mg/L), no detectable sulfide, and high iron (2,400 ug/L). The Fanhouse portal drainage is more comparable to the combined drainage than is the Skookum Slope portal drainage. This is expected because the Fanhouse portal accounts for about 67 percent of the combined Skookum mine area discharge, whereas the Skookum slope accounts for only about 2 percent.

The bottom material in the Skookum Slope drainage channel was a soft, white, gelatinous material overlying a soft black ooze that appeared to be composed of iron sulfide and decaying organic material. The channel bed in the Fanhouse drainage was coated with a reddish-yellow gel that appeared to be composed of iron hydroxide, decaying organic material, and silt. The gelatinous deposits were not analyzed chemically for either of the two drainages, but the contrasting appearance of the deposits were typical of unoxidized anaerobic and oxidized anaerobic conditions, respectively.

TABLE 3.--Comparison of water-quality data from the combined Skookum mine area drainage to mine drainage statewide

Data component	Statewide data			Combined Skookum Drainage		
	Number of analyses	Mean	Median	Number of analyses	Mean	Median
Specific conductance (microsiemens per centimeter at 25 °C)	51	500	357	9	374	375
pH (standard units)	50	7.0	7.0	8	7.1	7.2
Dissolved oxygen (percent saturation)	40	-----	61	10	72	73
Acidity (milligrams per liter as $CaCO_2$)	43	53	30	9	27	30
Alkalinity (milligrams per liter as $CaCO_3$)	31	210	180	9	184	190
Total iron, Fe (milligrams per liter)	43	2,300	550	9	1,800	1,800
Sulfate (SO_4) (milligrams per liter)	29	76	25	9	20	21

TABLE 4.--Comparison between the water quality of the drainage from the Skookum Slope and Fanhouse portals, July 21, 1976 and the combined Skookum area drainage July 1976 to May 1977

[Skookum Slope portal and Fanhouse portal data represent a single analysis value for July 21, 1976, the combined drainage data represent median values for the period July 1976 to May 1977]

Variable	Skookum Slope portal drainage	Fanhouse portal drainage	Combined drainage
Specific conductance (microsiemens per centimeter at 25 °C)	983	353	375
pH (units)	7.3	7.0	7.2
Temperature (0 °C)	11.6	9.3	9.7
Dissolved oxygen (percent saturation)	0	60	73
Acidity (milligrams per liter as $CaC0_3$)	50	30	30
Alkalinity (milligrams per liter as $CaC0_3$)	480	170	190
Total iron (micrograms per liter)	30	2,400	1,800
Dissolved sulfate (milligrams per liter)	120	33	21
Dissolved sulfide (milligrams per liter)	13	0	0
Discharge (cubic feet per second)	0.03	0.87	1.3

Biological Characteristics

Synoptic surveys were conducted to identify the invertebrate fauna in the drainages from the Skookum slope and Fanhouse portals. The results of these surveys (table 5) indicated that the biological communities in the Skookum slope drainage were distinctly different from those in the Fanhouse drainage.

Beetle larvae (Elodes sp.), midge larvae (Chironomus sp.), mosquito larvae (Culiseta sp.), false crane flies (Liriope sp.), and brine flies (ephydrids) were the most abundant organisms in the Skookum Slope drainage; whereas, mayflies, stoneflies, and caddisflies were notably absent. In the Fanhouse drainage, caddisfly larvae (Psychoglypha sp.) and false crane fly larvae (Bittacomorpha sp.) were the dominant fauna.

Photosynthetic purple sulfur bacteria, Chromatium okenii, were found in the Skookum slope drainage. The water was devoid of oxygen, low in iron, but high in dissolved sulfides. The anaerobic sulfur bacteria thrive in light, using hydrogen sulfide as a hydrogen donor to drive the photosynthetic and metabolic processes. There were no dissolved sulfides nor sulfur bacteria identified at the Fanhouse drainage, but two forms of aerobic iron bacteria (Thiobacillus sp. and Ferrobacillus sp.) were reported to be present (Gary Erlich, U.S. Geological Survey, oral commun., 1977).

TABLE 5.--Biological data from synoptic surveys of drainages from the Skookum Slope and Fanhouse portals, Washington

[++, abundant; +, rare; -, absent]

	Occurrence	
	Skookum Slope	Fanhouse
Order Ephemeroptera (mayflies)		
Family Baetidae		
Baetis sp.	-	+
Order Plecoptera (stoneflies)		
Family Nemouridae		
Malenka sp.	-	+
Order Trichoptera (caddisflies)		
Family Rhyacophilidae		
Rhyacophila grandis	-	+
Family Limnephilidae		
Clostoeca sp.	-	+
Ecclisomyia sp.	-	+
Halesochila taylori	-	+
Psychoglypha sp.	-	++
Order Diptera (true flies)		
Family Chironomidae (midge larvae)	++	-
Family Culicidae		
Culiseta sp. (mosquito larvae)	++	-
Family Ephydridae (brine flies)	++	-
Family Liriopeidae (false crane flies)		
Bittacomorpha sp.	-	++
Liriope sp.	++	-
Family Tipulidae		
Pedicia sp.	-	+
Order Coleoptera (beetle larvae)		
Family Dysticidae		
Agabus sp.	+	-
Family Helodidae		
Elodes sp.	++	+
Family Hydrophilidae		
Crenitis morata	+	-
Order Hemiptera (true waterbugs)		
Family Gerridae		
Gerris nyctalis	+	+
Trepobates sp.	+	+
Order Collembola (spring tails)		
Family Smynthuridae	-	+
Family Entomobrydae	-	+
Order Lepidoptera (moths)	-	+
Phylum Annelida (segmental worms)		
Class Clitellata		
Subclass Oligochaeta	+	+

Quality of Wilkeson Creek

Water-quality data collected at four sampling stations on Wilkeson Creek document significant changes that occurred in Wilkeson Creek as a result of the mine discharge. The four stations were located (1) about 1,500 feet upstream from the Skookum mine area discharge point, (2) a few feet above where the Skookum mine area drainage enters Wilkeson Creek, (3) about 20 feet below where the drainage enters, and (4) about 3,000 feet downstream where Wilkeson Creek and Skookum mine drainage are completely mixed. Differences in the water quality between stations were evaluated and differences were compared to observed changes in the benthic community.

Water Chemistry

Mean values for 21 of the 40 water-quality characteristics measured at the four Wilkeson Creek stations are summarized in table 6. A comparison is made between all data covering the period July 1976 to May 1977 and the 3 months of low-streamflow data from July to September 1976.

The station just below the mine discharge entry point showed more effects of the mine drainage than did the other three stations. This station had higher mean values for specific conductance, acidity, hardness, and dissolved calcium, magnesium, sodium, potassium, alkalinity, sulfate, silica, ammonia, total iron, and manganese for both the varied (all) and low-flow periods than the other stations. Dissolved-oxygen, pH, and temperature were lower during the low-flow period.

At the lower station, where the mine effluent and the stream water had mixed completely, the water quality was comparable to the upper station, but was slightly more mineralized, with increases in most constituents commensurate with the increase in specific conductance. These increases existed for both the varied (all) and low-flow periods, indicating that the mine drainage influenced the receiving stream throughout the year.

The low concentrations of dissolved trace metals were comparable at all four stations (Fuste' and others, 1983). Trace metals, especially the more insoluble ones, most likely coprecipitated with ferric oxides and hydroxides in the Skookum mine drainage, as determined in a similar study conducted in coal areas in Colorado (Wentz, 1974).

Ferrous and ferric iron concentrations were measured in the Skookum mine effluent water and found to have a ferrous to ferric ratio of about 1 to 5. This ratio, and the low dissolved oxygen in the mine drainage, indicate that iron in the effluent is not completely oxidized. Further oxidation occurs in Wilkeson Creek over a distance of about 300 feet downstream from the entry point of the effluence, as evidenced by ferric hydroxide and ferric oxide coating the channel and substrate along this reach during low flows. As the mine effluent water becomes mixed with Wilkeson Creek, this coating becomes less noticeable, and at the lower station it is seldom seen. During high flows, this coating is scoured from the channel and substrate, and for lengthy periods of time afterwards it is barely noticeable, even at the point where the mine effluent enters Wilkeson Creek.

TABLE 6.--Mean values for Wilkeson Creek water-quality data at different streamflow periods

[All: refers to mean flow for the period of study from July 1976 to May 1977;
Low: refers to mean flow for the low flow period July-September 1976;
All units in milligrams per liter (mg/L) unless otherwise stated]

Constituent or Characteristic	Flow	Number of samples per station	Station: Upper	Station: Above Skookum drainage	Station: Below Skookum drainage	Station: Lower
Specific conductance (microsiemens per centimeter at 25 °C)	All	10	59	64	184	88
	Low	6	66	71	321	121
Milliequivalents per liter for cations and anions	All	10	0.660	0.677	2.005	0.933
	Low	6	0.864	0.852	3.485	1.306
pH (standard units)	All	8	7.6	7.6	7.3	7.5
	Low	6	7.7	7.8	7.2	7.8
Temperature (°C)	All	10	7.5	7.4	7.4	6.7
	Low	6	13.1	12.9	10.1	11.9
Turbidity (NTU)	All	10	1.2	1.4	2.2	1.6
	Low	6	0.0	0.67	3.0	1.0
Dissolved oxygen	All	10	98	99	89	97
(percent saturation)	Low	6	95	99	81	96
Hardness (Ca+Mg)	All	10	26	27	76	37
	Low	6	32	35	130	52
Total acidity ($CaCO_3$)	All	10	2.0	3.5	14	5.0
	Low	6	3.3	6.7	27	6.7
Dissolved calcium	All	10	7.1	7.2	17	9.3
	Low	6	8.8	9.0	29	13
Dissolved magnesium	All	10	1.9	2.3	7.6	3.3
	Low	6	2.4	3.0	14	4.7
Dissolved sodium	All	10	3.4	3.0	11	4.4
	Low	6	4.7	3.5	19	5.7
Dissolved potassium	All	10	0.5	0.5	0.8	0.6
	Low	6	0.7	0.6	1	0.7
Alkalinity ($CaCO_3$)	All	10	25	26	85	38
	Low	6	33	35	147	54
Dissolved sulfate	All	10	4.5	4.5	13	5.8
	Low	6	4.7	5.4	26	8.5
Dissolved chloride	All	10	2.5	1.4	1.6	1.7
	Low	6	3.6	1.2	1.8	1.8
Dissolved silica, as	All	6	11	11	16	12
SiO_2	Low	--	--	--	--	--
Total nitrite plus	All	10	0.55	0.49	0.41	0.48
nitrate, as N	Low	6	0.06	0.05	0.01	0.05
Total ammonia, as N	All	10	0.05	0.04	0.10	0.03
	Low	6	0.06	0.03	0.12	0.04
Total iron (micrograms	All	8	350	390	990	460
per liter)	Low	6	240	240	1,630	380
Dissolved manganese	All	6	10	3	140	23
(micrograms per liter)	Low	--	--	--	--	--
Suspended sediment	All	10	5	4	5	5
concentration	Low	6	2	1	3	2

The similarity of water quality between the upper station and the station just above the Skookum mine effluent, the sharp contrast between this latter station and the station just downstream from where the mine effluent enters, and the contrast between the upper and lower stations, are indications that the Skookum mine drainage has a significant impact on the water quality of Wilkeson Creek. Specific conductance profiles made at several cross sections at the lower station and several feet upstream from the lower station during both low (11 ft^3/s) and intermediate flows (108 ft^3/s) in Wilkeson Creek indicate that the mine effluent water and Wilkeson Creek water are completely mixed at this point. Mass balance calculations using the major cations and anions data from samples during two low-flow months indicate that the Skookum drainage accounts for 85 to 90 percent of the change in water quality between the upper and lower stations. The other 10 to 15 percent of the change is attributed to the seepage from mine tailings along Wilkeson Creek and the small mine drainage entering Wilkeson Creek just above the Skookum mine drainage.

There is a general degradation in the water quality of Wilkeson Creek below the entry point of the Skookum mine area drainage, but the water quality improves downstream as Wilkeson Creek recovers and some of the metals precipitate. The upper station is unaffected by mine drainage or seepage from tailings. The station just above the entry point of the Skookum mine drainage reflects slight degradation due to drainage from a small mine and some seepage from a tailings pile between this station and the upper station. The station just below the entry of Skookum drainage has the most significant degradation in water quality of the four stations studied. Although the water at the lower station did not improve to the quality of the upper station or even to that at the station just above the Skookum drainage, it did have significant improvement over water quality at the station just below the Skookum drainage and shows signs of returning to a quality comparable to that at the upper station.

Biological Characteristics

The changes in water quality due to the effects of coal mine drainage on Wilkeson Creek also affect the stream biology (Fuste, 1978). The benthic invertebrate community in Wilkeson Creek was studied in riffles near each of the four stations to assess the impact that the coal mine drainage had on the community. Artificial substrate samplers, consisting of rock-filled wire baskets, were used to collect benthic organisms from August 1976 to March 1977 (Fuste' and others, 1983). Seven orders of aquatic insects and eight orders of other classes and phyla were identified in Wilkeson Creek. The benthic invertebrates identified are an excellent food supply for fish inhabiting Wilkeson Creek. Chinook, coho, pink and some chum salmon utilize this stream (Phinney and Bucknell, 1975). During the period of study, numerous trout and salmon yearlings were observed at all sampling stations.

Seasonal changes in the abundance of invertebrates at the two stations above Skookum mine drainage and the lower station were similar throughout the low-flow period (fig. 6). This similarity was noted between the upper and lower stations throughout the study period. Although abundance of invertebrates at the station just below the Skookum mine drainage followed trends similar to those at the other stations from September through November 1976, the invertebrates were less abundant than at the other stations except in October 1976, when abundance at this station was greater than at the lower station, and in February 1977, when abundance was greater than at any of the other three stations. Abundance shown in figure 6 between November 1976 and January 1977 can only be inferred because samples were not collected during December. The stream temperature at the station just below Skookum drainage is strongly influenced by the mine drainage; however, it could not be determined if differences in water temperature at the station had any effect on the seasonal emergence patterns of benthic organisms. All stations reflected seasonal temperature patterns, although the station just below the mine drainage had more moderate temperature changes throughout the study period than either the upper or lower stations (fig. 7).

The abundance of mayflies, caddisflies, stoneflies, and true flies, particularly the midges and blackflies, generally reflect seasonal trends, but there were some differences among stations (fig. 8). During the earlier part of the study period, in a seasonal trend reversal, caddisflies were usually less abundant at the station just below Skookum mine drainage than at the other three stations. By January the caddisflies at this station began a steady and significant increase in abundance and continued to increase in February and March while the other three stations had normal seasonal increases.

Many species of stoneflies emerge normally during the winter time. As shown in figure 8, stoneflies were most abundant during late summer and fall and least abundant during later winter and early spring. All sites had similar abundance patterns throughout the study period, indicating minimal influences due to mine drainage.

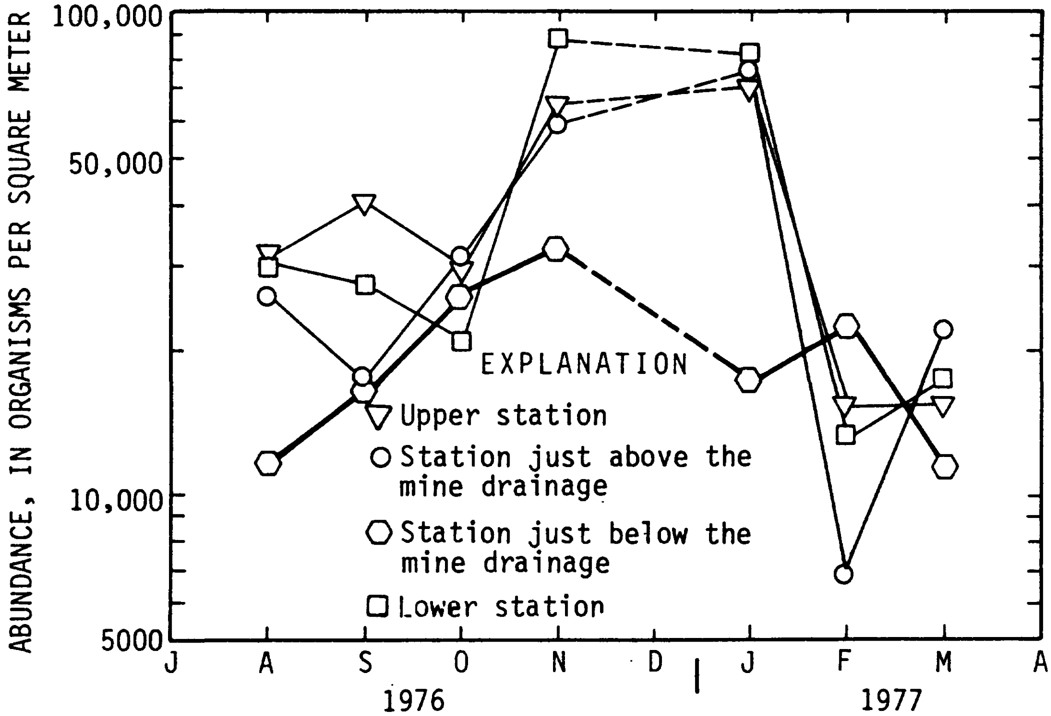


FIGURE 6.--Abundance of benthic organisms, August 1976 to March 1977, Wilkeson Creek, Washington.

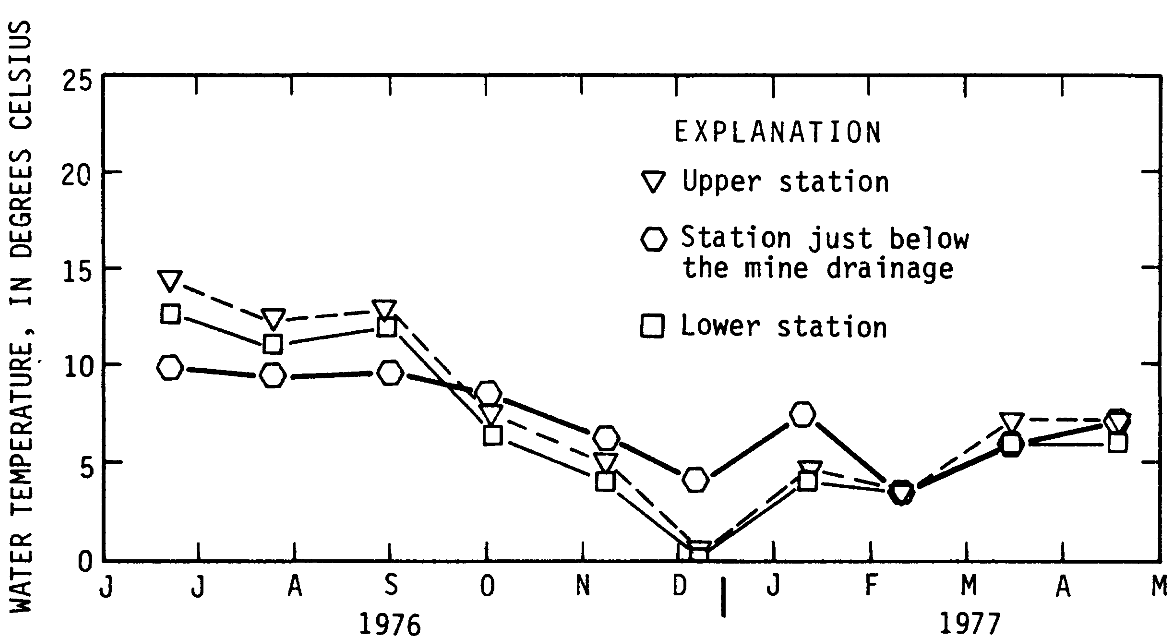


FIGURE 7.--Instantaneous water temperatures, June 1976 to May 1977, Wilkeson Creek, Washington.

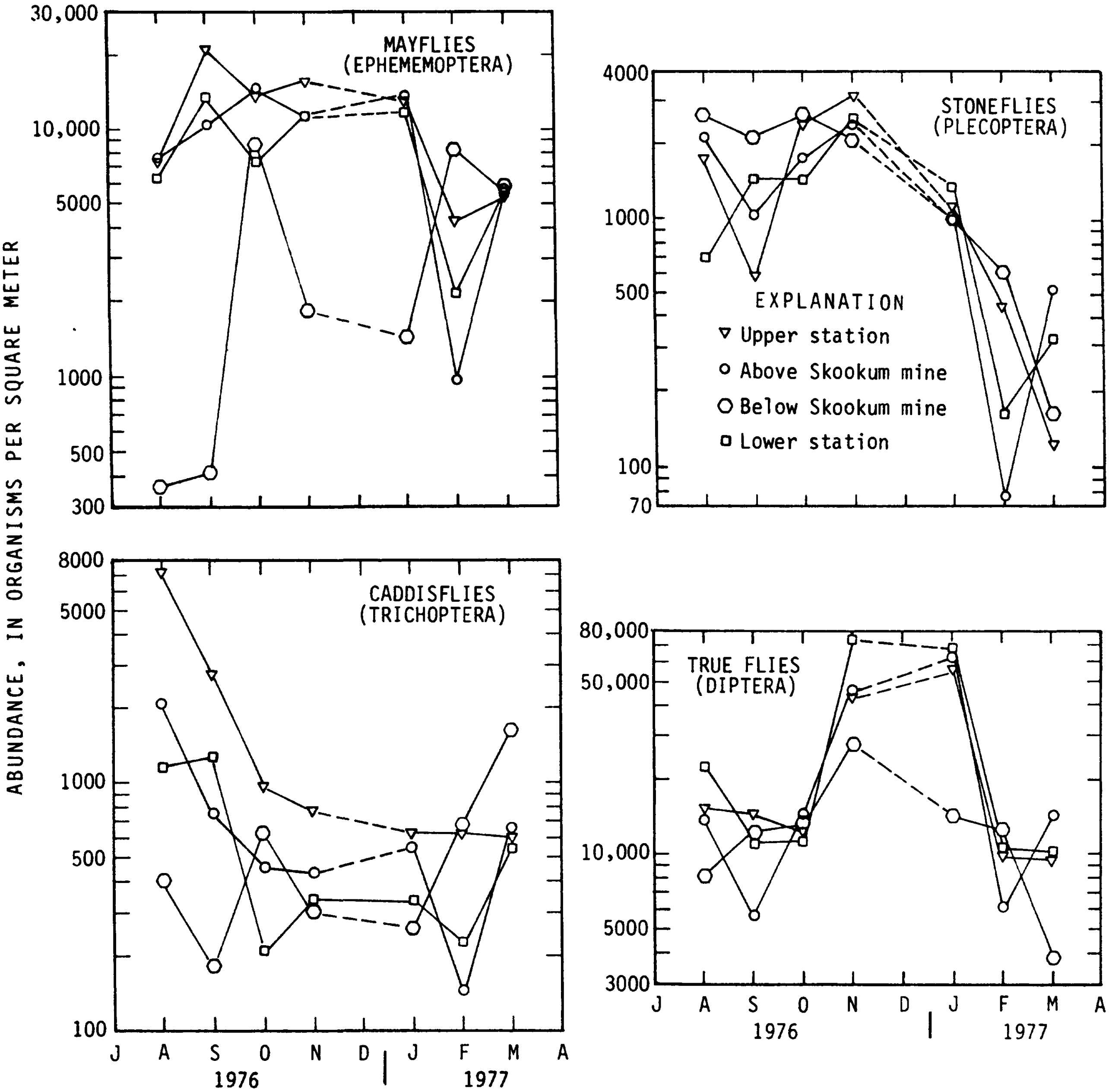


FIGURE 8.--Seasonal variation in abundance of the four major orders of aquatic insects, August 1976 to March 1977, in Wilkeson Creek, Washington.

True flies, mostly midges and blackflies, appeared to have a period of early fall emergence between September and October and an early winter emergence between January and March. All stations showed a similar response except the sampling station below the mine effluent point of entry, where the population of true flies was smaller.

Species diversity has been used in mine drainage studies to evaluate changes in aquatic communities caused by mine drainage (Koryak and others, 1972; Dills and Rogers, 1974), and the type of diversity index used for a particular circumstance has been related to sample size (Pielou, 1966). Samples were collected during this study with wire baskets filled with rocks. The sample sizes were small enough for all benthic invertebrates to be identified and counted. Pielou (1966) defined such fully censused communities as "collection" and regarded such samples as being populations themselves rather than samples of something larger. Stations that fit the "collections" criteria were compared by using the Brillouin diversity index, expressed in logarithmic units to a base 10 and referred to as DITS (Kaesler and Herricks, 1976). The Brillouin diversity index is calculated using the formula:

$$H = \frac{1}{N} \log \frac{N!}{N_1!\ N_2!\ N_3! \ldots N_i!} \qquad (1)$$

where H = the Brillouin diversity index,
N = total number of individuals,
N_i = the number of individuals in the i^{th} species, and
i = total number of species.

A measure of the relative evenness (Zand, 1976) was used to evaluate the uniformity of distribution of organisms among taxa and is calculated using the formula:

$$e = \frac{H - H_{min}}{H_{max} - H_{min}} \qquad (2)$$

where

$$H_{max} = \frac{1}{N} \log \frac{N!}{(m!)^s\ (m+1!)^r}$$

$$H_{min} = \frac{1}{N} \log \frac{N!}{[N-(s-1)]!}$$

and where m and r are the quotient and remainder, respectively, of N/s; that is, N = s [n/s] + r and r < s; H = the Brillouin diversity.

Similar patterns of diversity and relative evenness were found at the upper station, the station just above the Skookum mine discharge, and the lower station throughout the sampling period (fig. 9). At the station just below the mine drainage, diversity and relative evenness were more variable and usually lower than at the other stations, particularly during the low-flow months, but were similar to the other stations during high flow when dilution of the mine drainage by Wilkeson Creek was greater. No significant differences were found between the upper and lower stations, suggesting that any differences in species diversity that may occur as a result of the mine drainage is no longer evident at the lower station.

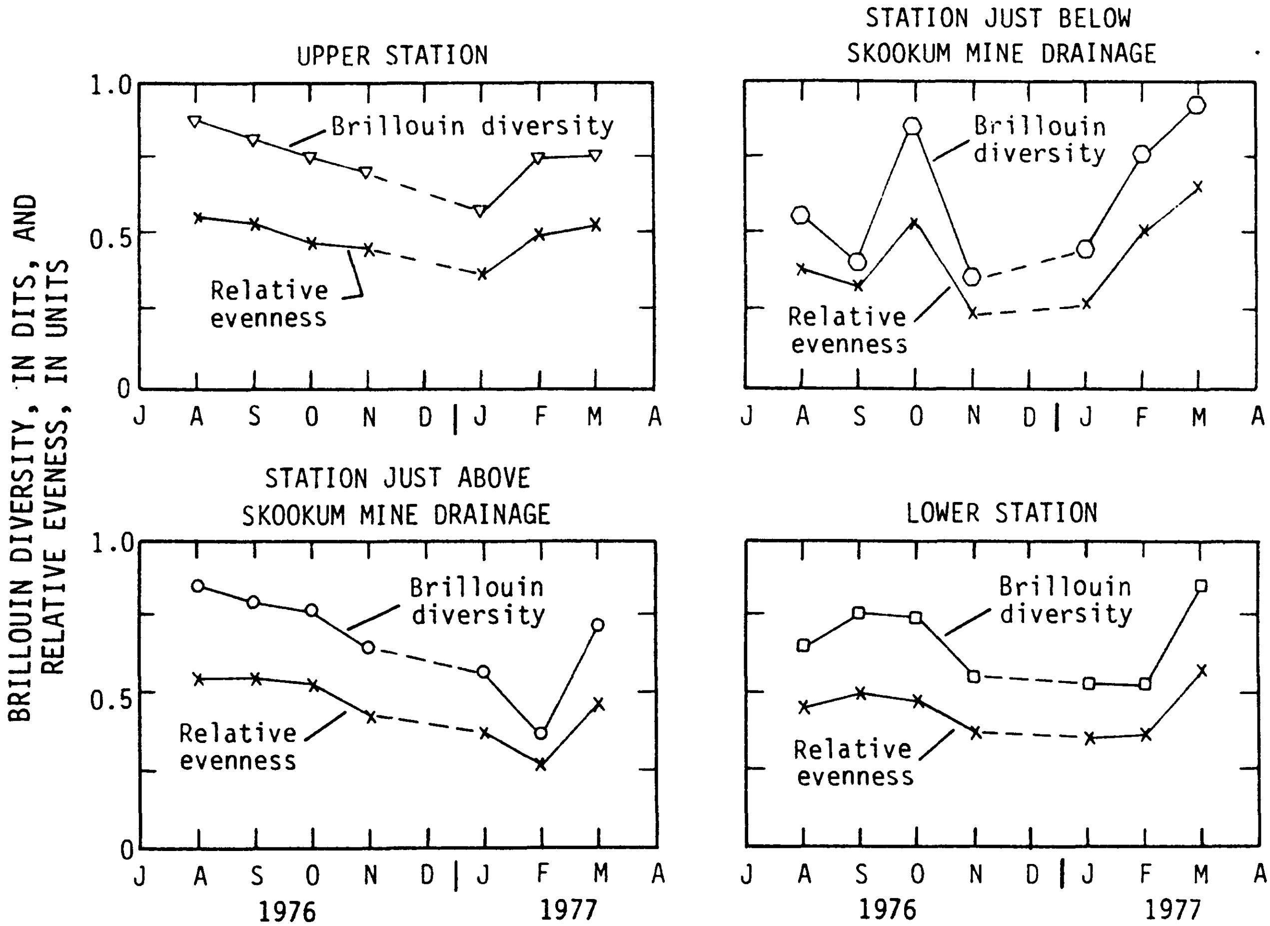


FIGURE 9.--Monthly diversities and relative evenness, August 1976 to March 1977, Wilkeson Creek, Washington.

Burlington similarity coefficients (Wilhm, 1972) were used to compare similarities between stations. These coefficients are calculated using the formula:

$$B = \frac{2(P_1)}{P_i + P_j} \tag{3}$$

where the prominence value (P) is obtained by multiplying the density of a group at a station by the square root of the frequency of the group at the two stations i and j being compared. Then P_i is the sum of the prominence values for all families at station i and P_j is the sum at station j. P_1 is the sum of the lower of the two prominence values that the two stations have in common for each group. Based on the 7 months of data, the similarity coefficients, in percent, indicate that the station just above the mine drainage, the upper station, and the lower station, were similar (between 64 and 71 percent). In contrast, the station just below the mine drainage, with similarity coefficient between 44 and 56 percent, was less similar to the lower station and even more disimilar to the two stations above the mine drainage.

BASELINE CONDITIONS IN PROSPECTIVE MINING AREAS

Several coal areas and basins were evaluated in order to select two study areas that would be representative of locations where underground coal-mining activity is expected to occur. The following criteria were used to select study areas: (1) underground coal mining is likely to begin within the next several years; (2) adjacent receiving streams are relatively small; (3) plans for the location of water level gangway portals were available; and (4) permission for access could be obtained easily. Two small basins in northwestern Washington, Gallop Creek basin (fig. 10), and Loretta Creek basin (fig. 11), were selected as baseline study areas. Two stations were selected on each of the two primary streams in the respective basins above and below areas of known coal deposits.

Basin Characteristics

The physiographic characteristics of the two baseline areas are summarized in table 7. In the lower reaches of Gallop and Loretta Creeks, the riffle reaches compare reasonably well with the riffle reaches of the four sampling stations in Wilkeson Creek. The relief and land-use patterns are similar for all three basins. The town of Glacier presently is diverting small quantities of water from Gallop Creek into a reservoir for domestic purposes. A brief description of the hydrological characteristics of each sampling station is summarized in table 8. Unlike the Wilkeson Creek stations, large differences in altitude exist between the upper and lower sampling stations on both Gallop and Loretta Creeks.

Climate

Climatological data were collected at different periods for Gallop Creek and for Loretta Creek basins during 1976 and 1977, but there was a 7-month overlap in data collection for the period July to December 1976 (fig. 12). Precipitation near the Gallop Creek basin was about normal during the sampling period (January to December 1976), compared to the average (mean monthly) for the 30-year period of record 1946 to 1976. Near the Loretta Creek basin, precipitation was near normal for only 6 of the 12 months of the sampling period (June 1976 to May 1977), compared to the averages for the 30-year period of record (1947 to 1977). Precipitation was below average September through December 1976, in the Gallop Creek basin and September 1976 through February 1976 in the Loretta Creek basin. Excessive precipitation during several months prior to September 1976 tended to minimize the effects of the subsequent months of deficient precipitation in both basins.

Air temperature in the Gallop Creek area was consistently below normal for all of 1976, but was near normal in the Loretta Creek area from June 1976 through May 1977, even though monthly departures from normal were noted.

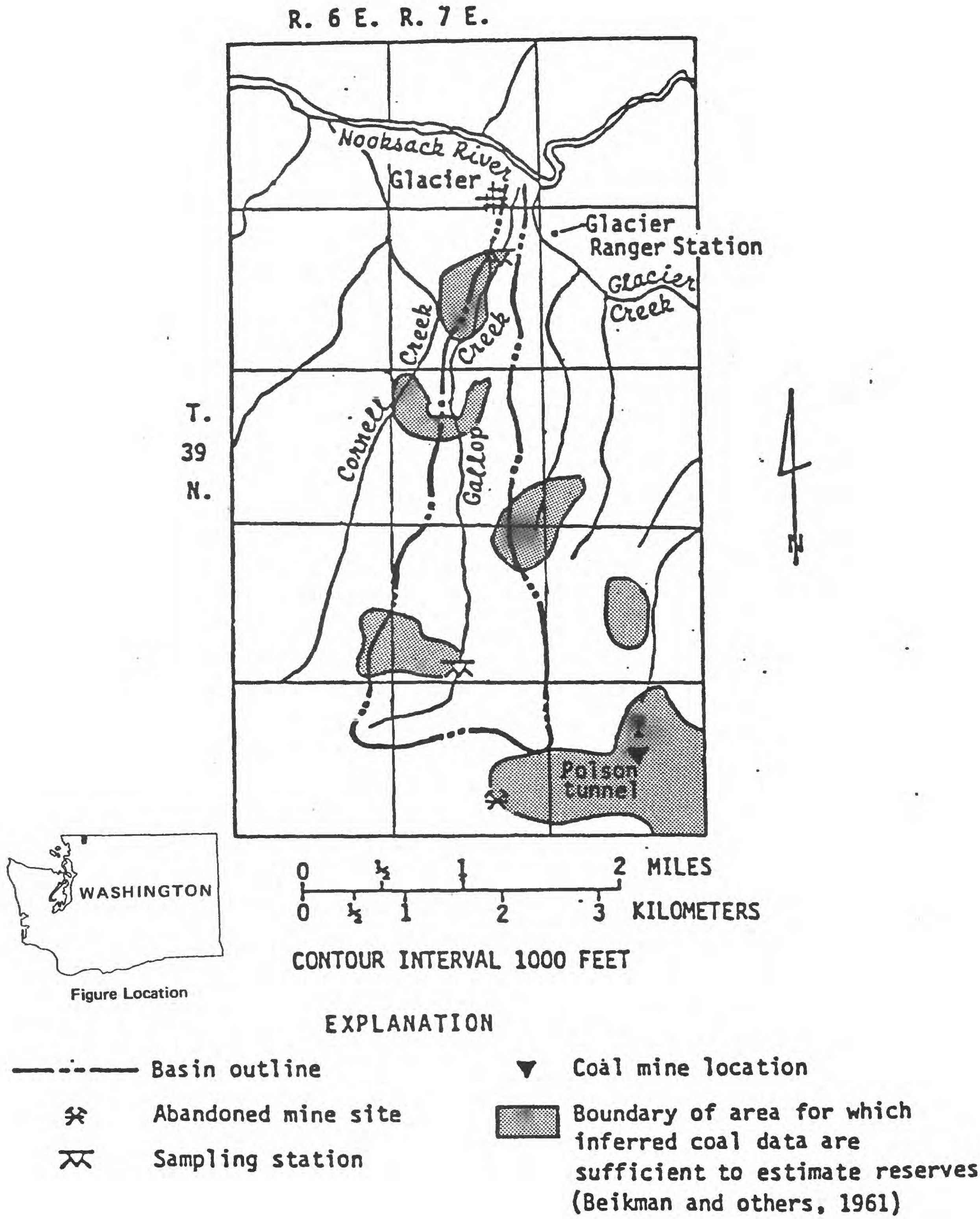


FIGURE 10.--Sampling sites in Gallop Creek basin, Whatcom County, Washington.

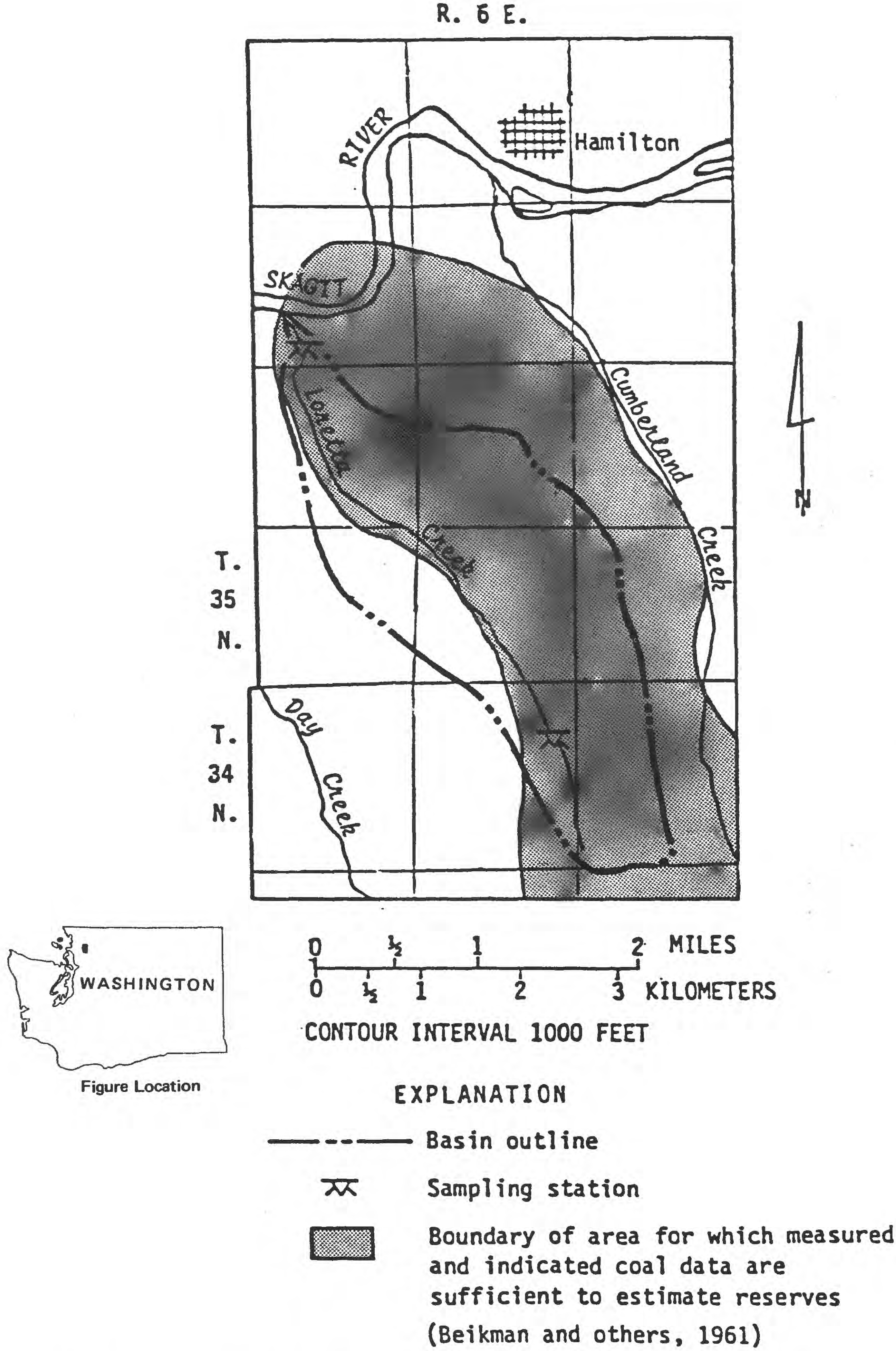


FIGURE 11.--Sampling sites in Loretta Creek basin, Skagit County, Washington.

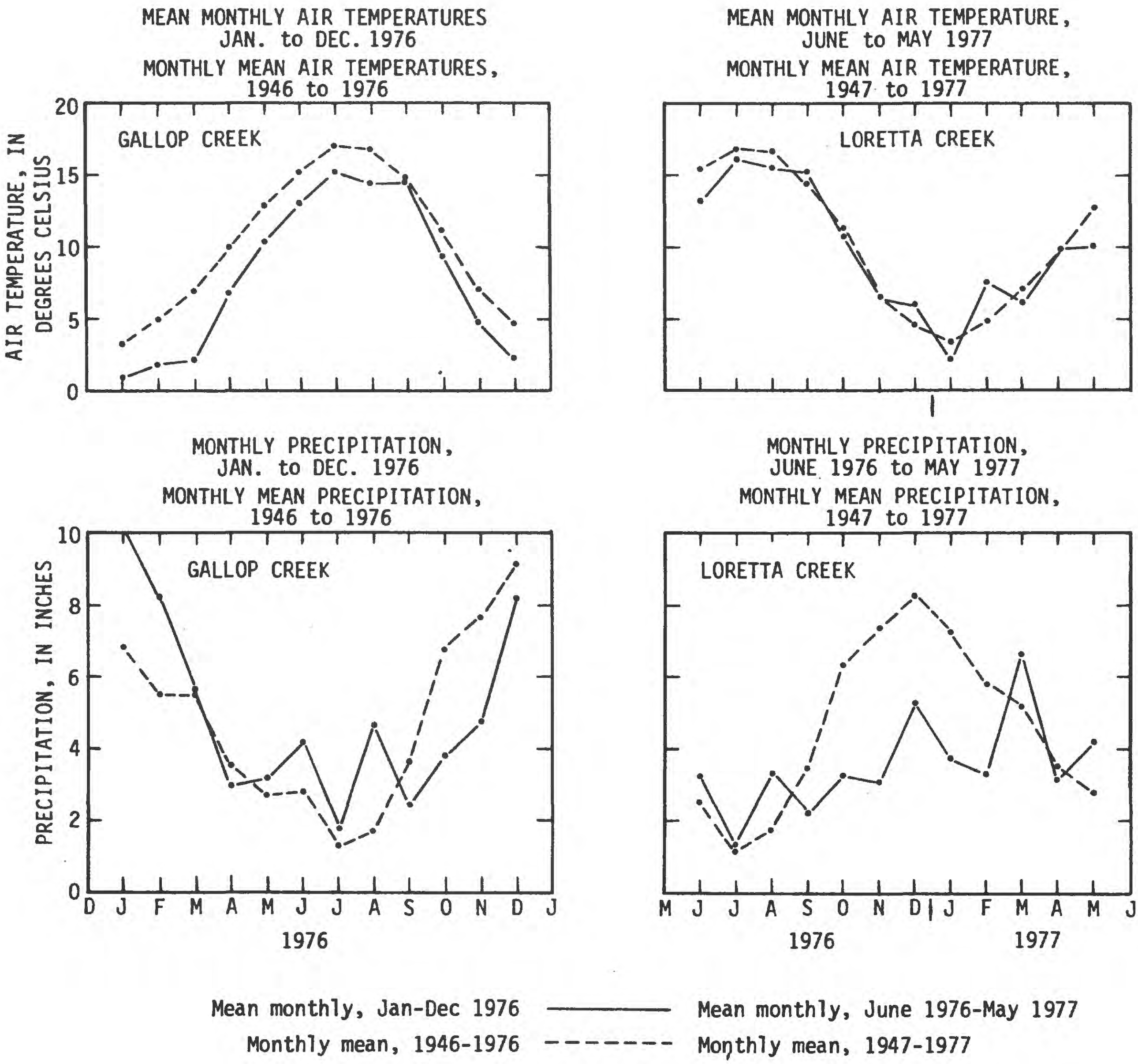


FIGURE 12.--Comparison of monthly mean air temperature and precipitation with the respective long-term records near the Gallop and Loretta Creek basins, Washington.

TABLE 7.--Physiographic characteristics of Gallop and Loretta Creek basins, Washington

Characteristic	Gallop Creek basin	Loretta Creek basin
Location	Whatcom County, T.39N., R.6E. and R.7E	Skagit County, T.34N. and T.35N., R.6E.
Area	2.18 square miles	3.80 square miles
Relief	4176 feet	3680 feet
Average altitude (above sea level)	2910 feet	2530 feet
Orientation	Axis N.7E., facing north	Axis N.32E., facing NNW
Axial slope	0.162 foot per foot	0.136 foot per foot
Average hillslope	0.54 foot per foot	0.39 foot per foot
Land use	Forest, 97 percent; urban, 2 percent; water, 1 percent with salmon spawning in lower 0.8 mile	Forest, 99 percent; water, 1 percent, limited spawning in lower 1.1 mile; mixed deciduous and coniferous growth

TABLE 8.--General hydrologic characteristics of Gallop and Loretta Creek basins, Washington

Characteristic	Station			
	Upper Gallop	Lower Gallop	Upper Loretta	Lower Loretta
Location	SE 1/4 SE 1/4 SW 1/4, sec. 19, T.39N., R.7E., approx. 0.2 mile SSE of sharp 160° turn in logging road.	NE 1/4 SW 1/4 NE 1/4, sec. 7, T.39N., R.7E., approx. 400 feet upstream from concrete bridge.	NW 1/4 SE 1/4 NE 1/4, sec. 2, T.36N., R.6E., approx. 100 feet upstream from bridge on logging road.	SE 1/4 SW 1/4 SW 1/4, sec. 22, T.35N., R.6E., approx. 100 feet upstream from concrete bridge.
Approximate stream slope	0.101 foot per foot	0.078 foot per foot	0.096 foot per foot	0.059 foot per foot
Stream order	2	3	2	4
Stream morphology	Pools separated by small cascades and riffles	Gravel bed with continuous rapids	Pools separated by small cascades and riffles	Gravel bed with moderate development of pools and riffles; some braiding
Average measured depth	0.49 foot	0.76 foot	0.41 foot	0.78 foot
Average measured water velocity	0.71 foot per second	1.44 feet per second	0.52 foot per second	0.79 foot per second
Approximate elevation (above sea level)	3300 feet	1000 feet	2620 feet	100 feet
Contributing drainage area	0.51 square mile	2.09 square miles	0.61 square mile	3.75 square miles

Mining and Geology

The Glacier coal field in the Gallop Creek area was discovered in 1902 (VonHeeder, 1975) and mining started soon thereafter. Over the years many unsuccessful attempts have been made to produce commercially the anthracite and bituminous coal contained within the seven mapped seams. Complex folding and thrusting of the Eocene coal-bearing sediments cause rapid changes in bed thickness, which makes tracing the beds difficult. Volcanic intrusion in the Mount Baker area probably accounts for the anthracitic nature of the coal (Moen, 1969). Sulfur content of the coal averages about 1 percent (VonHeeder, 1975).

Coal was discovered in the late 1800's in the Loretta Creek area. Mining began in 1891 and ceased in 1922 (Beikman and others, 1961; Jenkins, 1924). Several new prospecting tunnels have been driven recently into the seams in the Loretta Creek basin, but no commercial quantities of coal have been produced. Sulfur content of local coal averages about 0.5 percent and some coking-grade coal is present (VonHeeder, 1975). Seven seams of coal that have been found in the Cokedale mine 8 miles northwest of Loretta Creek are thought to extend into the Loretta Creek basin.

Quantity of Surface Water

Information on minimum streamflows in Gallop and Loretta Creeks is required in order to assess the dilution effects that the streams will have on mine effluents. A regression of streamflow measurements for both Gallop and Loretta Creeks was made against discharges from continuously gaged stations on the North Fork Snoqualmie River, South Fork of the Nooksack River, and North Fork Tolt River to determine long-term trends. Estimated low-flow frequencies were used to pick a correlated value for each of the baseline stations. To estimate low-flow frequencies, the regression lines were extended beyond the observed data for the lowest flows measured, and the 7-day mean flow for various recurrence intervals for each of the three gaged stations. A mean for the 7-day average flow at each recurrence interval was calculated from values derived at the three gaged sites. These 7-day average flow mean values are shown in figure 13.

An estimation of the relation at various recurrence intervals between 7-day mean low flows for different drainage subbasin areas within the basins between the upper and lower stations has been derived for both Gallop and Loretta Creeks (fig. 13). These data may be useful for calculating draft-storage relationships (Riggs and Hardison, 1973) if a water supply for coal-mining operations is needed. The relations are based on the assumption that each drainage subarea within the basin yields a consistent discharge per square mile over the basin.

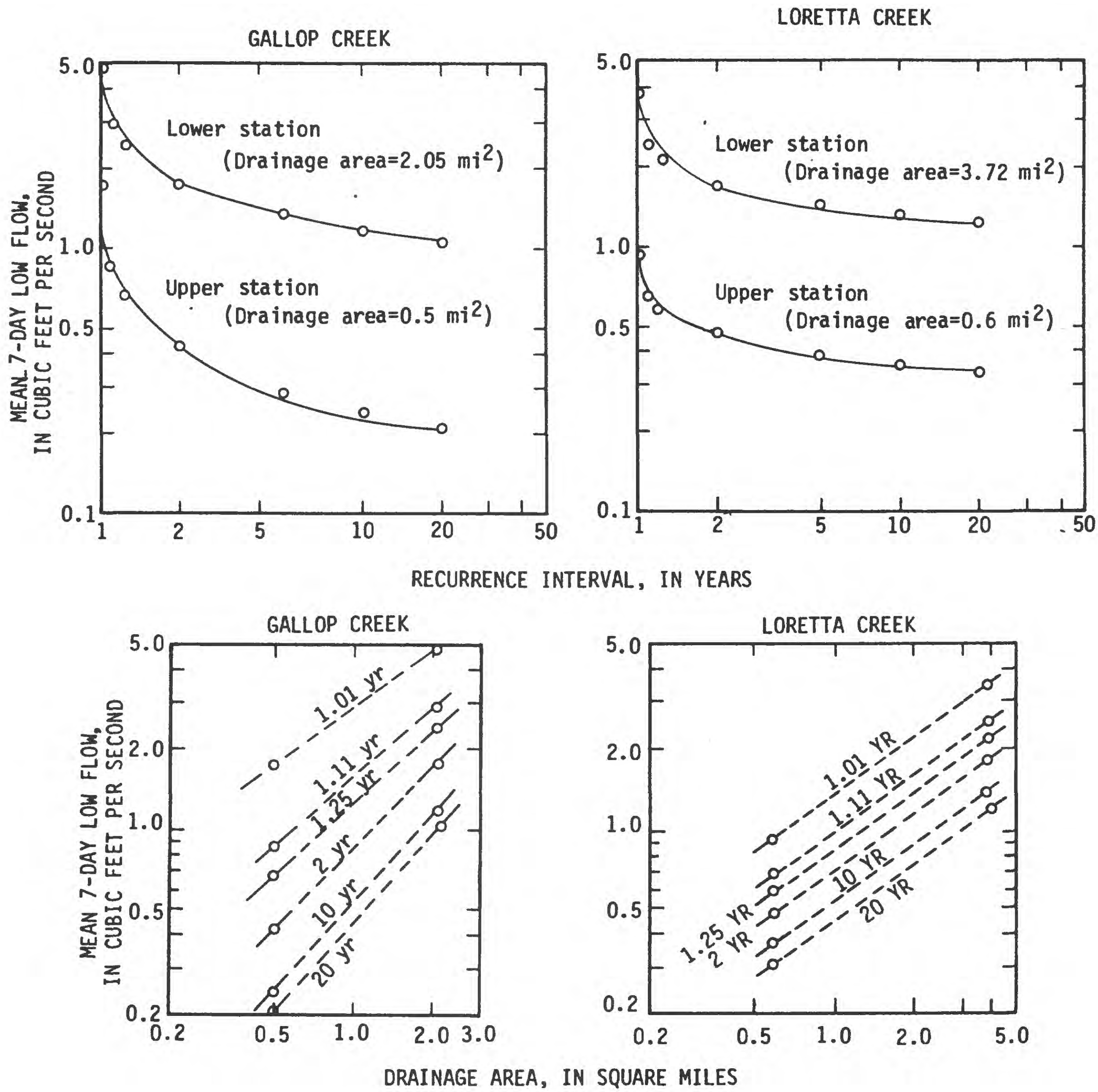


FIGURE 13.--Low-flow frequency curves (top) and relation of 7-day mean flow to different drainage areas in each basin for various recurrence intervals (bottom) for Gallop and Loretta Creek basins, Washington.

Quality of Surface Water

Baseline data for water chemistry, biology, and other water-quality characteristics must be available for streams that will receive drainage from coal areas as a result of mining, if the impact of such drainage on the receiving streams is to be understood and predictions made. Chemical constituents, benthic organisms, and other water-quality characteristics such as alkalinity, acidity, conductivity, dissolved oxygen, pH, temperature, and turbidity were collected in order to document the baseline conditions of the water quality in Gallop and Loretta Creeks. Considerable amounts of silt and clay entered the headwaters of Gallop Creek in November 1976 as a result of logging activities upstream of the upper station in the Rocky Creek basin, which is adjacent to Gallop Creek basin. The Rocky Creek area was logged prior to a short-term coal strip-mining venture.

Water Chemistry

The surface-water quality appears to be similar in Gallop and Loretta Creeks. Both streams have calcium-bicarbonate type water, but Gallop Creek has a slightly higher magnesium content than Loretta Creek. The anionic composition of both streams was comparable throughout the period of study. Changes in water chemistry were mostly a result of fluctuations in stream discharge due to precipitation and snowmelt. Documentation of concentrations determined for the water-chemistry constituents and other selected water-quality characteristics have been tabulated and published previously (Fuste' and others, 1983).

Regression equations were derived from the relation between specific conductance and discharge in Gallop and in Loretta Creeks (figs. 14 and 15). Although additional data would be needed to refine these equations, they could be useful in assessing future changes in water quality in the event that coal mining commences.

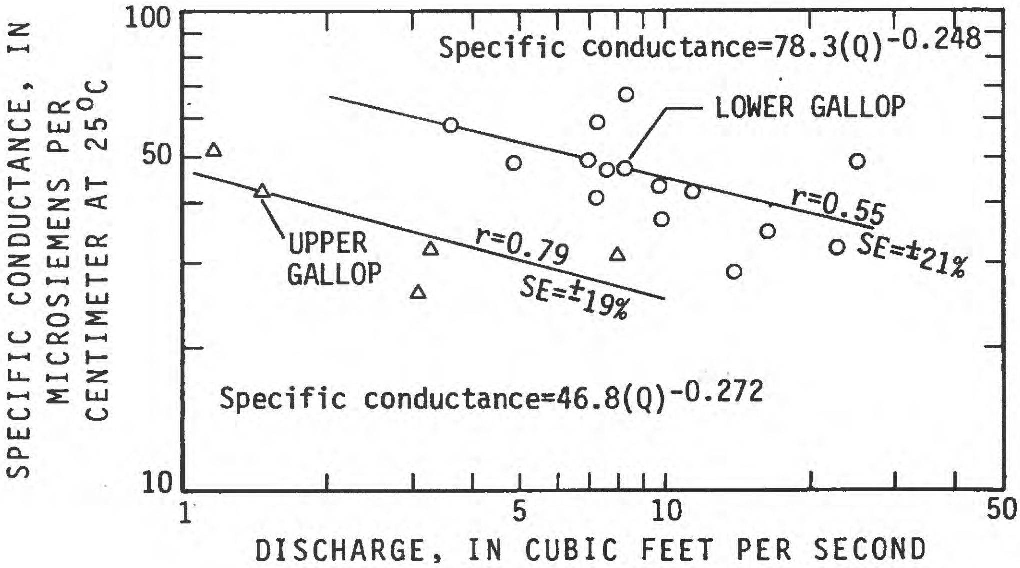


FIGURE 14.--Relation between discharge and specific conductance, January to December 1976, in Gallop Creek, Washington.

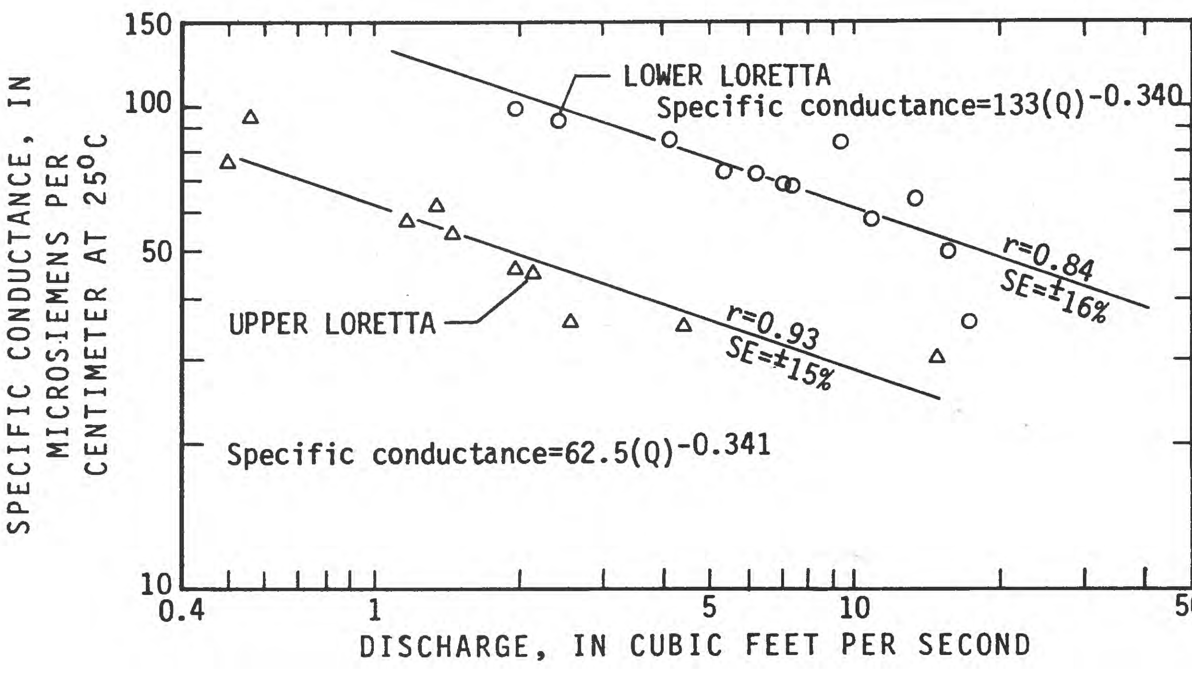


FIGURE 15.--Relation between discharge and specific conductance, June 1976 to May 1977, in Loretta Creek, Washington.

Biology

Data collected and collated for biological conditions in Gallop and Loretta Creeks include benthic invertebrates and fish. For purposes of establishing basin identities, making comparisons, and drawing contrasts, the biological baseline conditions for Gallop and Loretta Creeks are discussed separately.

Gallop Creek:

Benthic invertebrates.--Biological data were collected in Gallop Creek from January to December 1976 (Fuste' and others, 1983). Six orders of aquatic insects that include 31 families were identified in Gallop Creek. Eight orders of invertebrates from other classes and phyla also were identified. The estimated abundance of benthic invertebrates in Gallop Creek is shown in figure 16.

A flood in early December 1975, prior to the first sampling, drastically reduced the benthic population in Gallop Creek. During mid-December a field reconnaisance of the Gallop Creek basin revealed that the stream had been heavily scoured and contained few or no benthic inhabitants. During the first 3 months of sampling (January to March 1976), a rapid increase in the total number of organisms was observed at the lower station (fig. 16). Organisms were most abundant in the fall during the low streamflow season (August to December). Two major emergence periods of adult insects occurred in 1976. Mayflies, stoneflies, and caddisflies emerged first in May and June and again in August and September (fig. 17), but blackflies and midges emerged earlier in the spring during April and May and later in the fall during September and October.

Biological diversity was at its lowest in the summer (fig. 18), due mainly to the high number of midge and blackfly larvae present in the stream. The change in relative evenness of the distribution of organisms within the different taxa present closely resembled the diversity changes observed (fig. 18).

Comparison between the upper and lower sampling stations on Gallop Creek using Burlington's similarity coefficient shows very low similarity, ranging from 11 to 29 percent for the year. Similarity was higher between replicate samples (52 to 87 percent) collected at the downstream station during January through April and December, but was low during other months of the year.

The invertebrate fauna in Gallop Creek is typical of a riffle substrate fauna that is subject to significant erosion. The most numerous benthic organisms were the mayflies (*Baetis* sp. and *Cinygmula* sp.), stoneflies (*Taenionema* sp., *Nemoura* sp. and *Capnia* complex sp.), midges (Chironomidae) and blackflies (Simuliidae). Data collected between September and December 1976 should be interpreted with caution because logging and road building activities at the head of the basin caused significant fluctuations in the sediment carried by the stream.

Fish.--Spawning and juvenile count data for Gallop Creek, obtained from Washington State Department of Fisheries (Skagit Laboratory, Burlington, Washington), indicate that the stream is primarily a pink salmon spawning stream with some chum and coho salmon. Pink-salmon-run data collected by the Department of Fisheries for 14 years (1961 to 1975), reveal that the maximum numbers of fish occurred during the month of September, when the benthic invertebrates were most abundant.

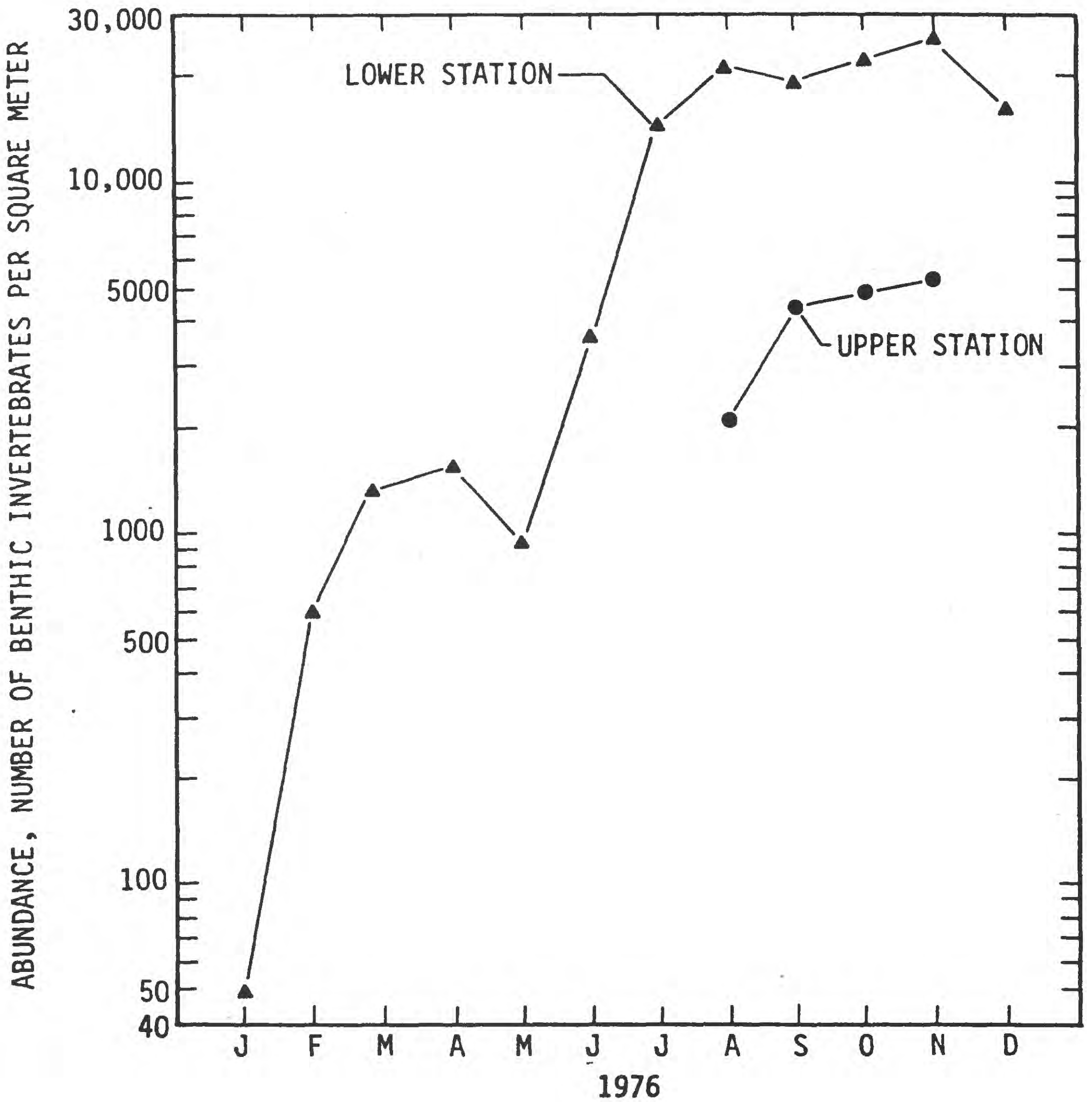


FIGURE 16.--Estimated abundance of benthic invertebrates, January to December 1976, in Gallop Creek, Washington.

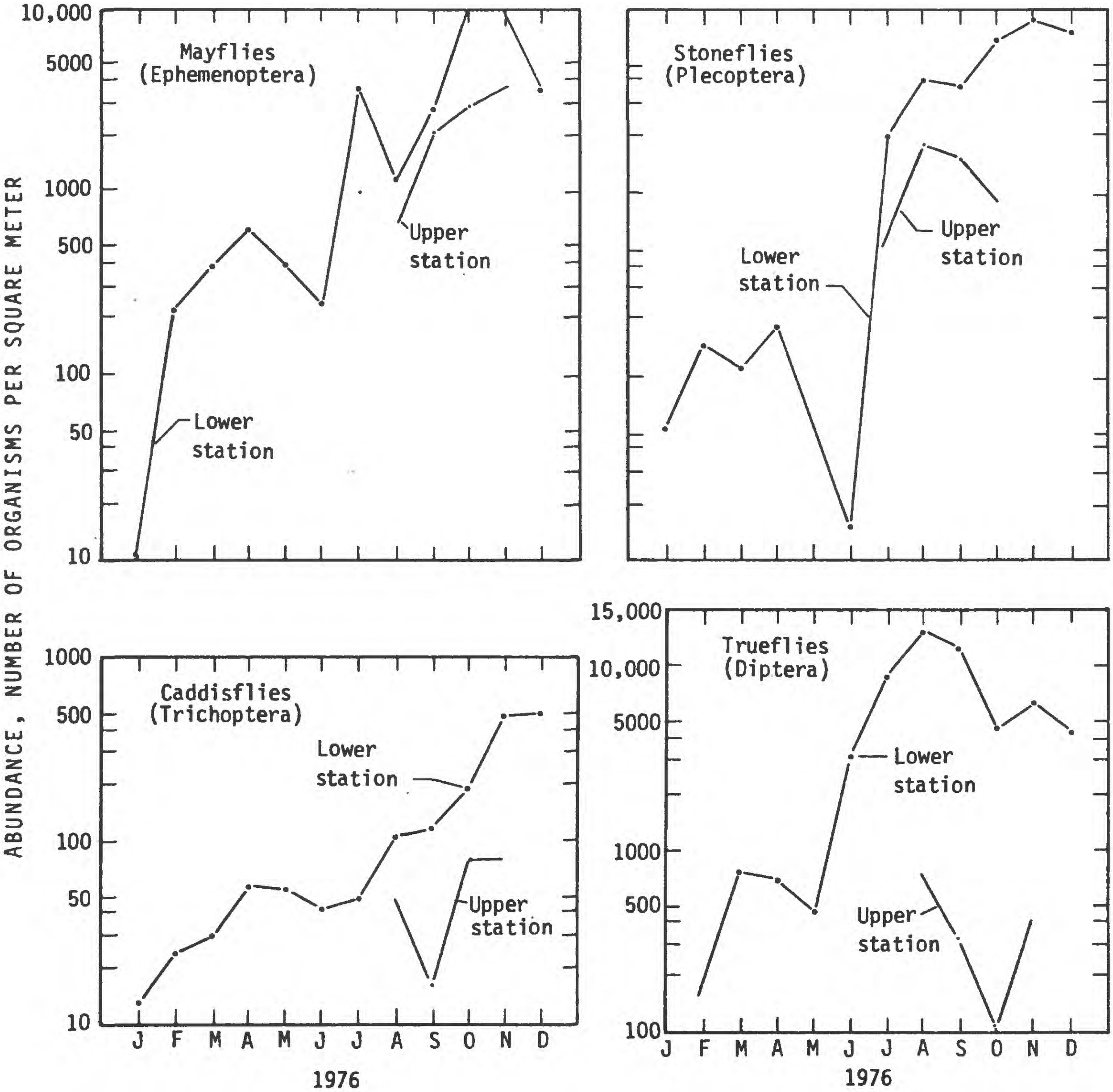


FIGURE 17.--Seasonal variation of the four major orders of aquatic insects, January to December 1976, in Gallop Creek, Washington.

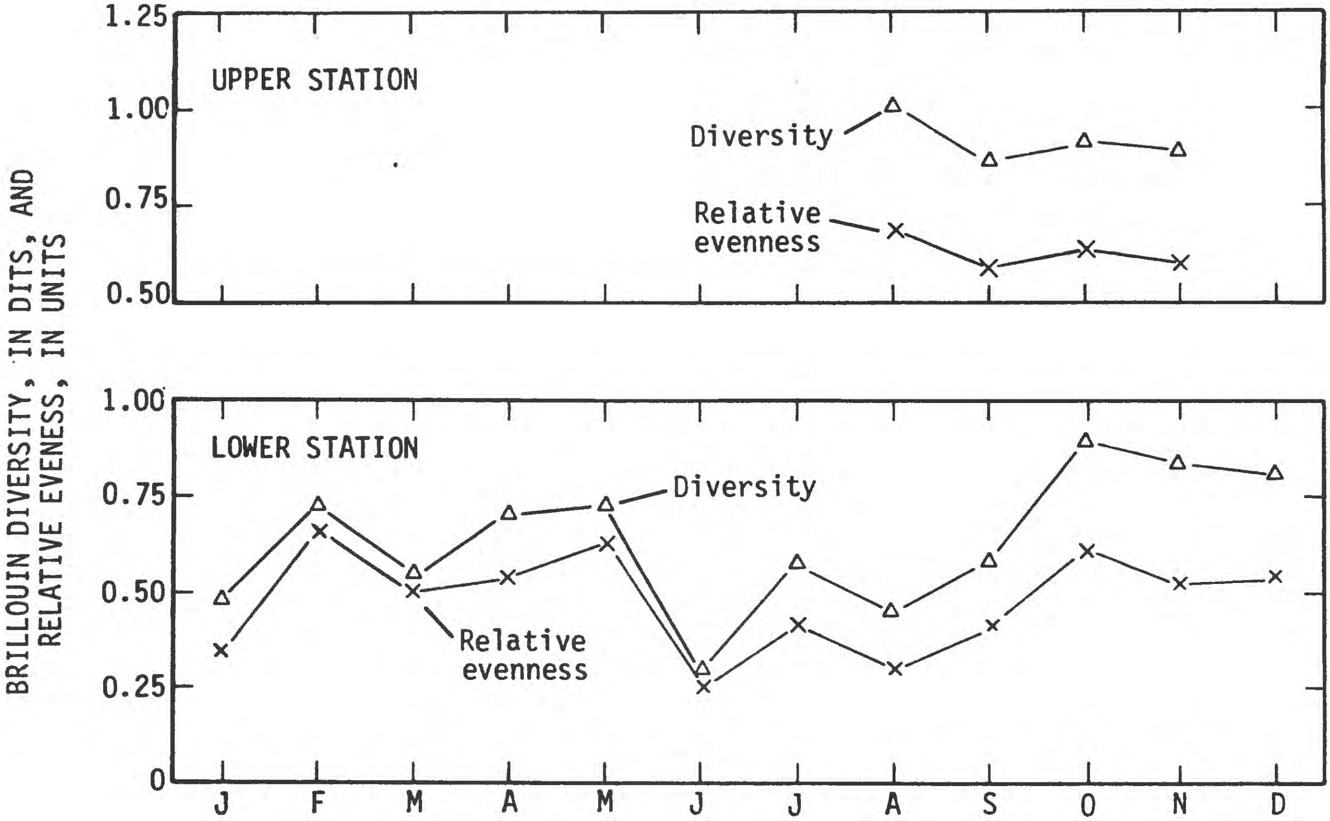


FIGURE 18.--Monthly diversities and relative evenness, January to December 1976, in Gallop Creek, Washington.

Loretta Creek:

Benthic invertebrates.--Biological data were collected in Loretta Creek from June 1976 to April 1977 (Fuste' and others, 1983). Six orders of aquatic insects that included 30 families were identified in Loretta Creek. Seven orders of invertebrates from other classes and phyla also were identified. The estimated abundance of benthic invertebrates in Loretta Creek is shown in figure 19.

The period of sampling for Loretta Creek does not correspond to that of Gallop Creek, but there is a 7-month overlap (June to December 1976) during which the patterns of seasonal abundance are similar (see figs. 16 and 19). Maximum abundance of benthic organisms probably occurred between October and December 1976. There appears to be a major period of insect emergence in November at the upstream station (fig. 20). The presence of large numbers of adult winged forms of blackflies and midges (true flies) at the lower station indicate that Loretta Creek is fairly similar to Gallop Creek. The upper and lower stations of Loretta Creek were similar, even though the benthic invertebrates were more abundant at the lower station.

Biological diversity was at its lowest in July at the lower station and in October and February at the upstream station (fig. 21). These low diversities coincide with periods of insect emergence. Changes in relative evenness closely follow the same patterns as diversity. During the first months of 1977, diversity and evenness increased as a result of a rapid decrease in number of true flies (Diptera) at the lower station. The mayfly population at the lower station did not change significantly during this period.

Comparison between the upper and lower sampling stations on Loretta Creek using Burlington's similarity coefficient indicates low similarity (5 to 55 percent). Comparison between replicate samples available upstream shows fairly high similarity (48 to 83 percent).

The type, number and emergence trends of invertebrate fauna in Loretta Creek are comparable to the Gallop Creek fauna. Mayflies (*Baetis* sp. and *Iron* sp.), stoneflies (*Taenionema* sp. and *Capnia* complex sps.), midge larvae (Chironomidae), and blackflies (Simuliidae) were the most abundant invertebrates.

Fish.--Based on a report by the Washington State Department of Fisheries (Phinney and Bucknell, 1975) Loretta Creek has a limited coho spawning and rearing area in the lower 1.1 miles of the stream.

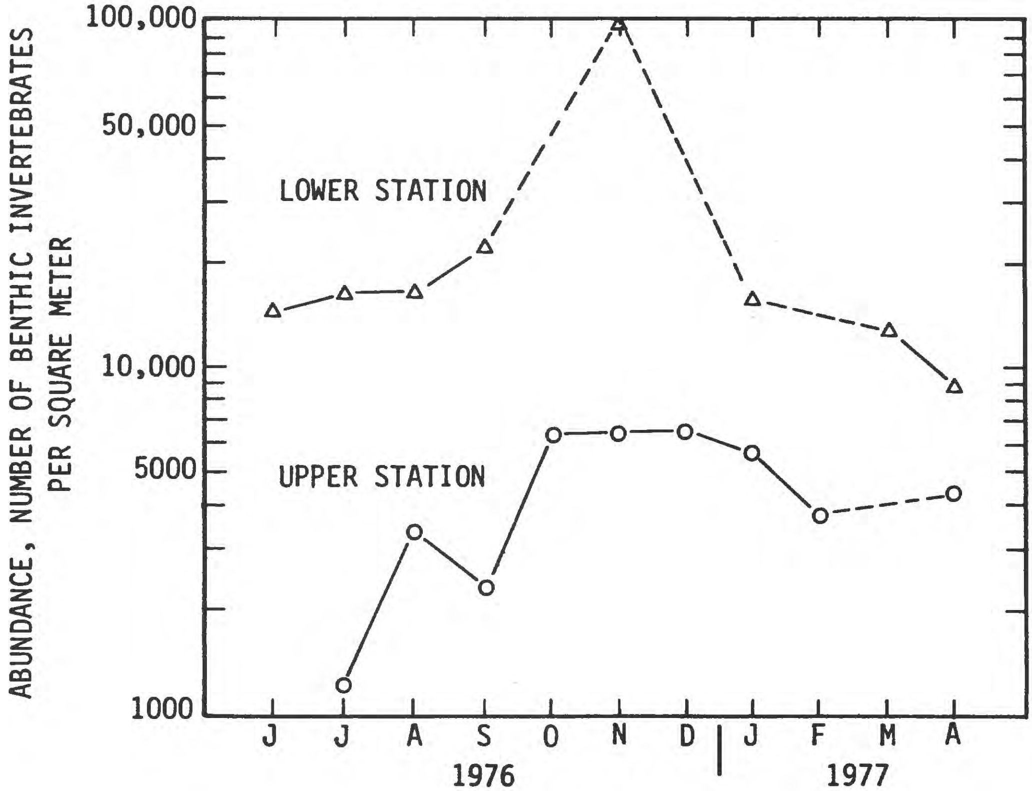


FIGURE 19.--Estimated abundance of benthic invertebrates, June 1976 to April 1977, in Loretta Creek, Washington.

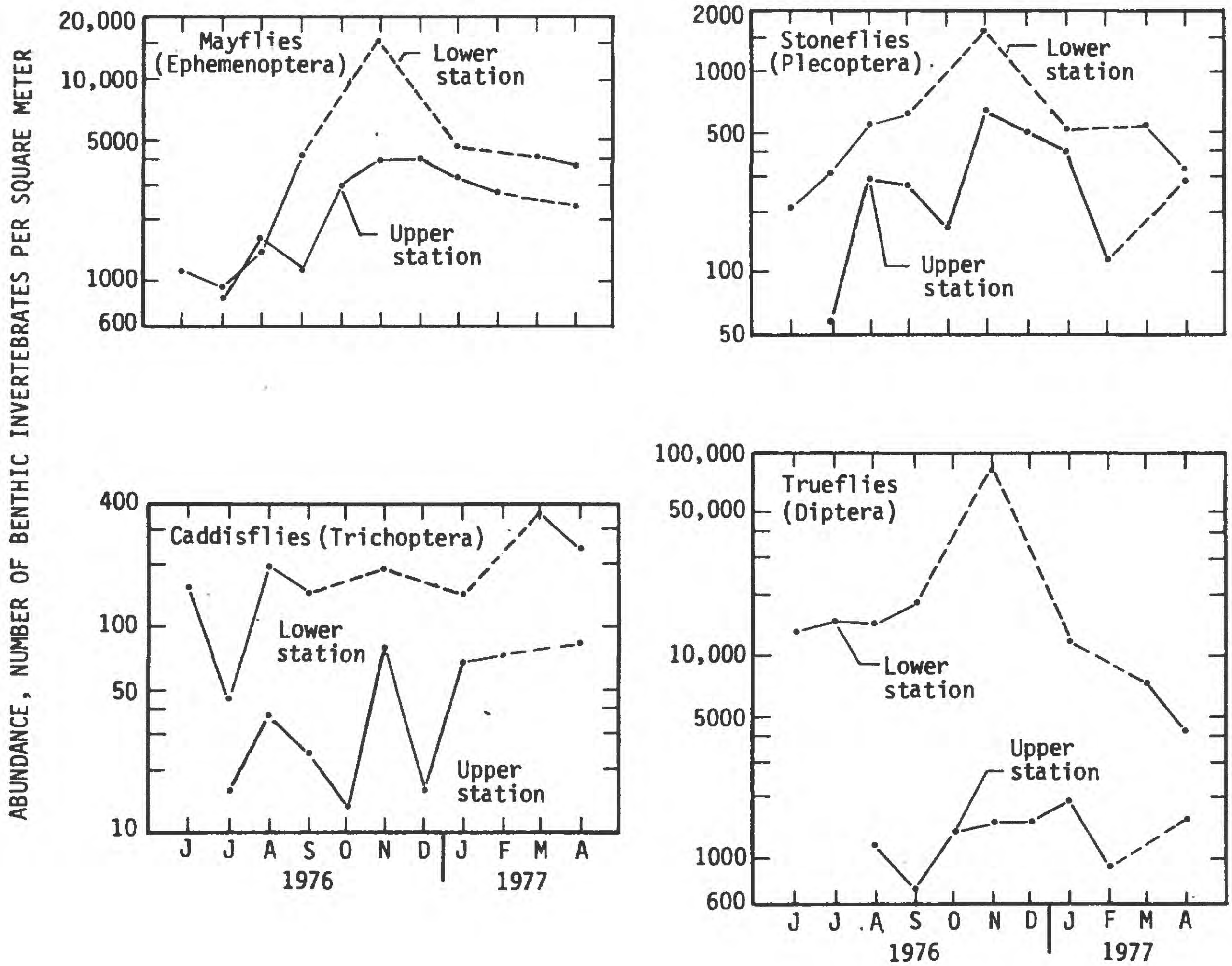


FIGURE 20.--Seasonal variation of the four major orders of aquatic insects, June 1976 to April 1977, in Loretta Creek, Washington.

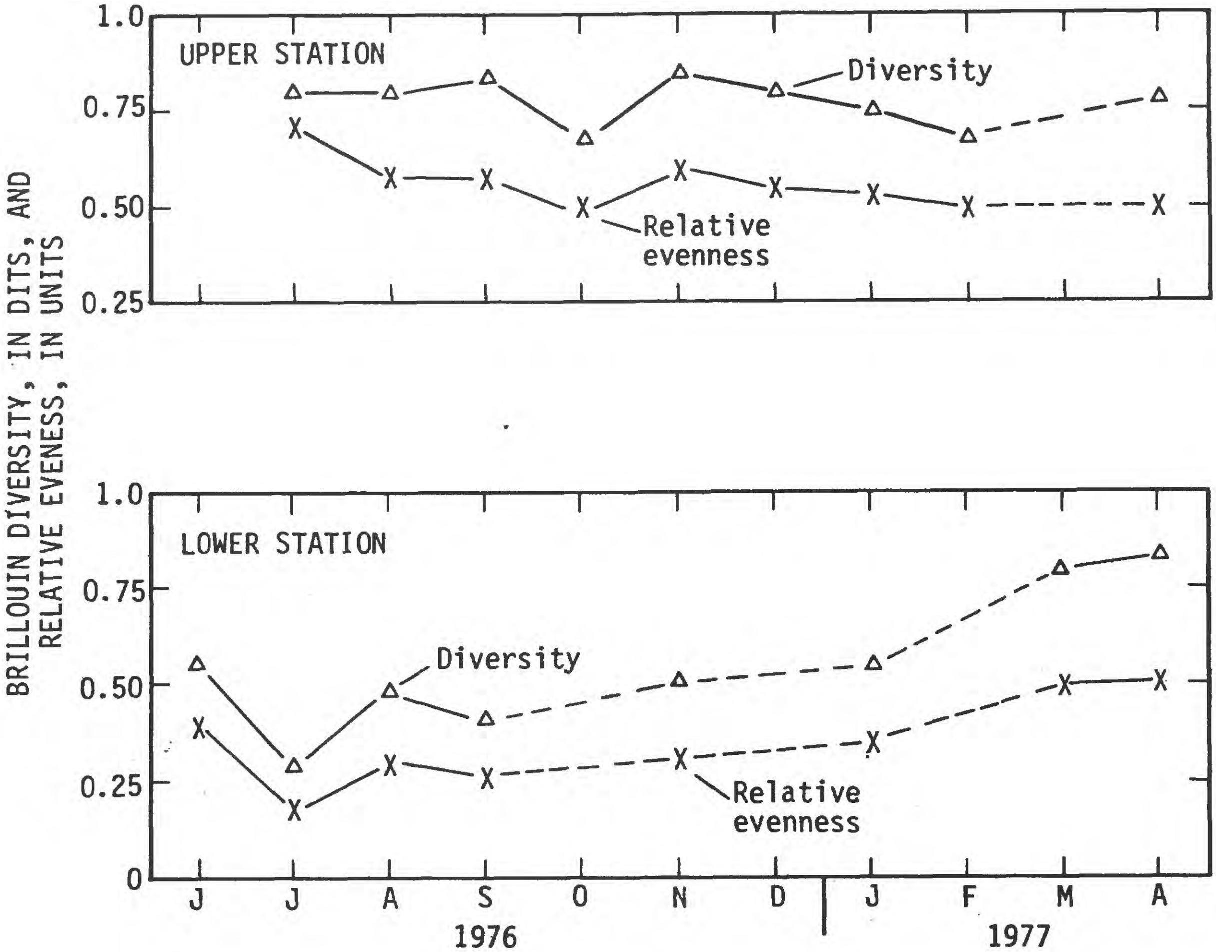


FIGURE 21.--Monthly diversities and relative evenness, June 1976 to April 1977, in Loretta Creek, Washington.

Comparison of Gallop and Loretta Creeks with Wilkeson Creek

The sampling stations on Gallop Creek in the Skagit County coal area, Loretta Creek in the Whatcom County coal area, and Wilkeson Creek in the Wilkeson-Carbondale coal area of Pierce County are alike. They contain graveled riffle reaches with comparable flow depths, velocities, and runoff characteristics (Moss and Haushild, 1978). All three basins have similar orientation, relief, and land-use patterns. The most important dissimilarities between the areas are that the Gallop and Loretta Creeks are lower order streams than Wilkeson Creek, and the upper stations on Gallop and Loretta Creeks lie at higher altitudes than the upper Wilkeson Creek station; consequently, a greater proportion of the precipitation at the upper Gallop and Loretta Creek stations is in the form of snow.

Several water-quality constituents and characteristics at both the upper and lower stations on both Gallop and Loretta Creeks were comparable to the upper station on Wilkeson Creek, where the streams are unaltered by mine drainage (table 9). Water quality at these sampling stations is characterized by low specific conductance, nutrients, and alkalinity, and neutral to slightly basic pH. Because canopy cover was fairly similar, temperature differences were mainly due to elevation. Water in Gallop and Loretta Creeks, like Wilkeson Creek, is calcium-bicarbonate type with similar anionic composition (fig. 22). Gallop and Loretta Creeks have higher calcium and less sodium than Wilkeson Creek.

Seasonal variation in abundance of benthic organisms is comparable in the three streams. The taxa abundance and diversity patterns are common to all stations. The benthic fauna is characteristically a riffle fauna that is sensitive to erosion; however, altitudinal and climatic differences should be considered when evaluating biological changes resulting from a mining operation.

TABLE 9.--Comparison of mean values of water-quality characteristics of samples collected during 1976 and 1977 for Gallop, Loretta, and Wilkeson Creeks, Washington

	Sampling stations				
	Wilkeson Creek	Gallop Creek		Loretta Creek	
Characteristics	Upper station	Upper	Lower	Upper	Lower
Specific conductance (microsiemens per centimeter at 25 °C)	59	33	49	53	70
pH (units)	7.6	7.0	7.3	7.4	7.6
Temperature (°C)	7.5	5.6	5.8	4.8	7.5
Alkalinity (milligrams per liter as $CaCO_3$)	25	17	23	26	32
Total nitrite plus nitrate (milligrams per liter as N)	0.55	0.21	0.20	0.07	0.24
Total ammonia (milligrams per liter as N)	0.05	0.08	0.04	0.03	0.02
Total orthophosphate (milligrams per liter as P)	0.01	0.04	0.01	0.01	0.00

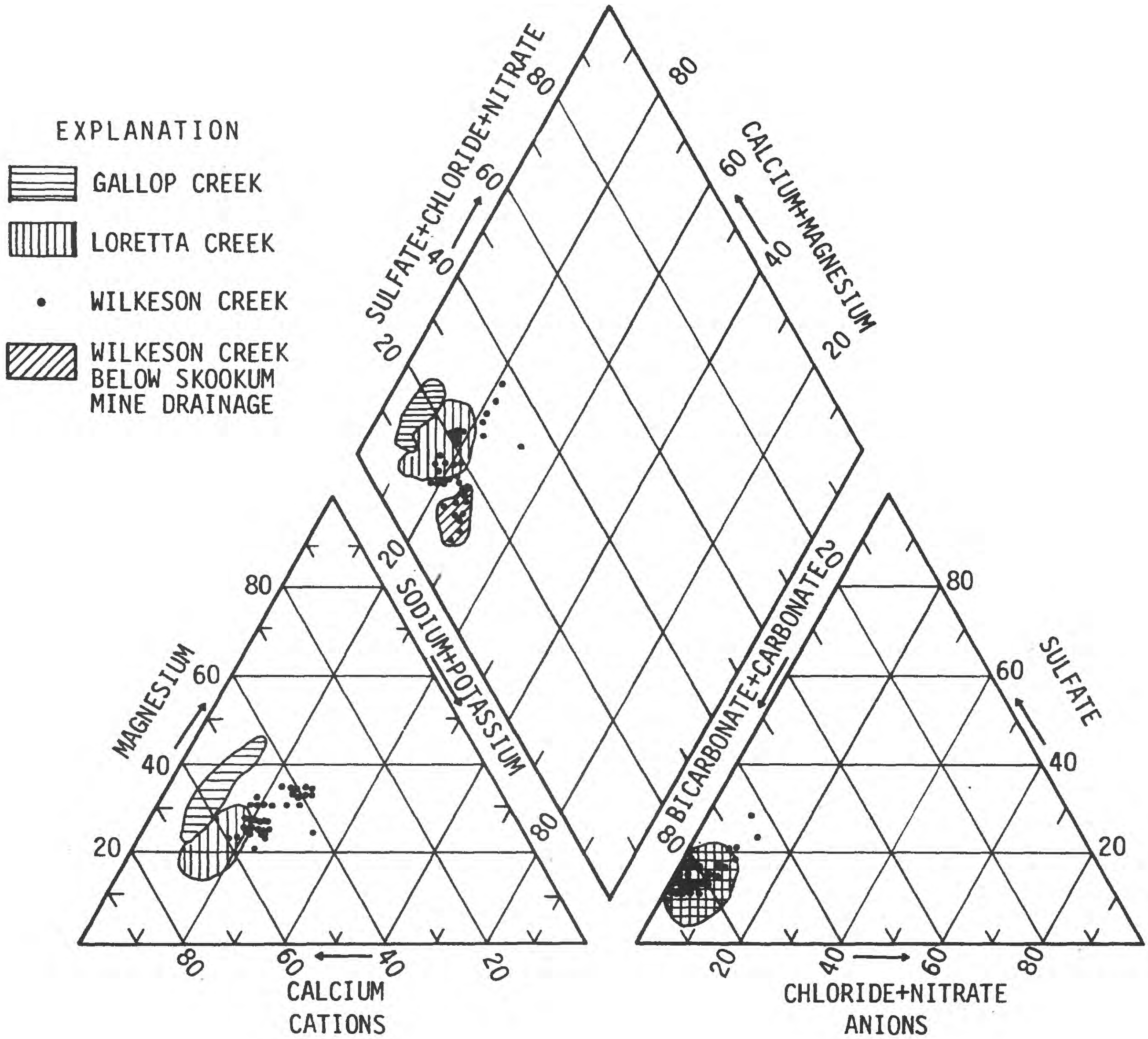


FIGURE 22.--Percentage composition of major cations and anions in Gallop, Loretta, and Wilkeson Creeks, Washington.

Acid-Producing Potential of Coal Deposits

The acid-producing potential of the coal deposits present in both baseline areas was determined by soxhlet extraction of fresh, unoxidized coal samples. These samples were obtained from the Gallop Creek coal seam No. 1 at the Polson Mine in the Whatcom County coal area, and from an unnamed coal seam in the Cumberland Mine in the Skagit County coal area near Loretta Creek. A coal sample was collected and processed from the Tono No. 1 seam of the Black Prince Mine, located in the Centralia-Chehalis coal area, for comparison as an area where mine drainage was more likely to produce water with pH lower than would be produced by either the Gallop Creek or Cumberland mine coals. This soxhlet extraction procedure speeds up oxidation of a sample so that natural weathering that normally requires years can be simulated in a matter of days or weeks (Emrich, 1973).

The coal samples collected from the three coal areas were crushed and sieved to obtain particles of 2 millimeters and less diameter. A 500-gram subsample of each crushed coal sample was packed in glass wool and placed in an aerated soxhlet extractor. Two liters of deionized water were vaporized and passed slowly through a condenser. The cooled condensate was passed over the coal sample until the extractor filled with water, and then siphoned back into the heated water flask. This cycle was repeated several times. After extraction, the water was removed from the flasks and analyzed for hot acidity, alkalinity, pH, sulfate, and iron. The flask was cleaned, 2 liters of deionized water added to the flask, and the process was repeated seven more times for the Gallop Creek and Cumberland mine coals and six times for the Tono No. 1 coal to obtain eight, eight, and seven extracts respectively.

Results of the analyses indicate that coals in the Gallop Creek area (fig. 23) produced lower alkalinity, sulfate, dissolved solids, and iron than coals in the Cumberland Creek area (fig. 24). No acidity was produced in the coal extract from either the Gallop or Cumberland Creek basin, even in the eighth extract that represented 50 cycles of water through the coal. The extracts were alkaline, with pH values greater than 8.5 for the Gallop Creek area and greater than 9.0 for the Cumberland Creek area. In contrast, similar extraction data from the Tono No. 1 coal (fig. 25) show less alkalinity and dissolved solids, and more total iron than coals from either the Gallop or Cumberland Creeks coal areas. The Tono No. 1 coal extract also contained acidity; pH values ranged from acid (5.6) to near alkaline (6.5), but did not produce net acidity (acidity minus alkalinity expressed in milligrams per liter as $CaCO_3$) because acidity produced is neutralized by the alkalinity produced. The decrease in alkalinity and lower pH in the Tono No. 1 coal extract is due to the carbonate and bicarbonate ions (components of alkalinity) combining with free hydrogen ions formed during the ionization process. This can be seen in the simple hydrolosis reaction (Hem, 1970):

$$CO_3^- + 2H^+ \quad HCO_3^- + H^+ \quad H_2CO_3$$

As more acid (H^+) is added, the pH becomes lower and alkalinity decreases.

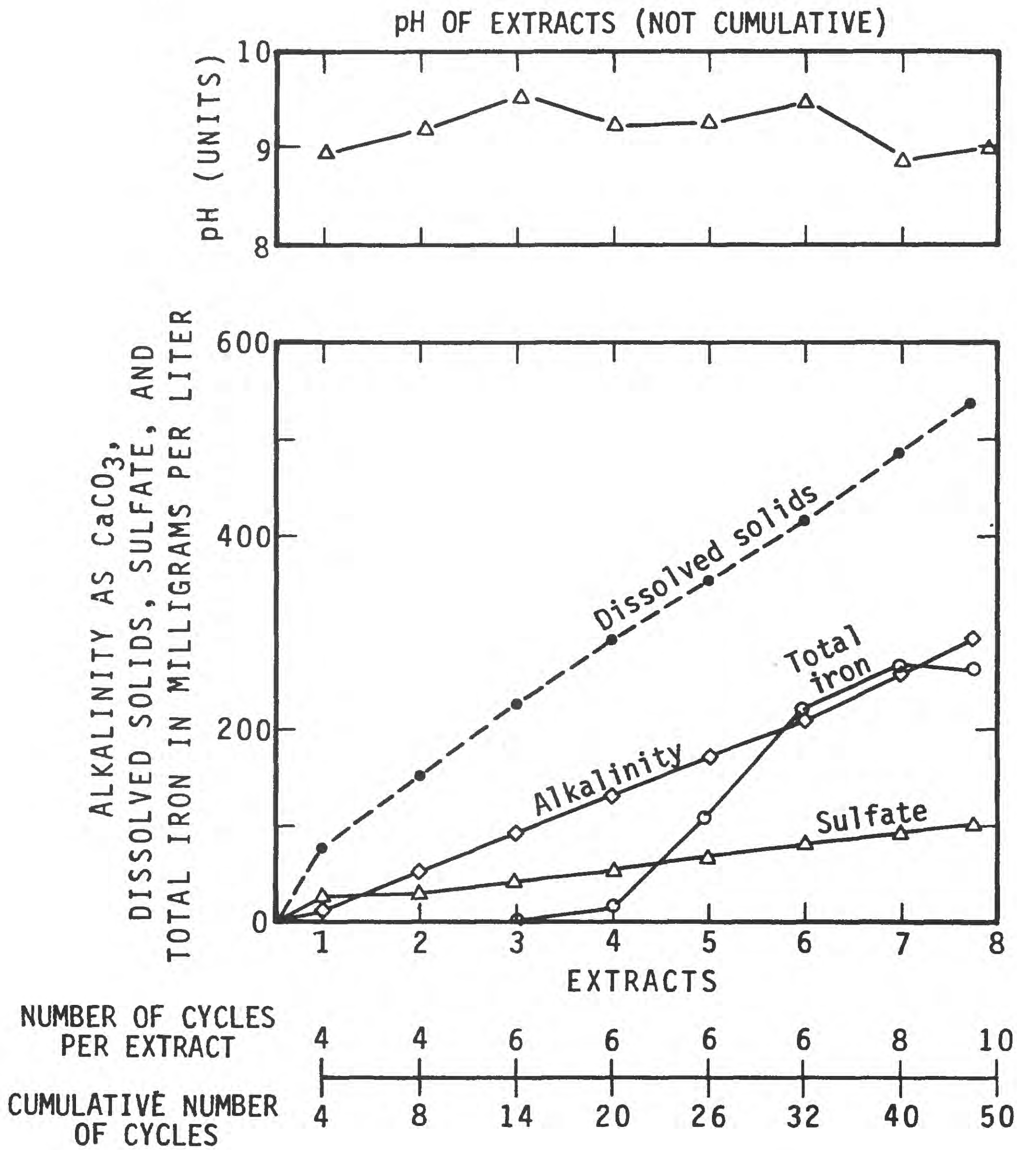


FIGURE 23.--Cumulative concentrations of alkalinity, dissolved sulfate, dissolved solids, and total iron from the soxhlet extraction analysis of Gallop Creek coal seam No. 1 near Glacier, Washington.

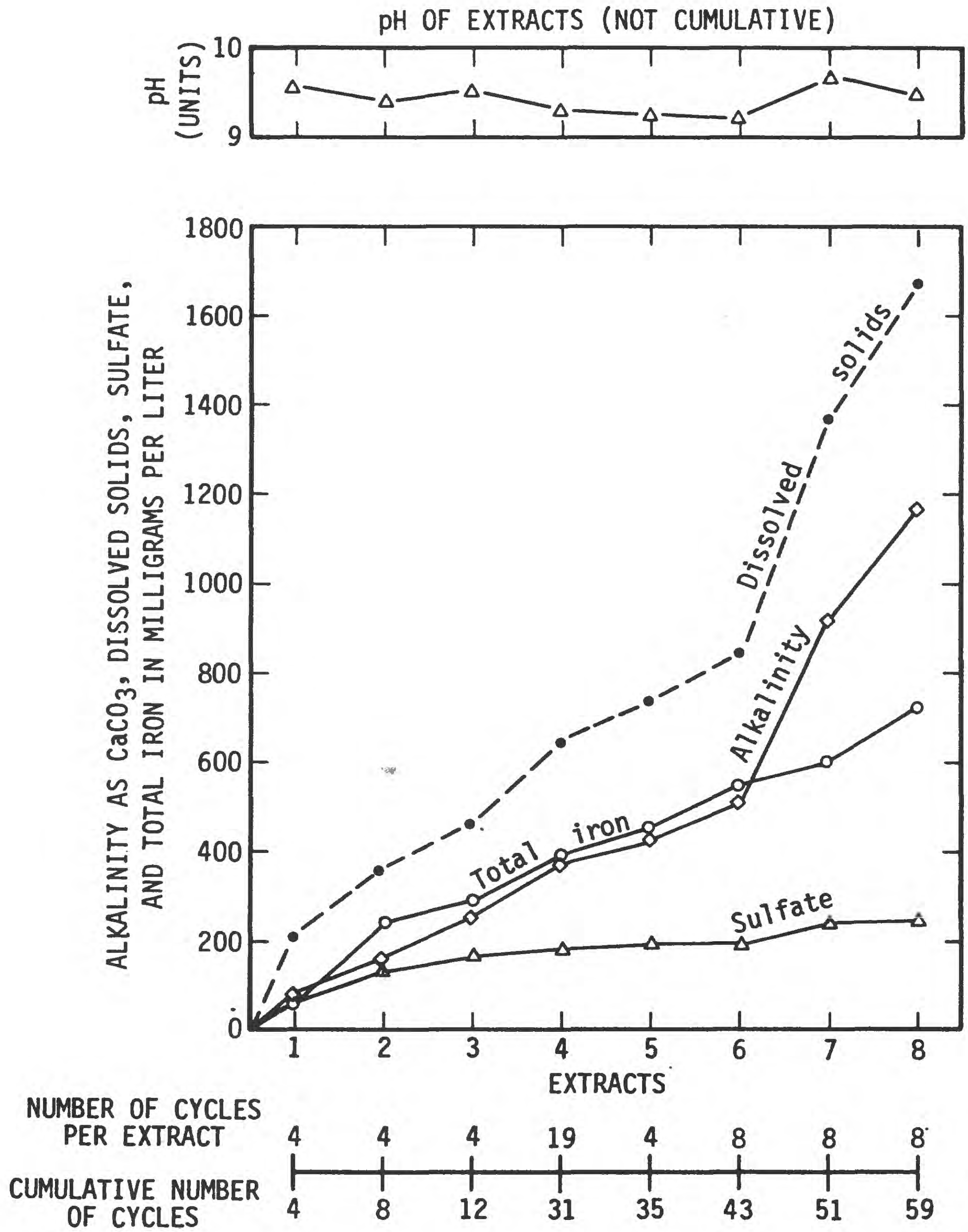


FIGURE 24.--Cumulative concentrations of alkalinity, dissolved sulfate, dissolved solids, and total iron from the soxhlet extraction analysis of the unnamed coal seam in the Cumberland Creek coal area near near Hamilton, Washington.

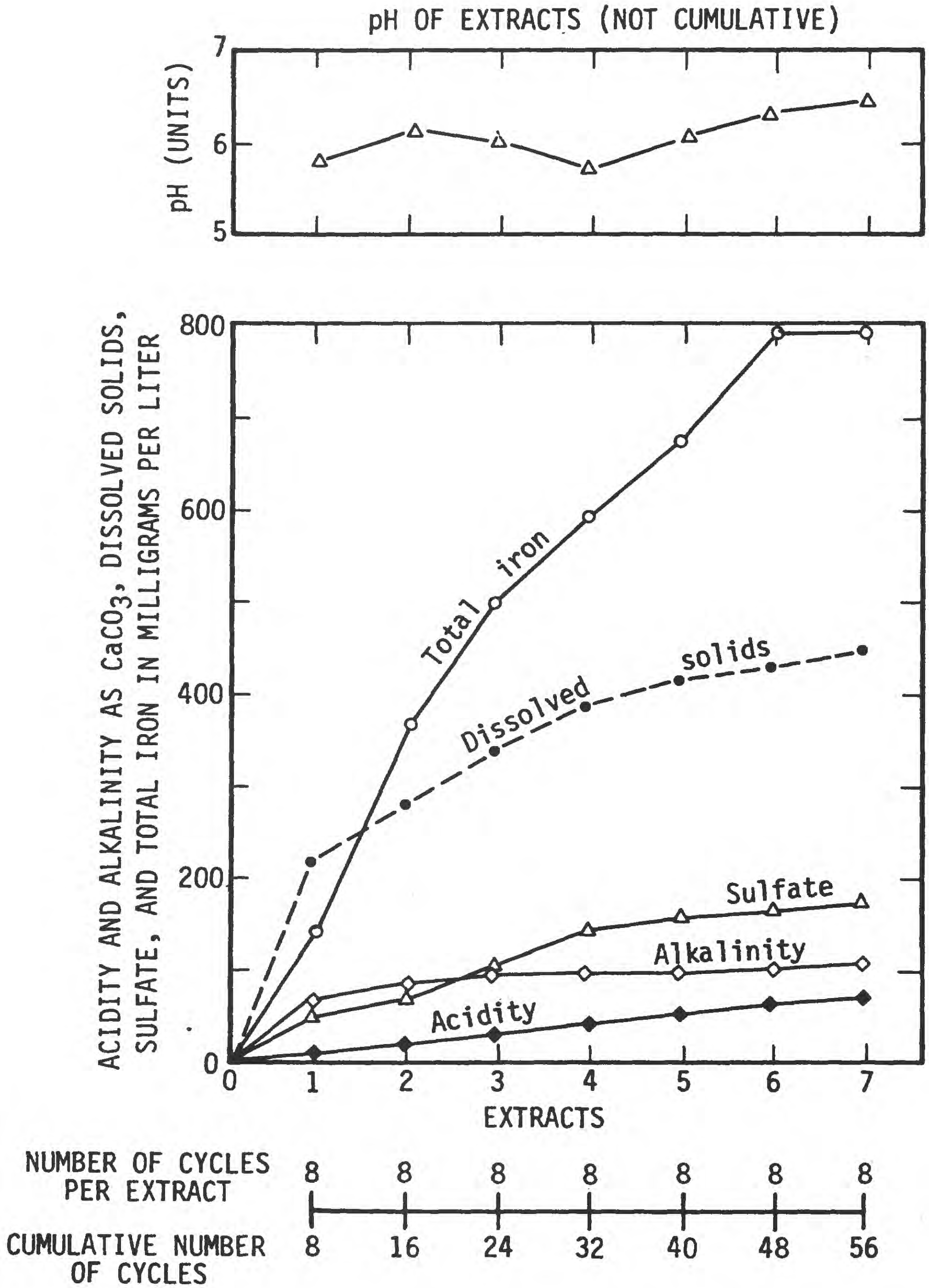


FIGURE 25.--Cumulative concentrations of acidity, alkalinity, dissolved sulfate, dissolved solids, and total iron from the soxhlet extraction analysis of Tono No.1 coal seam at Black Prince mine, Washington.

The soxhlet extraction data for the three coal seams that represented 50 cumulative extraction cycles were compared with the data from the actual mine effluents that drain the corresponding coal seams (table 10). Analyses of the soxhlet extraction do not reproduce totally the naturally occurring conditions characteristic of the mine. For example, there was no net acidity in the Tono No. 1 coal even after 50 cumulative extraction cycles, but net acidity has been reported for actual discharge from this coal seam in the Black Prince mine. However, the analyses do provide an approximation of the quality expected from mine water drainage and a relative comparison of water quality between the sets of coal tested. Tono coal seam No. 1, from the Black Prince Mine in the Centralia-Chehalis coal area, had the greatest net acidity and lowest pH than any of the three areas. The unnamed coal seams, from the Cumberland Mine in the Skagit Coal area, had the least net acidity and the highest pH. The coal from the Black Prince Mine had the highest concentrations of total iron and contained the most sulfate, expressed as a percentage of dissolved solids, of the three coals examined.

The soxhlet extraction technique, when used as a tool for making specific predictions, is limited. Accurate determination of the quality of future mine drainage water will be dependent upon adequate knowledge of the ground-water geochemistry, mode and distribution of particle size of pyrite, occurrence and abundance of calcareous minerals, presence of iron bacteria, and the manner in which all of these are allowed to interact by the nature of the land disturbance (Caruccio and others, 1981).

The soxhlet and mine drainage data suggest that the Cumberland Mine will contribute less acidity to Cumberland Creek than the Polson Mine will to Gallop Creek, and that both will contribute less acidity and higher pH and alkalinity to their respective receiving streams than the Black Prince Mine will contribute to its receiving stream (Hanaford Creek). The water-quality changes in Gallop and Loretta Creeks, if they become receiving streams for nearby coal-mining operations, will be a function of the ground-water and surface-water chemistry and the discharge ratio between the streamflow and mine drainage.

TABLE 10.--Comparison of soxhlet extraction water analyses with actual mine drainage water for corresponding coal seams and mines in Washington

Mine and coal seam	Net acidity (milligrams per liter as $CaCO_3$)	SO_4/DS (pct)	pH (units)	Total iron (milligrams per liter)
Polson Mine drainage water (single analysis)	-19	10	6.7	940
Gallop Creek coal seam No. 1 (after 50 cumulative cycles)	-293	19	8.9	270
Cumberland Creek Mine drainage water (single analysis)	-340	11	8.4	550
Cumberland Mine unnamed coal seam (after 50 cumulative cycles)	-975	18	9.8	620
Black Prince Mine drainage water (single analysis)	+33	62	6.0	8,300
Tono coal seam No. 1 (after 50 cumulative cycles)	-43	39	6.4	800

PROPOSED SURFACE-WATER QUALITY MONITORING FOR AREAS WITH PROSPECTS FOR MINING ACTIVITY

The suggested monitoring priorities described here are designed for the prospective mining areas in the Gallop and Loretta Creek basins. The suggestions are made with specific reference to underground coal-mining activities that might occur within these basins, based on specific conditions that are present. Monitoring of other basins in the State would require baseline information on the climate, geology, physiography, and hydrology of the basins.

Emphasis should be placed on sampling during periods of low flows, generally fall and early winter, when dilution of mine waters is minimal and benthic invertebrates are most abundant. These conditions would best represent the impacts that mine drainage has on receiving streams.

Sampling Locations

Quantity and quality measurements should be made for those streams that receive mine effluent at points upstream from the effects of the mine effluents, immediately below the mine effluent point of entry, and at a point downstream where the mine effluent has become chemically assimilated. The upstream location should be a sufficient distance above the point of effluent entry to insure that water quality is representative of unaltered, natural streamflow. The location immediately below the point of effluent entry should be selected so that the maximum impact of the effluent on the water quality of the stream can be assessed. The downstream location should be located a sufficient distance from the point of effluent to insure that the effluent has been completely integrated with the stream water during both high and low flows, and the stream quality has become stabilized.

Quantity of Water

To assess the overall impact that mine drainage has on receiving streams, it is necessary to collect quantity (discharge) data at all monitoring stations. Streamflow records, especially during low-flow periods, are required to determine the dilution effects of the receiving streams on mine effluents. The most ideal situation would be to establish continuous gaging stations at the upper and lower stations on each stream. If practicality and cost prohibit establishment of these gaging stations, then correlations of instantaneous discharge with nearby gaging stations should be used.

Quality of Water

Water-quality changes caused by mine drainage are considered to be the most significant impacts that mine drainage has on receiving water bodies. Changes in water chemistry often affect the biota, making biological measurements an important characterization of the impacts that mine drainage has on receiving water bodies.

Chemistry

The water-quality variables that involve water chemistry have been ranked on the basis of the relative monitoring importance. The variables designated as priority 1 would be measured most frequently. Variables designated as priority 2 through 4 would be measured periodically, or when on-site measurements indicate a change.

Priority 1 field measurements include acidity and alkalinity, dissolved oxygen, pH, specific conductance, and temperature. Priority 1 laboratory measurements include suspended-sediment concentrations and particle-size distribution. Priority 2 measurements include laboratory analysis for total iron and dissolved sulfate. Priority 3 measurements include laboratory analysis for selected minor elements that include both the dissolved and total phases of trace metals. Priority 4 measurements include trace metals in bottom sediments. Manganese should be given high priority among the metals to be analyzed in both the water and sediment phases.

Biology

Monitoring of benthic invertebrate communities can be used often as a measure of stream health because of the sensitivity of the biota in the stream ecosystem to changes that occur in the stream. The presence, absence, and community makeup of benthic organisms can be used as an integrator of previous stream conditions. This is especially important in assessing the effects that coal-mining activities are having or have had on receiving waters. It is desirable to select sites with similar physical characteristics such as substrates, turbulence, velocity, depth, and light exposure in order to compare or contrast the stations. Such prudent selection of stations can reduce the variation between replicate samples used to compare the collection stations (Chutter and Noble, 1966). The physical habitat chosen for sampling should be characteristic of the streams, and the samplers should be left in place long enough (3 to 4 weeks) to permit effective colonization of the benthic organisms.

Reproducibility with respect to time and space requires that all benthic samplers have the same surface area for colonization (Beak and others, 1973). Rocks used in the artificial substrate samplers should be similar in size, usually 2.5 to 3.5 inches on an intermediate axis (Lium, 1974). A 210-micrometer collection net will obtain the optimum spectrum of benthic organisms (Zelt and Clifford, 1972; Mason and others, 1975). Even if the best equipment and collection methods are used, the ranges of diversity will vary from stream to stream and from station to station within a drainage basin if climatic, geologic, physiographic, and hydrologic differences exist between them.

It would be desirable to have baseline conditions which have been described for Gallop and Loretta Creeks in this report, be re-examined about 1 year prior to commencing mining activity to insure that conditions have remained unchanged. If conditions have changed, then additional sampling for chemical and biological characteristics should be intensified.

SUMMARY AND CONCLUSIONS

The purpose of this study was to characterize the water quality of drainage from abandoned mines in the 11 coal-bearing areas of the State, to show the water-quality effects of drainage from an abandoned coal mine on a receiving stream, identify the baseline water-quality conditions in two prospective underground coal mine areas, and to propose a scheme for monitoring stream quality in a baseline area in the event that mining occurs.

An assessment of the water-quality characteristics of 51 mines in the State that had drainage shows that in almost all mine drainages sampled there is excess alkalinity capable of neutralizing any acidity that may form. Less than 2 percent of the drainage from any of the mines sampled had a pH of 5.6 or less, the theoretical pH of water in a natural equilibrium with atmospheric carbon dioxide. The Centralia-Chehalis coal district has the greatest potential of all coal areas studied to produce water with pH 5.6 or less, due to high sulfur content of the coal (1.12 percent on weighted average). Mine effluent with low dissolved oxygen is likely to have lower net acidity and higher alkalinity and specific conductance than mine effluents with high dissolved oxygen. The sulfur as sulfuric acid and metal contents of the coal are likely to be the controlling factors associated with degration of receiving streams. Water-quality data from a hydraulic mining test on a research borehole in steeply dipped coals near Wilkeson, Washington, indicate that hydraulic mining operations would result in large increases in suspended sediment and turbidity, less significant increases in dissolved solids and temperature, and a slight increase in pH and trace metals.

Drainage from the Skookum mine near the town of Wilkeson was found to be typical of drainage from most underground coal mines in the State of Washington. The most visible effect that mine drainage had on the receiving stream was the deposition of ferric hydroxide on the streambed in the zone where the mine drainage and receiving stream are not mixed. These deposits clog rock interstices and minimize microhabitats for benthic organisms.

Water chemistry of samples that were collected at various stream discharges for stations on Wilkeson Creek above and below the Skookum mine effluent discharge showed comparable results in most instances, but contrasting results in some instances. Significantly higher average concentrations of specific conductance, hardness, acidity, calcium, magnesium, sodium, potassium, alkalinity, sulfate, total ammonia, total iron, and manganese were found at the station just below the mine effluent discharge, but pH and dissolved oxygen were lower. At the most downstream (lower) station specific conductance, hardness, magnesium, and alkalinity were significantly higher than at the two stations located above the mine effluent discharge.

Biological diversity was similar at all of the Wilkeson Creek sampling stations based on average values for all flows, but significant diversity differences were observed at the station just below the Skookum drainage during periods of low flow. Biological effects at a community level were found to be improved downstream and no detectable anomalies existed at the most downstream station (3,000 ft below the mine effluent point of entry) even during low flows.

The Gallop and Loretta Creeks baseline-study areas were found to have calcium-bicarbonate type waters. Gallop Creek had slightly higher magnesium but both creeks had similar anionic composition. Regression equations describing the relation between specific conductance and streamflow indicated that water quality in Gallop and Loretta Creeks was similar to that of Wilkeson Creek above the influence of the Skookum mine point of discharge. Except for minor differences, the physiographic and water-quality characteristics of both downstream stations of Gallop and Loretta Creeks are comparable to the Wilkeson Creek study area.

Fresh, unoxidized coal samples from a seam in the Gallop Creek basin and a seam in the Cumberland mine area next to the Loretta Creek basins and from the Centralia-Chehalis coal area were leached using a soxhlet extractor, and the leachate analyzed to compare acid-producing potentials for those coal areas. The analyses indicated that coal near Loretta Creek (Cumberland Mine) is less likely to produce mine water with net acidity (acidity minus alkalinity) than Gallop Creek coal (Polson tunnel), and both are less likely to produce net acidity than the Centralia-Chehalis coals.

In areas where coal deposits can be expected to be mined in the next few years, a water-quality monitoring scheme is proposed to monitor the effects that the mining activity is likely to have on the receiving streams. Emphasis is placed on monitoring during periods of low flow, when the mine drainage has the greatest impact on the receiving streams. Streamflow, pH, acidity, alkalinity, dissolved oxygen, temperature, specific conductance, and suspended sediment would be the primary characteristics measured. Iron, dissolved sulfate, and minor elements (trace metals) in water and minor elements in bottom sediments are secondary constituents that would be measured periodically or if baseline conditions change. Benthic invertebrates should be studied sufficiently to determine if the mine drainage and the ensuing changes in water quality have an adverse impact on the stream biota and ecosystem. It would be desirable to have previously determined baseline conditions verified at least 1 year prior to commencement of mining activity.

REFERENCES CITED

Arndt, H. H., and Kent, B. H., 1980, Evaluation of the Wilkeson-Carbonado coal field, Pierce County, Washington, for hydraulic coal mining: U.S. Geological Survey Open-File Report 80-802, 109 p.

Beak, T. W., Griffing, T. C., and Appleby, A. G., 1973, Use of artificial substrate samplers to assess water pollution, in J. Cairns and K. L. Dickson, eds., Biological methods for the assessment of water quality: American Society for Testing and Materials, STP 528, p. 227-241.

Beikman, H. M., Gower, H. D., and Dana, A. M. T., 1961, Coal reserves of Washington: Washington Division of Mines and Geology Bulletin no. 47, 115 p.

Caruccio, F. T., Ferm, J. C., Home, J. G., Geidel, Gwendelyn, and Baganz, B., 1977, Paleoenvironment of coal and its relation to drainage quality: U.S. Environmental Protection Agency, Interagency Energy-Environment Research and Development Report, Washington, D.C., EPA-600/7-77-067, 108 p.

Caruccio, F. T., Geidel, Gwendelyn, and Pelletier, Mike, 1981, Occurrence and prediction of acid mine drainages: Proceedings of the American Society of Civil Engineers, Journal of the Energy Division, v. 107, no. EY1, p. 167-178.

Conover, W. J., 1971, Practical non-parametric statistics: New York, John Wiley and Sons, Inc., 462 p.

Chutter, F. M., and Noble, R. G., 1966, The reliability of a method of sampling stream invertebrates: Archives fur Hydrobiologie, v. 62, no. 1, p. 95-103.

Daniels, Joseph, 1914, The coal fields of Pierce County: Washington Geological Survey Bulletin no. 10, 146 p.

Dills, Gary, and Rogers, D. T., Jr., 1974, Macroinvertebrate community structure as an indicator of acid mine pollution: Environmental Pollution, v. 6, no. 4, p. 239-262.

Emrich, G. H., 1973, Tests for evaluating the quality of mine drainage characteristics of coal seams: Mine Drainage Technical Bulletin no. 2, in: Mine Drainage Manual, (2nd ed.), Pennsylvania Department of Environmental Resources Bureau of Waste Quality, Harrisburg, Pa., 9 p.

Evans, G. W., 1912, The coal fields of King County, Washington: U.S. Geological Survey Bulletin no. 3, 247 p.

Fuste', L. A., 1978, Effects of coal mine drainage on Wilkeson Creek, a stream in western Washington: M.S. Thesis, University of Washington, Seattle, Washington, 103 p.

Fuste', L. A., Packard, F. A., Fretwell, M. O., and Garland, Dave, 1983, Data supplement: Quality of coal mine drainage in Washington, 1975-77: U.S. Geological Survey Water Resources Investigations Open-File Report 83-205, 61 p.

Gower, H. D., and Wanek, A. A., 1963, Preliminary geologic map of the Cumberland quadrangle, King County, Washington: Washington Division of Mines and Geology, Geologic Map GM-2, map and text on one sheet.

Hem, J. D., 1970, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 1473, 363 p.

Hollyday, F. F., and McKenzie, S. W., 1973, Hydrogeology of the formation and neutralization of acid waters draining from underground coal mines of western Maryland: Maryland Geological Survey Report of Investigations no. 20, 50 p.

Jenkins, O. P., 1924, Geological investigation of coal fields of Skagit County, Washington: Department of Conservation and Development, Division of Geology Bulletin no. 29, 63 p.

Kaesler, R. L., and Herricks, E. E., 1976, Analysis of data from biological surveys of streams: Diversity and sample size: Water Resources Bulletin, v. 12, no. 6, 11 p.

Koryak, Michael, Shapiro, M. A., and Sykora, J. L., 1972, Riffle zoobenthos in streams receiving acid mine drainage: Water Research, v. 6, no. 10, p. 1239-1248.

Livingston, J. E., Jr., 1966, Geology and mineral resources of the Kelso-Cathlamet area, Cowlitz and Wahkiakum Counties, Washington: Washington Division of Mines and Geology Bulletin no. 54, 110 p.

-----1971, Geology and mineral resources of King County, Washington: Washington Division of Mines and Geology Bulletin no. 63, 200 p.

-----1974, Coal in Washington, in: Energy resources of Washington, Washington Division of Geology and Earth Resources, Information Circular no. 50, p. 35-67.

Lium, B. W., 1974, Some aspects of aquatic insect populations of pools and riffles in gravel streambeds in western United States: Journal of Research of the U.S. Geological Survey, v. 2, no. 3, p. 379-384.

Mason, W. T., Jr., Lewis, P. A., and Hudson, P. L., 1975, The influence of sieve mesh size selectivity on benthic invertebrate indices of eutrophication: Verhandlingen Internationale Vereinigung für Theoretische and Angewandte Limnologie, p. 1550-1561.

Moen, W. S., 1969, Mines and mineral resources of Whatcom County, Washington: Washington Division of Mines and Geology Bulletin no. 57, 134 p.

Moss, M. E., and Haushild, W. L., 1978, Design recommendations for a streamflow-data network in Washington: U.S. Geological Survey Open-File Report WA-76-186-30, 43 p.

Phinney, L. A., and Bucknell, P., 1975, A catalogue of Washington streams and salmon utilization, v. 2, Coastal Region: Olympia, Washington, Washington Department of Fisheries.

Pielou, E. C., 1966, The measurement of diversity in different types of biological collections: Journal of Theoretical Biology, v. 13, p. 131-144.

Riggs, H. C., and Hardison, C. H., 1973, Storage analyses for water supply: Techniques of Water-Resource Investigations of the U.S. Geological Survey, Book 4, Chapter B2, 20 p.

Roberts, A. E., 1958, Geology and coal resources of the Toledo-Castle Rock district, Cowlitz and Lewis Counties, Washington: U.S. Geological Survey Bulletin 1062, 71 p.

Saunders, E. J., 1914, The coal fields of Kittitas County, Washington: Washington Geological Survey Bulletin no. 9, 204 p.

Scott, R. L. and Hayes, R. M., 1975, Inactive and abandoned underground mines - water-pollution prevention and control: U.S. Environmental Protection Agency, Office of Water Planning and Standards, Washington, D.C., EPA-440/9-75-007, 349 p.

Snavely, P. D., Jr., Brown, R. D., Jr., Roberts, A. E., and Rau, W. W., 1958, Geological and coal resources of Centralia-Chehalis district, Lewis and Thurston Counties, Washington: U.S. Geological Survey Bulletin 1053, 159 p.

U.S. Bonneville Power Administration, 1963, Wilkeson area coal study (Pierce County, Washington): U.S. Bonneville Power Administration, Portland, Oregon, 54 p.

U.S. Department of Interior, 1969, Stream pollution by coal mine drainage in Appalachia: Federal Water Pollution Control Administration, p. 11-35.

Vine, J. D., 1969, Geology and coal resources of the Cumberland, Hobart, and Maple Valley quadrangles, King County, Wash.: U.S. Geological Survey Professional Paper 624, 67 p.

VonHeeder, E. R., 1975, Coal reserves of Whatcom County, Washington: Unpublished Open-File Report, State of Washington, Department of Natural Resources, Division of Geology and Earth Resources, 86 p.

Walsh, Fraser, and Mitchell, Ralph, 1972, A pH dependent succession of iron bacteria: Environmental Science and Technology, v. 6, no. 9, p. 809-812.

Warren, W. C., 1945, Preliminary geologic map and brief description of the coal fields of King County, Washington: U.S. Geological Survey Preliminary Map, scale 1:31,680.

Wentz, D. A., 1974, Effect of mine drainage on the quality of streams in Colorado, 1971-72: Colorado Water Resources Circular no. 21, 117 p.

Wilhm, J. L., 1972, Graphic and mathematical analyses of biotic communities in polluted streams: Annual Review of Entomology, v. 17, p. 223-252.

Woodruff, E. G., 1914, The Glacier coal field, Whatcom County, Washington: U.S. Geological Survey Bulletin 541, p. 389-398.

Zand, S. M., 1976, Indices associated with information theory in water quality: Journal of the Water Pollution Control Federation, v. 48, no. 8, p. 2026-2031.

Zelt, K. A., and Clifford, H. F., 1972, Assessment of two mesh sizes for interpreting life cycles, standing crop, and percentage composition of stream insects: Freshwater Biology, v. 2, no. 3, p. 259-269.