HYDROLOGY OF POTENTIAL MINING AREAS IN THE WARRIOR COAL FIELD, ALABAMA

By Celso Puente and J. G. Newton

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JAMES G. WATT, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

U.S. Geological Survey
520 19th Avenue
Tuscaloosa, Alabama 35401

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FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM (SI) UNITS

To obtain inch-pound units	By	Divide SI units
inch (in)	25.4	Millimeter (mm)
inch (in)	2.540	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
ton (short, 2,000 lbs)	0.9072	metric ton (t)
tons per day (ton/d)	0.9072	metric tons per day (t/d)
tons per square mile (ton/mi^2)	0.3503	metric tons per square kilometer (t/km^2)
cubic foot per second (ft^3/s)	28.32	liter per second (L/s)
gallon per second (gal/min)	0.06309	liter per second (L/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.010934	cubic meter per second per square kilometer [$(m^3/s)/km^2$]

Temperature, (°C [Celsius] x 1.8) + 32 = °F [Fahrenheit].

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Mean Sea Level."

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ABSTRACT

Hydrologic data for four small basins and for numerous other sites in the Warrior coal field are used to define the potential impact of surface mining on water resources. Bear and Blue Creek basins are underlain predominantly by relatively impermeable consolidated rocks in the Pottsville Formation. Turkey and Yellow Creek basins are underlain predominantly by permeable unconsolidated rocks in the Coker Formation.

Well yields from the Pottsville Formation generally range from 0 to 5 gallons per minute and those from the Coker Formation generally range from 5 to 100 gallons per minute. With the exception of locally objectional concentrations of dissolved iron and manganese, ground water in the basins is suitable for most uses.

Streamflow distribution reflects seasonal precipitation. Storm runoff is characterized by concentrated peakflows of short duration that rapidly recede to low flow. Streams draining basins underlain mainly by the Pottsville Formation frequently go dry, whereas those draining basins underlain chiefly by the Coker Formation have well-sustained low flows.

Surface water is generally acidic and low in dissolved solids. Water in streams draining basins underlain chiefly by the Pottsville Formation is slightly more mineralized and less acidic than water in streams draining areas underlain chiefly by the Coker Formation.

Climatic, physiographic, hydrologic, and land-use data are analyzed by regressions to derive relations for estimating water quality in streams draining mined and unmined areas.

The impacts of mining on the hydrologic systems are identified as increased erosion and sedimentation, baseflow augmentation, decline in ground-water levels, and degradation of water quality.

A digital model was calibrated to simulate streamflow for Bear, Blue, and Yellow Creeks under unmined conditions. The model, when calibrated and verified under mined and unmined conditions, can be coupled with developed water-quality relationships. This will permit a general examination of surface-water characteristics (quantity and quality), and estimation of hydrologic impacts that will result from surface mining.

INTRODUCTION

Maximum development of coal as a source of energy will require the mining of Federal reserves. In Alabama, these reserves underlie about 711,000 acres of which 70,500 are in the Warrior coal field (fig. 1).

Figure 1 (caption on next page) belongs near here.

Surface mining of Federal coal reserves will be accompanied by environmental changes that will impact water resources. In anticipation of this mining, it is necessary to define existing hydrologic conditions and processes in order to identify mining and reclamation procedures that will minimize resulting impacts.

Figure 1.--Areas of study and principal coal fields in Alabama.

In March 1976, the U.S. Geological Survey, Water Resources Division, in cooperation with the U.S. Bureau of Land Management, initiated a hydrologic investigation of selected basins in the Warrior Coal Field. The investigation was designed to provide hydrologic information to the Bureau of Land Management to aid in the preparation of their environmental impact statements. The objectives of the study are:

1. To define existing hydrologic conditions and basic hydrologic processes in the areas prior to coal mining.
2. To assess impacts that surface mining will have on the hydrology of the areas during and after mining.
3. To derive methods for estimating impacts resulting from mining.

The purpose of this report is to summarize the hydrology of the areas studied, describe the impacts of mining on the hydrologic system, and describe a digital watershed model that can be used to simulate the surface-water system under existing conditions and to estimate the impacts of mining.

Previous Investigations

Recent reports from this and related investigations provide information on the water resources of the area. Reports by Knight and Newton (1977), Puente and Newton (1979), and Harkins and others (1980) provide information describing water-related impacts resulting from surface mining in the Warrior Coal Field. Puente and others (1980) defined baseline conditions and basic hydrologic processes in the area of study and Puente and others (1981) described methods of estimating hydrologic conditions in mined and unmined areas in the Warrior coal field.

Acknowledgments

Acknowledgment is made to several individuals, agencies, and companies for their contributions to this investigation. Mr. Sam Baker, National Weather Service, provided weather forecasts during climatic events. Messrs. Don Prestley and Ken Wilson, U.S. Soil Conservation Service, provided soil information and soils maps. Messrs. Thomas W. Daniel, Jr., and Charles W. Copeland, Geological Survey of Alabama, furnished information on coal beds and associated strata. Mr. Rex Mitchell, Mitchell and Neely Mining Company, Mr. Mitchell Hilton, Black Jack Mining Company, Mr. Roland Pugh, Pugh Construction Company, Mr. William O'Dell, Big Bend Mining Company, and Mr. Joe Stevenson, Carbon Fuels Company, provided access to mining areas and information pertaining to coal beds, production and reclamation. Gulf States Paper Corporation, Holman Lumber Company, and Republic Steel Corporation provided access to their property to establish a surface and ground water data collection network. Numerous private land owners provided information for their wells and access to their property.

PHYSICAL SETTING

The two areas of study (fig. 1) are in the Cumberland Plateau section of the Appalachian Plateau's physiographic province which consists chiefly of a submaturely to maturely dissected upland developed largely on nearly flat-lying rocks (Johnston, 1933). Maximum relief in Bear and Blue Creek basins, the northernmost areas, is about 300 feet with numberous tributaries incised sharply into shale and sandstone that support ridges and steep slopes. Overland slopes generally range from 45 percent on hillsides to about three percent on the hilltops. Most basins are separated by sharp ridges. This is modified somewhat in Turkey and Yellow Creek basins, the southernmost areas, where sand, gravel, and clay overlie shale and sandstone. In this area, hilltops and ridges tend to be less sharp, and in places, relatively flat. Most roads are on ridges and most land development is along the roads and in the flatter areas.

Climate

The study area has a subtropical climate characterized by warm and humid weather. According to U.S. National Weather Service records (Frentz and Lynott, 1978), the average annual temperature is about 17°C. January is generally the coldest month with an average temperature of 6.7°C, and July the hottest with an average temperature of 26.5°C. The growing season averages 225 days, the frost-free season extending from late March through early November.

The average annual precipitation, almost all in the form of rain, is about 55 inches. Snowfall is very light and infrequent. The wettest month is March and the driest is October; drought conditions seldom occur. Summer rains, produced by convective storms, are more intense but briefer and smaller in area than rains associated with winter and early spring frontal systems.

Precipitation on the study area exceeded the average during the period 1977 through 1979. Based on records at nearby long-term station Bankhead Lock and Dam (1938-76), precipitation from January 1, 1977 to December 31, 1979, exceeded the average by 13.08 inches. The yearly average rainfall for this period exceeded the long-term yearly average by 4.36 inches.

Land Use

Aerial photography flown annually from 1977 to 1980 shows that the major study areas (fig. 1), with the exception of Blue Creek basin, are undisturbed and free of most activities that significantly affect the availability and distribution of water and its quality. Land-use data for the areas in 1980 are given in table 1. The area disturbed in Blue Creek basin increased from about ten acres in February 1977 (Puente and others, 1980) to about 260 acres in March 1980. Other land use in the study areas varied little during the same period.

Table 1.--Land use, March 1980

Bear and Blue Creek basins			Turkey and Yellow Creek basins		
Land use	Area (mi^2)	Percent	Land use	Area (mi^2)	Percent
Forest	18.65	91	Forest	13.00	91
Agriculture	1.00	5	Agriculture	.34	2
Rural	.12	1	Rural	.44	3
Coal Mining	.40	2	Coal Mining	0	0
Industry	.20	1	Industry	.58	4
	20.37	100		14.36	100

Geology

The areas of study are in the outcrops of the Pottsville Formation of Pennsylvanian age and the overlying Coker Formation of Late Cretaceous age (fig. 2). The two formations are sedimentary in origin but contrast greatly;

Figure 2 (caption on next page) belongs near here.

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the Pottsville is consolidated and the Coker is unconsolidated. Regionally, strata in the Pottsville in the Warrior Coal Field strike northwestward and dip southwestward from about 30 to 200 feet per mile (Culbertson, 1964). The unconformable contact between the Pottsville and overlying Coker Formation strikes northwestward and dips southwestward from about 30 to 35 feet per mile (Paulson and others, 1962). The dip and strike of strata in the Coker Formation parallel those of the contact.

The Pottsville Formation in the area of study generally ranges in thickness from 2,700 to 3,000 feet (Metzger, 1965), and consists chiefly of shale, sandstone, and siltstone. Shale is the dominant rock type. The uppermost bed in the Pottsville is generally a leached plastic gray clay. Its thickness is generally less than 10 feet.

Several intervals in the Pottsville Formation contain beds of coal and underclay. Coal beds cropping out in Bear and Blue Creek basins are in the Utley coal group and those cropping out in Yellow and Turkey Creek basins are in the Brookwood coal group (Puente and others, 1980).

Figure 2.--Geologic map of areas of study.

The Coker Formation in Tuscaloosa County is as much as 490 feet thick, however, only the lower 120 feet crop out in the area of study. The basal 26 to 98 feet generally consist of fine- to coarse-grained sand, gravelly sand, and sandy gravel separated in places by lenticular beds of gray, sandy clay. Strata overlying the basal unit consist largely of thin-bedded to massive clay and sandy clay with occasional beds of fine- to medium-grained sand.

The geology of the areas studied differ in that most of Bear and Blue Creek basins are in the outcrop of the Pottsville Formation and most of Yellow and Turkey Creek basins are in the outcrop of the Coker Formation (fig. 2). Detailed descriptions of the geology and the occurrence and distribution of the coal resources in the two study areas are given in Puente and others (1980).

HYDROLOGIC SETTING

Ground Water

The occurrence, movement, and quality of ground water described in the study area is based on geologic and hydrologic data for wells and springs. Summaries of the data are given by Puente and others (1980) and the locations of wells and springs are shown in figure 3.

Figure 3 (caption on next page) belongs near here.

Precipitation is the primary source of recharge. Discharge from aquifers is mainly by evapotranspiration, discharge from small springs, and pumpage from wells.

The Pottsville and Coker Formations have diverse water-bearing characteristics. Consolidated rocks in the Pottsville are relatively impermeable, whereas unconsolidated sand and gravel in the Coker is permeable.

Figure 3.--Study areas and locations of wells and springs.

The Pottsville Formation is the only aquifer tapped by wells in Bear and Blue Creek basins. Most water-bearing openings occur along fractures and bedding planes at depths less than 250 feet. The yield of wells tapping the formation in this area averages less than 5 gal/min; yields exceeding 25 gal/min are rare.

Water in the Pottsville Formation occurs under perched, confined, and unconfined conditions. Perched bodies of water commonly occur where fractures and joints are absent or are sealed by underclay or soft shale. A schematic diagram illustrating the occurrence and movement of water in the Pottsville is shown in figure 4. Water levels in wells generally range from 20 to 150 feet

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on hilltops, 5 to 30 feet in lowland areas, and on hill slopes are generally between the two extremes.

The Coker Formation in Bear and Blue Creek basins, because of its thinness and limited area of outcrop, generally does not yield supplies adequate for domestic use.

Figure 4.--Schematic diagram showing occurrence and movement of water in the Pottsville Formation.

Sand and gravel beds at the base of the Coker Formation are the principal sources of domestic water supply in Turkey and Yellow Creek basins. Wells tapping the Coker, most of which are shallow dug wells, range in depth from 9 to 100 feet. The saturated zone at the base of the Coker is generally uncon-

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fined, thin, and perched on clay at the top of the Pottsville Formation (fig. 5). The yield of wells generally ranges from 6 gal/min near outcrop boundaries to about 100 gal/min where beds are thickness.

Figure 5.--Schematic diagram showing occurrence and movement of water in the Coker Formation.

Surface Water

Streamflow characteristics described are based primarily on data collected at sites shown in figure 6. Information for the sites including

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the type and frequency of data collection, is given in table 2.

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Streamflow distribution generally reflects seasonal precipitation. Stream discharges are usually highest during November through April and lowest during May through October. In late spring and summer, streamflow is mainly ground-water discharge from storage. Ground-water discharge and total streamflow generally increase during the fall when evapotranspiration decreases and precipitation increases. Discharge data for sites 1, 3, and 7 are summarized in table 3. The flow-duration curves in figure 7 show the

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percent of time a specific discharge was equaled or exceeded during the period

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of record. Curves having steep slopes denote highly variable streamflow derived chiefly from direct surface runoff, whereas curves having moderate to flat slopes indicate streamflow derived from both direct runoff and ground-water discharge. The curves in figure 7 are plotted on a unit area basis for comparison.

Figure 6.--Location of surface-water data collection sites.

Figure 7.--Flow duration curves for sites 1 (Bear Creek near Samantha), 3 (Blue Creek near Oakman), and 7 (Yellow Creek near Northport), October 1976 - July 1980.

Table 2.--Summary of surface-water data collection network.

Table 3.--Monthly and annual mean, maximum, and minimum discharge summaries for sites 1, 3, and 7 October 1976 - September 1979.

Estimates of low-flow and flood-flow frequencies for sites 1, 3, and 7 are based on regression equations developed by Bingham (1979) and Hains (1973). The low-flow estimates are given in table 4.

Table 4.--Estimated low-flow characteristics ($7Q_2$, $7Q_{10}$) at selected sites

Site Number	$7Q_2$	$7Q_{10}$
	$(ft^3/s)/mi^2$	$(ft^3/s)/mi^2$
1	0	0
3	0	0
7	.325	.186

The values agree closely with those reported from previous low-flow investigations (Hayes, 1978; Peirce, 1967) for other nearby streams in similar basins.

Equations for flood frequency estimates (Hains, 1973) similarly relates basin characteristics, percipitation, and geology to floods for 2-, 5-, 10-, 25-, 50-, and 100-year recurrence intervals. Flood magnitudes and frequencies for sites 1, 3, and 7 are given in figure 8.

Figure 8 (caption on next page) belongs near here.

Figure 8.--Estimated magnitude and frequency of flood discharges at sites 1, (Bear Creek near Samantha), 3 (Blue Creek near Oakman), and 7 (Yellow Creek near Northport).

Water Quality

The lowest dissolved-solids concentrations in ground water generally occur in aquifers at shallow depths beneath ridges. The highest concentrations generally occur in aquifers underlying lowland areas or in aquifers underlying ridges at depths exceeding 50 feet. The increased mineralization generally results from longer contact-time of water with soluble minerals.

Most constituents in ground water in the study area are within limits of drinking water criteria set by the U.S. Environmental Protection Agency (1977). Locally, however, concentrations of iron and manganese exceed those limits. Water-quality data are summarized in tables 5 and 6. The summaries

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Tables 5 and 6 (captions on next page) belong near here.

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show that water in the Coker Formation is less mineralized than that in the Pottsville.

Table 5.--Summary of selected chemical and physical properties of water in the Coker Formation.

Table 6.--Summary of selected chemical and physical properties of water in the Pottsville Formation.

Water collected at different rates of streamflow was analyzed for concentration of major constituents, selected nutrients (nitrogen and phosphorus series), trace elements, and suspended sediment. Stream bottom materials were also collected for trace element analyses. Chemical quality data for sites 1 and 7 are shown graphically in figure 9. The chemical composition and its

Figure 9 (caption on next page) belongs near here.

variability with stream discharge at these sites is similar to that in other streams draining undisturbed basins in the outcrop of the Pottsville and Coker Formations. Detailed descriptions of the water quality and tabulated data are given by Puente and others (1980).

Figure 9.--Chemical composition of stream discharge (Q) at sites 1 (Bear Creek near Samantha), and 7 (Yellow Creek near Northport).

Seasonal variations in specific conductance, water temperature, and stream discharge at sites 1 and 7 are illustrated in figures 10 and 11. The

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Figures 10 and 11 (captions on next page) belongs near here.

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inverse relation between specific conductance and stream discharge at site 1 results from base flow contributed by the Pottsville Formation. Base flow from the Pottsville is more mineralized than overland flow (table 6) because of its longer contact time with rock. Because of this, a decrease in overland flow results in an increase in specific conductance. Seasonal variation in specific conductance is small at site 7 on Yellow Creek (fig. 11) because base flow from the Coker Formation (table 4) is very similar to that of rainwater (Puente and others, 1980). Variations in monthly mean water temperatures are similar to variations in seasonal air temperatures (Puente and others, 1980).

Water quality at site 3 is more mineralized than that at other sites. This mineralization results from surface coal mining in Blue Creek basin (Puente and others, 1980).

Figure 10.--Variations in monthly mean discharge, specific conductance, and water temperature at site 1 (Bear Creek near Samantha).

Figure 11.--Variations in monthly mean discharge, specific conductance, and water temperature at site 7 (Yellow Creek near Northport).

Nutrients in the form of various nitrogen and phosphorus compounds are present in surface water in small concentrations. In streams studied, they are largely derived from natural sources such as precipitation and decomposition of organic matter. Concentrations of nitrate-Nitrogen (NO_3-N) at all sites were below the recommended limits for drinking water standards (U.S. Environmental Protection Agency, 1977).

Trace element concentrations, except those for iron and manganese, were well below the maximum recommended for drinking water by the U.S. Environmental Protection Agency (1977). Concentrations of dissolved iron and manganese exceeding maximums recommended (300 and 50 ug/L, respectively) at sites 1, 2, 6, and 7 were few, and generally occurred during highflow. Concentrations of dissolved manganese exceeded the recommended limits at sites 3, 8, and 9 frequently throughout the range of flow sampled. This reflected the presence of coal-mine drainage. Concentrations of dissolved iron at all sites were generally similar to concentrations of dissolved manganese.

Total recoverable concentrations of trace elements attached to sediment suspended in water, and recoverable concentrations from bed material indicated that only a small fraction of aluminum, iron, and manganese are in solution. Much larger concentrations are absorbed on solid materials in the streams.

Suspended-sediment discharge data for selected sites in the study area for 1977-79 water years are summarized in table 7. Approximately 8, 7, and

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4 percent of the basins upstream from sites 3, 8, and 9, respectively, have been disturbed by mining. Annual sediment yields in disturbed basins (sites 3, 8, and 9) ranged from 250 to 4,000 (tons/mi^2)/yr. Relations between suspended-sediment concentrations and stream discharge for other disturbed basins are probably similar (Puente and others, 1980). Because of above-normal precipitation during the 1979 water year, sediment yields for streams draining undisturbed basins (sites 1 and 7) were higher than would be expected for other years. Relations between sediment yield and unit stream discharge are illustrated in figure 12.

Figure 12 (caption on next page) belongs near here.

Suspended-sediment samples collected during high flow at sites 1, 3, and 7 were analyzed for particle size distribution. At sites 1 and 7 the analyses indicated a composition of 50 percent clay and silt (finer than 0.062 mm), and 50 percent sand (0.062-2.0 mm). The composition at site 3 was about 98 percent clay and silt, and 2 percent sand.

Bed material size composition for sites in Pottsville areas averaged 20 percent sand, and 80 percent gravel (2.0-6.4 mm). Bed material size composition for sites in Coker areas averaged 80 percent sand and 20 percent gravel.

Table 7.--Summary of annual suspended-sediment discharge and sediment yields for selected sites, October 1976 - September 1979.

Figure 12.--Relation between sediment yield and unit stream discharge for selected sites (locations of sites shown in figure 3).

Biology

Benthic invertebrate and periphytic diatom communities are sensitive to chemical and physical changes in streams and may be used as indicators of water quality. Comprehensive analyses of aquatic community structures in streams draining the four study basins (fig. 6) are presented by Hill (written commun., 1981). Hill's summaries of the results of monthly sampling in riffle areas are the basis for the following summaries of biologic conditions.

A total of 215 invertebrate taxa were identified during the period of study. Approximately 95 percent of the fauna are represented by the class Insecta. The aquatic invertebrate insects, from most- to least-abundant, were: Diptera, Coleoptera, Plecoptera, Ephemeroptera, and Trichoptera. The cumulative percentages of the major insect orders collected at each sampling site are shown in figure 13. Asellidea (Crustacea) were the predominant non-

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insect aquatic invertebrates.

The Brillouin diversity index was used as an indicator of the diversity of the sample population and, thus, as a measure of the stream's ability to support a varied benthic community. Mean and range values of benthic invertebrate diversity at sampled sites are shown in figure 14. Diversity values equal to or greater than 3.00 indicate healthy nonstressed conditions in

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streams, while values less than 2.00 indicate unfavorable, stress conditions (Wilhm and Dorris, 1968).

Figure 13.--Cummulative percentages of major insect orders collected at sites 1 through 9, January 1977 - June 1979.

Figure 14.--Mean and range of species diversity for benthic invertebrates at sites 1 through 9, January 1977 - June 1979.

A total of 137 diatom species were identified. Of these, only 3 species were abundant and constant in occurrence at all sites. The community types reflect the naturally occurring differences in water quality between streams draining areas in the outcrops of the Coker and Pottsville Formations. Diatom communities characteristic of streams with acidic water (pH less than 7.0) and extremely low dissolved mineral content occurred at sites draining the Coker. In contrast, communities characteristic of streams with alkaline water (pH greater than 7.0) and relatively low dissolved mineral content occurred at sites draining the Pottsville.

Benthic invertebrate and periphytic diatom community structures indicated that the streams monitored support a large variety of species and reflect natural conditions in the study area.

FUNCTIONAL RELATIONSHIPS BETWEEN WATER-QUALITY VARIABLES

Surface water quality relationships, in areas of similar geology and land use, often exist between specific ion concentrations and physical properties. Some of the more common relations include: specific conductance versus dissolved solids; specific conductance versus inorganic constituent concentrations; specific conductance versus streamflow; suspended-sediment concentrations versus streamflow; and suspended-sediment concentrations versus total recoverable concentrations of trace elements. Quantification of these relationships through regression analyses provides an estimating capability that can reduce sampling programs or change network design.

Regression Approach

Climatic, physiographic, hydrologic, and land-use data from sites in the study area and from many partial-record sites areally distributed in the Warrior coal field were analyzed by regressions. Relations derived from the analyses are useful for estimating water quality in streams draining mined and unmined areas. Site locations are shown in figure 15.

Figure 15 (caption on next page) belongs near here.

Models used in the regression analyzes are of the form

$$Y = ax_1^{b_1} x_2^{b_2} \ldots . x_n^{b_n},$$

where Y (dependent variable) represents water quality characteristics, X (independent variables) are climate, basin characteristics, and land use, a is the regression constant, b's are regression coefficients, and n is the total number of independent variables. Dependent variables are estimated from a combination of known independent variables. Lystrom and others (1979) have used the same approach in similar studies.

Figure 15.--Regional surface-water data collection network.

The chemical quality of mine drainage varies as functions of the quantity of water leaving the mined areas, the presence of reactive minerals in spoil materials, and the length of exposure of the reactive minerals to weathering. In the regression approach, the selected dependent variable representing mineralization of water in streams is specific conductance.

The equation for estimating specific conductance of water in streams draining mined areas is:

Equation (A) $$\text{SP. COND.} = 28.84 \frac{(\text{PBM})^{.407} (\text{MAF})^{.476}}{(\text{Q/A})^{.369} (\text{CL})^{.381}}$$

Where SP. COND. is specific conductance, in micromhos per centimeter at 25°C,

PBM is percent of basin mined,

Q/A is streamflow, in cubic feet per second per square mile,

CL is average channel length or distance between stream sampling site and mined area (a weighted average in basins with two or more mines), in miles, and

MAF is a mine age-weight factor based on observed increases in mineralization of mine drainage with time. The numerical values are:

Mine age in years after mine start	MAF
1	2
2	3
3	7
4	10
5	15
6	18
7	20
8	20
9	20
10	19
11	15
12	9
13	6
14	4
15	3

Mine age-weight factors (MAF) were determined from plots of specific conductance versus stream discharge based on the age of surface mines contributing drainage to streams. The above table represents an interpolation of a bar graph where MAF = 2 when mine age is less than 3 year; MAF = 10 when mine age is 3 but less than 6 years. MAF = 20 when mine age is 6 but less than 12 years, and MAF = 5 when mine age is 12 or more years.

The relation for specific conductance (Equation A) was developed from a sample size of 93 data points from 35 sites. The correlation coefficient (R) is 0.93 and the standard error of estimate (S.E.) is 148 umhos or 40 percent of the dependent variable mean. The regression constant and coefficients are significantly different from zero at the 5 percent significance level. The correlation coefficient is a measure of the degree of association between the dependent variable and the independent variables. A perfect relationship between the variables would have an R value equal to 1.00. Values of R equal to or greater than 0.80 are considered to be significant. The standard error of estimate is a measure of the variation or scatter of points about the line of regression and may be expressed in the same units as the dependent variable or as a percentage of the mean of the dependent variable. Graphical solution of the equation is given in figure 16.

Figure 16 (caption on next page) belongs near here.

Estimates of specific conductance greater than 3,000 umhos exceed the range of observed data and should be set equal to 3,000. The equation is applicable only for ranges of data defined by the family of curves (fig. 16).

Figure 16.--Graphical solution for specific conductance relation for streams draining mined areas.

Relations between specific conductance versus major dissolved constituents in water of streams draining mined and unmined areas in the Warrior coal field are given in table 8. The regression coefficients were signifi-

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Table 8 (caption on next page) belongs near here.

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cantly different from zero at the 5 percent level of significance. Suspended-sediment concentrations versus total recoverable iron and manganese concentrations are also given in table 8. Some of the more meaningful relations have been described and illustrated by Puente and others (1981).

Table 8.--Regression equations, correlation coefficients, and standard errors of estimate of water-quality relations for streams in the Warrior coal field.

Application of Estimating Methods

The equations given in table 8 provide a simple method for estimating constituent concentrations using specific conductance data. However, when used in conjunction with daily records of specific conductance or suspended-sediment and stream discharge, the equations provide a means for estimating solute loads transported by the streams.

Estimated dissolved solids loads computed from the regression equations are illustrated in figure 17. Daily dissolved solids loads (observed) were

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Figure 17 (caption on next page) belongs near here.

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simulated by equation 8 (table 8) using daily mean discharge-weighted specific conductance and daily mean stream discharge records. Dissolved solid loads (computed) were similarly simulated by equation 8 using estimated specific conductance values derived from equation (A) and daily mean discharge. The error of estimates of constituent concentrations derived from equations 1 through 8 (table 8) in conjunction with equation A are somewhat greater than those derived from the same equations and observed specific conductance. The concentration estimates, however, are reasonable and of acceptable accuracy. The graphs (fig. 17) show that dissolved solids loads using both methods were in close agreement.

The equations may also be used for detecting water quality changes in streams as a result of changing land use. Equations 11 through 20 in table 8 define water quality relations representative of streams draining relatively undisturbed basins. Substantial and consistent deviations from the regression lines may indicate water quality deterioration resulting from man's activities in the basins.

Figure 17.--Estimated dissolved solids loads at site 3 (Blue Creek near Oakman), October 1978 - September 1979.

Equation (A) in conjunction with equations 1 through 8 in table 8 are particularly useful for estimating future water quality changes in streams draining surface mined areas. Estimates may be made under various conditions imposed by the user. These conditions include variable mining progression rate, streamflow leaving mined areas, downstream distance between sampling points and mined areas, and mine age.

For example, a new surface mining operation in a small basin with a drainage area (D.A.) of 3.0 square miles starts with an expected rate of mining of 100 acres (0.155 mi^2) per year for 5 years. The problem is to estimate the specific conductance, hardness, sulfate, and dissolved solids concentrations in water in a stream for the following time frames and conditions:

1. at the start of mining and 2, 5, 10, and 15 years after mining is initiated,
2. at a constant streamflow (Q) of 1.0 ft^3/s, and
3. at a downstream sampling distance (CL) of 0.5 mile.

A summary of the problem conditions and estimated water quality parameters are given in table 9.

Table 9 (caption on next page) belongs near here.

Table 9.--Estimated water quality parameters in a hypothetical stream draining a mined area.

IMPACTS OF SURFACE MINING

Surface mining impacts the hydrology of previously undisturbed basins. The impacts can include erosion and sedimentation, flooding, diversion of drainage, declines of water-levels, and degradation of water quality. Impacts on the study area are based primarily on data collected at sites 3, 8, and 9 (fig. 6), and other nearby areas with similar geology, basin characteristics, and land-use.

The impact of surface mining on the ground water system results from (1) the removal of parts of aquifers during mining, (2) modification of ground water movement and storage by removal of overburden and replacement of the overburden with spoil, and (3) changes in ground water quality caused by leachate from mine spoil areas and water impoundments.

The intersection of surface mining with water-bearing openings results in draining of the openings and a corresponding decline in water levels adjacent to the mine. The decline in water levels may be temporary or permanent, depending on mining and reclamation practices (Knight and Newton, 1977).

Springs in high walls at surface mines in Blue Creek basin indicate that water-bearing openings adjacent to and updip from the mine excavations are being dewatered. The resulting decline of water levels is illustrated by the hydrograph of observation well 50 (fig. 18). The hydrographs shows a downward trend in 1978. In March 1978, mining progressed northward to

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Figure 18 (caption on next page) belongs near here.

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within 0.1 mile of the observation well. Since then, the water level in the well has declined periodically to the approximate elevation of the lowest adjacent coal bed mined.

Placement of spoil materials in mined areas upstream from sites 3, 8, and 9 (fig. 3) has created spoil aquifers that generally rest on underclay or shale. Perched water in the spoil is a source of recharge to underlying aquifers and a source of base flow to nearby streams. In Blue and Cripple Creek basins (fig. 3), the spoil aquifers store and transmit more water than the original aquifers.

Figure 18.--Water levels in observation well 50 in Blue Creek basin.

Impacts of mining on streamflow are apparent in the low flow of Blue Creek (site 3). Streamflow records for site 3 during the 1979 and 1980 water years indicate a substantial increase in base flow. The increase is reflected in annual flow-duration curves for sites 1 and 3 (fig. 19). The large difference in the annual flow-durations indicates an increase in basin storage

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Figure 19 (caption on next page) belongs near here.

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that provides larger baseflows at site 3. The increase in low flow results from seeps that issue from spoil areas and impoundments upstream from site 3.

Storage of water in mined areas in Blue Creek basin is expected to increase as mining progresses and may result in low flows significantly exceeding those prior to mining.

Impacts of mining on high flow were not determined due to insufficient data.

Figure 19.--Annual flow-duration curves for sites 1 (Bear Creek near Samantha), and 3 (Blue Creek near Oakman).

Impacts of Surface Mining on Water Quality

Ground-water quality degradation was detected only in Cripple Creek basin near the areas studied. Water in test well 29 (fig. 3) near and downdip from a mine had a specific conductance of 1220 umhos, a sulfate concentration of 392 mg/L, calcium and magnesium concentrations of 72 and 80 mg/L respectively, and a dissolved solids concentration of 817 mg/L. The quality of water in the well differs significantly from that in Pottsville wells summarized in table 6. Ground-water quality impacted by mine drainage in the Warrior coal field is generally characterized by large increases in total hardness, dissolved solids, and sulfate concentration. Dissolved iron and manganese concentrations exceeding 300 and 50 ug/L, respectively, are also a common occurrence.

The pH of mine water, depending on the geochemistry of rocks in the mines, may be acidic or alkaline. Acidic recharge from mines is generally neutralized by the alkalinity of natural ground water in the Pottsville Formation. The degradation of ground water quality is usually restricted to the general vicinity of the mines and to nearby downdip areas.

The quality of water in streams draining mined basins is characterized by marked increases in mineral concentrations and sediment yield. The following ranges in physical properties and chemical constituents reflect the effects of mine drainage in the study areas and in the Warrior coal field (Puente and others, 1981).

Specific conductance:	100 - 3,000 umhos,
pH:	2.5 - 8.8 units,
sulfate:	15 - 1,800 mg/L,
hardness ($CaCO_3$):	50 - 1,800 mg/L,
noncarbonate hardness:	20 - 1,800 mg/L,
bicarbonate:	0 - 450 mg/L, and
dissolved solids:	60 - 2,000 mg/L.

High specific conductance and sulfate concentrations that occur at sites 3, 8, and 9 (fig. 6) during low flow reflect mine drainage. Mineralization of water at these sites increased rapidly in a relatively short period of time. For example, the specific conductance at site 3 on Blue Creek during low flow (less than 1.0 ft^3/s) increased from 58 umhos in November 1976 to 1550 umhos in July 1980. The pH of water at the same sites generally was not lowered by the mine drainage. This was probably due to calcareous minerals such as siderite, calcite, and ankerite that are commonly present in spoil. Similar occurrence of calcareous minerals in spoil in much of the Warrior coal field has been reported by Puente and Dark (1980).

Total recoverable iron and manganese concentrations were higher at sites draining mined areas than those in streams draining unmined areas (Puente and others, 1980). Concentrations increase with increases in suspended-sediment concentrations during high flow. Aeration of mine drainage containing high dissolved iron and manganese concentrations results in deposits of insoluble precipitates ("Yellow Boy") frequently observed on stream bottoms and banks in and near many mined areas. Sorption of these precipitates on stream sediments results in the higher total recoverable iron and manganese concentrations observed in streams draining mined basins.

Surface mining activities in the areas of study have resulted in substantial increases in suspended sediment. This is due to activities that include the removal of forest cover, construction of haul roads, excavation, and creation of spoil areas. The maximum suspended-sediment concentration recorded during the study was 5,400 mg/L at site 3 in Blue Creek basin where approximately 8 percent of the upstream area has been disturbed. Relations between sediment yield and unit discharge are illustrated in figure 12, and given in table 7.

WATERSHED MODEL

The goal of the watershed model being calibrated as a part of this study is to provide a means for transferring basic hydrologic characteristics to basins where hydrologic data are lacking. The model will provide the capability of estimating impacts of surface mining on hydrologic systems.

The model used is a modular design system to evaluate the impacts of various combinations of climate and land use on surface runoff, sediment yields, and basin hydrology (Leavesley and others, written commun., 1981). Each component of the hydrologic cycle is defined by one or more subroutines (modules) which are maintained in a computer-system library. All modules are compatible with each other and may be accessed as needed for specific hydrologic problem application. Other modules contained in the system library provide automatic model parameter optimization, sensitivity analysis, and model-output analysis.

Modules representing the hydrologic cycle will simulate the basin water balance, streamflow and volumes, soil-water relationships, and ground-water recharge. Additional model components needed include (1) a sediment module that will simulate sediment detachment from soils and subsequent transport and deposition by surface runoff, (2) a module that will route streamflow through the basin, and (3) a module that will simulate the transport of specific water-quality constituents.

The general structure, data requirements, and application of the watershed model are documented in reports by Weeks, Leavesley, Welder, and Saulnier, 1974, and Leavesley, Lichty, Troutman, and Saindon, 1981 (written commun., 1981). The information contained in their reports is the basis for the following summaries on model concepts, components, and data requirements.

Model Concepts

The model used in this study is designed on the concept of partitioning a basin into subunits. Partitioning attempts to account for temporal and spatial variations of basin physical and hydrologic characteristics and total system response. The basin subunits are assumed to be homogeneous with respect to their hydrologic response (figs. 20, 21, and 22). The homogeneous

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Figures 20, 21, and 22 (captions on next page) belong near here.

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subunits are defined as hydrologic response units (HRUs). The sum of the responses of all HRUs, weighted by unit area produces the system response, which in this report is daily mean streamflow.

The model attempts to reproduce the physical processes of the hydrologic system. Each component of the hydrologic cycle is expressed by physical laws or empirical relationships which have physical interpretation and measurable basin characteristics. Characteristics of the hydrologic units are summarized in table 10.

Table 10 (caption on next page) belongs near here.

Figure 20.--Hydrologic response unit subdivision in Bear Creek basin.

Figure 21.--Hydrologic response unit subdivision in Blue Creek basin.

Figure 22.--Hydrologic response unit subdivision in Yellow Creek basin.

Table 10.--Summary of characteristics of the hydrologic response units used in the model.

The watershed system is described as a series of linear or nonlinear reservoirs with outputs combined to produce the system response. The upper soil zone is a linear reservoir where storage is increased by rainfall or snow and depleted by evapotranspiration (fig. 23). Seepage to the subsurface

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Figure 23 (caption on next page) belongs near here.

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reservoir (S_1) and surface runoff (Q_1) occur only after the upper soil zone reaches field moisture capacity. Surface runoff (Q_1) occurs when rainfall exceeds the maximum infiltration rate. The subsurface reservoir, representing saturated parts of the soil zones, is the source of all subsurface flow (Q_2) that moves through the soil from the point of infiltration to some point of discharge above the water table or into the ground water reservoir (S_2). Subsurface flow moves relatively rapid to stream channels. The ground water reservoir is assumed to be a linear reservoir where input (S_2) is the source of all long-term base flow (Q_3) to streams. Movement of water through the ground water system to points beyond the area of interest is by seepage (S_3). Outputs Q_1, Q_2, and Q_3 are combined to produce the total daily streamflow (Q_4).

Figure 23.--Schematic diagram of the watershed model.

Model Components

The watershed model structure identifies those model components that attempt to reproduce the physical processes of the hydrologic cycle. Each component represents a path water can move through the physical system (fig. 24).

Figure 24 (caption on next page) belongs near here.

The model structure can be divided into three general areas of emphasis (components) with regards to the hydrologic cycle. These general areas of emphasis are climatic components, land-phase components, and snow components. The snow components are not applicable in Alabama because runoff is derived from rainfall.

The climatic components are those subroutines that accept and adjust data to better define the climate in each HRU. Variations in climate, resulting from changes in physical characteristics, vegetation cover, and time are corrected for each HRU, using adjustment factors that are functions of the HRUs median altitude, slope, aspect (compass direction of slope), and vegetation cover.

The land-phase components simulate the effects, responses, and interactions of the vegetation, soil, and geology of an HRU. This includes interception, infiltration, evapotranspiration, soil-water accounting, surface runoff, subsurface flow and ground-water flow.

Figure 24.--Flow chart of the digital watershed model.

Data Requirements

Basin descriptive data characterizes the physiography, soils, and vegetation of each HRU. The physiographic data, consisting of area, overland slope, aspect, and altitude, were obtained from topographic maps. Soils data, consisting of type, water-storage capacity, and infiltration characteristics, were obtained from the U.S. Soil Conservation Service and from field observations and measurements. Vegetation data including type, density, interception storage capacity, and transpiration characteristics were obtained from aerial photography and from field observations and measurements.

Climatic data required to drive the model consist of precipitation and pan-evaporation data. Precipitation data, recorded at five-minute intervals, were obtained from stations 2 and 7 (figs. 20 and 22). Daily pan-evaporation data were obtained from the National Weather Service for Lake Martin located approximately 100 miles southeast from the study basins. In the absence of daily pan-evaporation data, the model will accept daily solar radiation, or minimum and maximum air temperature data to compute daily potential evaporation.

Hydrologic data requirements consist mainly of streamflow records. Records for sites 1, 3, and 7 were obtained from annual water data reports for 1977-79 by the U.S. Geological Survey (1978-80). Measured streamflow records are the standard against which simulations are compared and also provide information to define ground-water storage and routing coefficients.

Model Calibration

Calibration of the watershed model was necessary to obtain optimum estimates of parameters defining hydrologic properties of watersheds. Some of these include soil moisture accretion and depletion rates, evapotranspiration losses, and subsurface-ground water storage and routing coefficients. Calibration consisted of fitting simulated discharge to measured daily mean discharge. The criteria for assessing the accuracy of simulated to measured discharge or the "goodness of model fit" was determined from (1) comparisons of annual discharge volumes, (2) comparisons of seasonal runoff distribution, hydrologic response timing, peakflows, and recession rates, and (3) comparison of annual water-balance components.

The calibration approach was based on a combination of trial and error and automatic parameter optimization. Trial and error optimization provided first approximations of specific parameters. A constraint automatic search algorithm procedure was then used to refine initial approximations. The automatic optimization procedure was developed by Rosenbrock (1960) and uses the following objective function:

$$\mathrm{MIN} \sum i \left| P_i - O_i \right|$$

where P_i and O_i are the simulated and observed daily mean streamflow on the i^{th} day. This equation is the minimization of the sums of the absolute differences between the simulated daily mean flow and the observed daily mean flow.

Hydrographs shown in figures 25, 26, and 27 illustrate results obtained

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Figures 25, 26, and 27 (captions on next page) belong near here.

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through calibration efforts. Calibration for sites 3 and 7 (figs. 26 and 27) consisted of the 1979 and 1978 water years, respectively. The simulation for site 1, shown in figure 25, is based on model parameter values obtained from topographic maps and model parameter values calibrated for use in unmined areas in Blue Creek basin. The simulation for site 1 provides a limited measure of the adequacy and transferability of estimated model parameter values from Blue Creek basin to other nearby areas of similar physiography, geology, and land use.

Although Blue Creek basin has been disturbed by surface mining, the relatively small size of the disturbed area during 1979 was not sufficient to substantially affect the overall streamflow regime and annual water balance. The impact of mining on streamflow in Blue Creek basin primarily affects low flow (less than 0.50 ft^3/s). As mining progresses in the basin, however, redefinitions of affected HRU's and recalibration of model parameters representing pre-mining and altered hydrologic processes within the HRU's will be required.

Figure 25.--Observed versus simulated daily mean streamflow at site 1 (Blue Creek near Samantha), October 1978 - September 1979.

Figure 26.--Observed versus simulated daily mean streamflow at site 3 (Blue Creek near Oakman), October 1978 - September 1979.

Figure 27.--Observed versus simulated daily mean streamflow at site 7 (Yellow Creek near Northport), October 1977 - September 1978.

A comparison of the hydrographs shown in figures 25 and 26 indicates that predicted daily mean discharges at sites 1 and 3 are in fairly good agreement with measured discharges. The simulated discharges at site 7 (fig. 27) are in good agreement with observed discharges greater than 4.0 ft^3/s. Generally, the seasonal runoff distribution, hydrologic response timing, peakflows, and baseflow recessions closely approximated observed values. The lower simulated baseflow recessions indicate that further refinement of model parameters defining soil-water relations and ground-water discharge in the basins may be required.

Annual measured and simulated discharge volumes for sites 1, 3, and 7 are summarized in table 11. The difference between the simulated and observed

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Table 11 (caption on next page) belongs near here.

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annual discharge volumes are given as both a volume error and a percentage of error in terms of the observed discharge. The annual discharge volumes and associated errors shown in table 11 similarly reflect good agreement between measured and simulated discharges.

Table 11.--Summary of measured and simulated annual discharge and associated error for the period of simulated record at sites 1, 3, and 7.

The modeling errors associated with simulated monthly mean discharges are mainly attributed to model parameters that define soil-moisture accretion and depletion rates, subsurface and ground water storage volumes, and discharge routing coefficients. Other sources of modeling errors are probably due to inadequate definition of precipitation and pan-evaporation input data. Model simulations were based on precipitation data from only one rain-gage in or adjacent to each modeled basin and pan-evaporation data from a recording site approximately 100 miles from the study basins.

On the basis of the accuracy criteria for the "goodness of model fit," and the given constraints on input data, the overall quality of the simulated streamflow in the modeled basins is considered good. The model fit appears to be of sufficient accuracy to provide definition of the basin's hydrologic processes and to permit a general examination of the hydrologic system under unmined conditions. Model estimates must be qualified as being the best initial estimates based on current assumptions, input data constraints, model imperfections, and achieved levels of accuracy. Better definition of climatic input data from additional precipitation sites in the study area in conjunction with additional refinement of specific model parameters will improve accuracy and estimating capability.

SUMMARY AND CONCLUSIONS

To meet the objectives of the investigation, hydrologic data were collected at sites in Bear, Blue, Turkey, and Yellow Creek basins and from many other discharge sites in the Warrior coal field. These data were used to describe hydrologic systems and to develop methods to estimate the effects of surface mining on the hydrology of watersheds in the Warrior coal field.

The basins studied are in two different geologic and hydrologic environments. Bear and Blue Creek basins are predominantly underlain by the Pottsville Formation, which consists mainly of alternating beds of shale, sandstone, and siltstone interbedded with conglomerate, under-clay, and coal. Turkey and Yellow Creek basins are predominantly in the outcrop of the Coker Formation which overlies the Pottsville Formation. The Coker consists of unconsolidated beds of sand, clay, and gravel.

Rocks in the Pottsville Formation are relatively impermeable; whereas those in the Coker Formation are permeable. Well yields from the Pottsville generally range from 0 to 5 gal/min and those from the Coker generally range from 5 to 100 gal/min.

Ground water in the Pottsville Formation is generally slightly acidic. Dissolved solids concentrations ranged from 50 to 360 mg/L and hardness generally exceeded 120 mg/L. Water in the Coker Formation is less mineralized and more acidic than water in the Pottsville. Dissolved solids concentrations were generally less than 20 mg/L and the hardness was generally less than 10 mg/L. With the exception of locally objectional concentrations of dissolved iron and manganese, ground water in the study area is suitable for most uses.

Streamflow distribution reflects seasonal precipitation; storm runoff is characterized by sharply concentrated peakflows of short duration that rapidly recede to low-flow conditions. Streams draining Bear and Blue Creek basins frequently go dry, whereas low flows in Turkey and Yellow Creek basins are well sustained by ground-water discharge from the Coker Formation.

Surface water in streams draining undisturbed areas is generally of suitable quality for most uses. The water is generally acidic, low in dissolved solids, and is calcium-magnesium, sodium-bicarbonate in type. Dissolved solids concentrations range from 10 to 40 mg/L and pH ranges from 4.3 to 8.2. Water in streams draining basins underlain chiefly by the Pottsville Formation is slightly more mineralized and less acidic than that in streams draining basins underlain chiefly by the Coker Formation.

Climatic, physiographic, hydrologic, and land-use data from over 50 basins in the Warrior coal field were analyzed by regression techniques to derive relations for assessing water quality in streams draining mined and unmined areas. In this approach, an equation was derived for estimating specific conductance of water in streams draining mined areas. Other equations, based on relations between specific conductance and other constituents, provide estimates of mine drainage indicators such as hardness, dissolved solids, and sulfate contents.

The impacts of mining on the hydrologic systems of basins draining mined areas were identified as increased erosion and sedimentation, baseflow augmentation, decline in ground-water levels, and degradation of water quality. Ground-water impacts such as declines in water levels and degradation of water quality were generally restricted to the vicinity of mined areas. The impact of mining on streamflow rates primarily affected the low flow regime of streams draining Pottsville areas.

The quality of water in streams draining mined basins is characterized by increases in dissolved calcium, magnesium, bicarbonate, sulfates, aluminum, iron, and maganese concentrations. At discharges of less than 1.0 ft^3/s, the specific conductance of water at the outflow site in Blue Creek basin (site 3 on fig. 6) increased from 58 umhos in November 1976 to 1550 umhos in July 1980. The pH of water fluctuated in the near neutral range (Puente and others, 1980) and generally was not lowered by the mining operations. The average annual sediment yield at sites draining mined basins exceeded those at sites draining unmined basins.

A digital watershed model was calibrated to simulate the hydrologic systems of Bear, Blue, and Yellow Creek basins under unmined conditions. Temporal and spatial variations of basin descriptive, climatic, and hydrologic characteristics were accounted for by partitioning the basins into subunits. The sum of each subunit's hydrologic response, weighted on a unit-area basis, produced the total basin system response measured as daily mean discharge.

Model calibrations, based on 1978 and 1979 water year discharge records for outflow sites in Blue and Yellow Creek basins respectively, are generally considered to be good. Calibration consisted of comparisons of simulated and observed seasonal runoff distribution, hydrologic response timing, peakflows, annual discharge volumes, and annual water-balance components.

The model, when calibrated and verified under mined and unmined conditions, can be coupled with developed water-quality relationships for streams draining mined and unmined areas. This will permit a general examination of surface-water characteristics (quantity and quality), and estimation of hydrologic impacts that will result from surface mining.

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Table 2.--Summary of surface-water data collection network.
(Site numbers correspond to those on figure 6)

Site number	Name	USGS station number	Drainage area (MI^2)	Period of record	Type data and sampling frequency 1/			
					Streamflow	Water quality	Suspended sediment	Aquatic biology
1	Bear Creek near Samantha	02463900	15.0	Oct. 1976-July 1980	C	C	D	M
2	Dry Branch near Samantha	02463890	0.72	Nov. 1976-Sept. 1978	M, F	M, F	M, F	M
3	Blue Creek near Oakman	02462600	5.32	1959-65 and Oct. 1976-July 1980	C	M, G, C 2/	M, F, D 3/	M
4	Turkey Creek near Tuscaloosa	02464145	6.13	Nov. 1976-Sept. 1978	M, F	M, F	M, F	M
5	Yellow Creek above Northport	02462980	3.64	Nov. 1976-Sept. 1978	M, F	M, F	M, F	M
6	Tributary to Yellow Creek near Northport	02462985	2.49	Nov. 1976-Sept. 1978	M, F	M, F	M, F	M
7	Yellow Creek near Northport	02462990	8.23	Oct. 1976-July 1980	C	C	D	M
8	Tributary to Yellow Creek above Watermelon Road near Tuscaloosa	02462991	1.49	Jan. 1977-July 1980	M, F	M, F	M, F	M
9	Cripple Creek east of Samantha	02464035	16.4	Aug. 1977-July 1980	M, F	M, F	M, F	M

1/ C-continuous, D- daily, M-monthly, F-flood events.
2/ Monthly and flood - Oct. 1976-Sept. 1978; continuous - Oct. 1978-July 1980.
3/ Monthly and flood - Oct. 1976-Sept. 1978; daily - Oct. 1978-July 1980.

Table 3.--Monthly and annual mean, maximum, and minimum discharge summaries for sites 1, 3, and 7 October 1976 - September 1979 (ft^3/sec - day)

Water Year		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual ft^3/sec	Annual (ft^3/sec)/mi2
								Site 1 (Bear Creek Near Samantha)							
1977	Mean	0.62	2.72	19.5	46.0	34.5	88.9	81.9	1.53	0.17	0.065	0.11	1.54	23.1	1.53
1977	Max	1.4	28	85	320	303	495	772	3.3	.50	.39	.58	5.9	772	
1977	Min	.18	.33	3.2	5.9	5.4	19	3.6	.58	.00	.00	.00	.00	.00	
1978	Mean	37.0	33.0	25.5	44.3	14.9	44.5	8.06	33.5	16.6	1.06	.46	.00	21.7	1.44
1978	Max	484	163	74	204	63	147	25	300	108	3.8	5.2	.00	484	
1978	Min	1.9	6.2	11	17	6.4	9.2	3.1	4.1	1.4	.15	.00	.00	.00	
1979	Mean	.00	.00	4.82	86.6	46.3	84.0	225	7.95	3.28	17.7	1.66	37.9	42.6	2.83
1979	Max	.00	.00	29	722	191	1,060	2,900	52	20	150	4.8	245	2,900	
1979	Min	.00	.00	.00	9.8	13	12	7.3	1.3	.36	.36	.43	1.2	.00	
								Site 3 (Blue Creek Near Oakman)							
1977	Mean	.13	.40	4.74	19.9	14.3	38.5	25.4	.41	.44	.096	.16	1.13	8.77	1.65
1977	Max	.20	2.70	26	139	150	250	263	.93	3.9	.43	.62	10	263	
1977	Min	.07	.14	.27	2.4	2.1	7.9	1.1	.20	.00	.00	.00	.00	.00	
1978	Mean	19.0	14.0	10.8	17.1	4.66	15.5	2.71	11.8	5.23	.59	.30	.068	8.55	1.61
1978	Max	262	56	31	87	23	44	10	137	27	2.3	1.1	.31	262	
1978	Min	.64	3.0	4.8	5.1	1.8	3.0	1.2	1.1	.62	.06	.00	.00	.00	
1979	Mean	.00	1.93	1.88	32.6	17.7	30.8	47.5	2.39	1.33	8.03	1.02	15.3	13.3	2.50
1979	Max	.00	4.6	11	298	126	529	616	11	7.2	67	5.8	87	616	
1979	Min	.00	.00	.16	3.6	3.0	3.6	1.6	.36	.30	.27	.30	.30	.00	
								Site 7 (Yellow Creek Near Northport)							
1977	Mean	8.08	8.47	13.3	18.4	14.0	31.4	39.9	10.1	6.85	8.14	6.04	14.4	14.9	1.81
1977	Max	25	18	37	75	52	157	342	15	11	25	15	82	342	
1977	Min	6.1	6.8	7.2	8.8	8.2	14	12	7.5	5.6	4.6	4.4	4.4	4.4	
1978	Mean	21.4	18.1	13.9	18.4	14.2	19.2	11.1	21.1	12.9	6.16	6.79	4.61	14.0	1.70
1978	Max	209	35	23	56	31	45	26	114	70	24	21	11	209	
1978	Min	7.2	11	11	11	11	11	8.3	8.5	5.4	4.3	4.0	3.6	3.6	
1979	Mean	3.85	5.18	11.0	32.1	22.4	35.9	64.6	16.7	9.74	10.6	7.43	12.6	19.3	2.35
1979	Max	5.6	16	53	189	63	267	625	28	18	27	22	42	625	
1979	Min	3.2	3.5	5.0	12	12	13	18	11	7.3	6.7	4.6	4.8	3.2	

Table 5.--Summary of selected chemical and physical properties of water in wells in the Coker Formation

(Analyses in milligrams per liter unless otherwise noted)

Property	Number Analyses	Mean	Range
Specific Conductance (micromhos at 25°C)	12	22	14-45
Temperature (C°)	10	17.5	5-24.0
pH (units)	12	1/5.3	4.4-5.7
Color (units)2/	8	6	0-15
Hardness as $CaCO_3$	12	4	2-10
Noncarbonate Hardness	12	1	0-4
Total Acidity as H+	7	0	0
Total Acidity as $CaCO_3$	8	0	0
Calcium (Ca)	11	1.4	.3-3.6
Magnesium (Mg)	11	.4	.2-1.0
Sodium (Na)	11	1.0	.6-1.7
Percent Sodium (%)	10	31	14-45
Sodium adsorption ratio (SAR)	10	.2	.1-.3
Potassium (K)	11	1.0	.2-5.0
Bicarbonate (HCO_3)	11	6	0-15
Carbon Dioxide (CO_2)	6	50	0-121
Carbonate (CO_3)	11	0	0
Sulfate (SO_4)	10	.80	0-4.2
Chloride (Cl)	12	2.0	.4-6.6
Fluoride (F)	12	0	0-.1
Silica (SiO_2)	11	7.2	6.0-9.6
Dissolved Solids (calc.)	--	<20	<20
Total Nitrate (N)	11	.16	0-.54
Total Nitrate (NO_3)	5	.90	.18-1.9
Total Nitrite (N)	8	.00	.00-.01
Total Organic Nitrogen (N)	3	.07	.00-.20
Total Kjeldahl Nitrogen	3	.13	.10-.20
Phosphate (PO_4)	1	.03	.03
Phosphorus (P)	8	.00	.00-.10
Arsenic (A) (ug/L)	11	0	0-1
Boron (B) (ug/L)	1	0	0
Cadmium (Cd) (ug/L)	11	1	0-4
Chromium (Cr) (ug/L)	10	<10	<10
Cobalt (Co) (ug/L)	11	1	0-3
Copper (Cu) (ug/L)	11	50	1-170
Iron (Fe) (ug/L)	12	250	10-1,500
Lead (Pb) (ug/L)	11	9	0-39
Lithium (Li) (ug/L)	11	1	0-5
Manganese (Mn) (ug/L)	11	20	0-80
Mercury (Hg) (ug/L)	11	.5	0-.6
Selenium (Se) (ug/L)	10	0	0
Strontium (Sr) (ug/L)	11	20	0-40
Zinc (Zn) (ug/L)	11	130	10-1,100

1/ Median Value
2/ Platinum - Cobalt

Table 6.--Summary of selected chemical and physical properties of water in wells in the Pottsville Formation

(Analyses in milligrams per liter unless otherwise noted)

Property	Number Analyses	Mean	Range
Specific Conductance (micromhos at 25°C)	37	287	59-555
Temperature (C°)	34	18.2	16.0-22
pH (units)	38	[1]6.9	5.6-8.0
Color (units)[2]	27	17	5-100
Hardness as $CaCO_3$	34	117	19-220
Noncarbonate Hardness	37	5	0-59
Total Acidity as H+	18	0	0
Total Acidity as $CaCO_3$	26	0	0
Calcium (Ca)	37	26.8	2.5-46
Magnesium (Mg)	37	11.6	2.8-26
Sodium (Na)	37	16.5	2.7-63
Percent Sodium (%)	37	25	8-63
Sodium adsorption ratio (SAR)	37	.7	.2-2.8
Potassium (K)	37	2.6	.6-7.0
Bicarbonate (HCO_3)	37	159	4-280
Carbon Dioxide (CO_2)	30	54	3.1-217
Carbonate (CO_3)	37	0	0
Sulfate (SO_4)	34	12	.2-59
Chloride (Cl)	33	3.4	.8-14
Fluoride (F)	32	.1	.0-.3
Silica (SiO_2)	31	20	.1-34
Dissolved Solids (calc.)	21	175	50-360
Total Nitrate (N)	23	.25	.01-2.4
Total Nitrate (NO_3)	18	1.7	.00-5.0
Total Nitrite (N)	15	.00	.00
Total Organic Nitrogen (N)	19	.33	.00-1.1
Total Kjeldahl Nitrogen	21	.42	.00-1.3
Phosphate (PO_4)	5	1.2	.09-2.9
Phosphorus (P)	27	.23	.00-.96
Arsenic (A) (ug/L)	28	1	0-4
Boron (B) (ug/L)	5	0	0
Cadmium (Cd) (ug/L)	37	1	0-5
Chromium (Cr) (ug/L)	30	3	0-10
Cobalt (Co) (ug/L)	36	1	0-9
Copper (Cu) (ug/L)	32	3	0-17
Iron (Fe) (ug/L)	34	762	0-11,000
Lead (Pb) (ug/L)	37	3	0-65
Lithium (Li) (ug/L)	37	16	0-40
Manganese (Mn) (ug/L)	37	139	0-1,100
Mercury (Hg) (ug/L)	35	.4	.0-.6
Selenium (Se) (ug/L)	27	.1	0-2
Strontium (Sr) (ug/L)	35	278	0-1,000
Zinc (Zn) (ug/L)	37	84	0-370

1/ Median Value
2/ Platinum - Cobalt

Table 7.--Summary of annual suspended-sediment discharge and sediment yields for selected sites, October 1976 - September 1979.
[locations of sites in fig. 16]

Site no.	Drainage area (mi^2)	Suspended sediment concentration range (mg/L)	1977		1978		1979		Mean annual sediment yield (t/mi^2)
			Annual sediment discharge (t)	Annual sediment yield (t/mi^2)	Annual sediment discharge (t)	Annual sediment yield (t/mi^2)	Annual sediment discharge (t)	Annual sediment yield (t/mi^2)	
1	15.0	1-2,500	4,430	294	1,980	131	27,100	1,800	742
3	5.32	1-5,400	3,510	660	1,330	250	9,580	1,800	903
7	8.23	1-1,600	886	109	436	54	3,200	390	184
8	1.49	1-3,010	1,480	990	640	430	5,960	4,000	1,807
9	16.4	2-2,840	20,500	1,250	6,230	380	49,200	3,000	1,540

Table 8.--Regression equations, correlation coefficients, and standard errors of estimate of water-quality relations for streams in the Warrior coal field.

Equation number	Equation	R[1/]	S.E.[2/]	Dependent variable	Independent variable	N[6/]
				STREAMS DRAINING MINED AREAS		
1	$Ca = 0.03 (Sp. Cond.^{1.15})$	.97	26	Calcium, in mg/L	Specific Conductance [4/]	109
2	$Mg = 0.02 (Sp. Cond.^{1.14})$	.98	19	Magnesium, in mg/L	Specific Conductance	109
3	$Na = 0.14 (Sp. Cond.^{0.66})$	.78	56	Sodium, in mg/L	Specific Conductance	80
4	$K = 0.20 (Sp. Cond.^{0.43})$	.66	51	Potassium, in mg/L	Specific Conductance	80
5	$HD = 0.20 (Sp. Cond.^{1.12})$	.99	16	Total hardness, in mg/L	Specific Conductance	75
6	$NCH = 0.08 (Sp. Cond.^{1.24})$	.98	17	Noncarbonate hardness, in mg/L	Specific Conductance	52
7	$SO^4 = 0.10 (Sp. Cond.^{1.23})$	.99	17	Sulfate, in mg/L	Specific Conductance	94
8	$DS = 0.57 (Sp. Cond.^{1.02})$	.99	11	Dissolved solids, in mg/L	Specific Conductance	55
9	$FE = 97.10 (SS^{0.73})$	.93	74	Total iron, in ug/L [3/]	Suspended-sediment[5/]	18
10	$Mn = 29.00 (SS^{0.47})$	.87	70	Total manganese, in ug/L[3/]	Suspended-sediment	15
				STREAMS DRAINING UNMINED AREAS		
11	$Ca = 0.04 (Sp. Cond.^{1.10})$	.89	46	Calcium, in mg/L	Specific Conductance[4/]	136
12	$Mg = 0.02 (Sp. Cond.^{1.15})$	.93	37	Magnesium, in mg/L	Specific Conductance	135
13	$Na = 0.028 (Sp. Cond.^{0.55})$	.79	28	Sodium, in mg/L	Specific Conductance	105
14	$K = 0.05 (Sp. Cond.^{0.79})$	.81	37	Potassium, in mg/L	Specific Conductance	105
15	$HD = 0.19 (Sp. Cond.^{1.11})$	.93	37	Total hardness, in mg/L	Specific Conductance	138
16	$NCH = 0.13 (Sp. Cond.^{0.89})$	.81	64	Noncarbonate hardness, in mg/L	Specific Conductance	71
17	$SO^4 = 0.19 (Sp. Cond.^{0.92})$	.86	45	Sulfate, in mg/L	Specific Conductance	136
18	$DS = 0.83 (Sp. Cond.^{0.94})$	.96	24	Dissolved solids, in mg/L	Specific Conductance	29
19	$FE = 99.34 (SS^{0.64})$	.82	58	Total iron, in ug/L[3/]	Suspended-sediment[5/]	39
20	$Mn = 7.06 (SS^{0.52})$	.80	46	Total manganese, in ug/L[3/]	Suspended-sediment	37

1/ R - Correlation coefficient
2/ S.E. - Standard error expressed as percent of mean of dependent variable
3/ Total recoverable concentration in a water-suspended sediment solution
4/ Specific conductance in micromhos per centimeter at 25°C
5/ Suspended-sediment concentration in mg/L
6/ Number of data observations

Table 9.--Estimated water quality parameters in a hypothetical stream draining a mined area

Mining progression (years)	Given				Estimated			
	Q/D.A. $(ft^3/s)mi^2$	PBM (percent)	CL (mi)	MAF (unit)	Specific[1/] conductance (umhos)	Hardness[2/] (mg/L)	Sulfate[3/] (mg/L)	Dissolved[4/] dissolved (mg/L)
0	0.33	0	0.5	--	50[5/]	16[5/]	7[5/]	32[5/]
2	.33	10	.5	3	240	93	85	150
5	.33	26	.5	15	770	340	360	500
10	.33	26	.5	19	860	390	410	560
15	.33	26	.5	3	360	150	140	230

1/ Estimated from equation (A).
2/ From equation 5 in table 8.
3/ From equation 7 in table 8.
4/ From equation 8 in table 8.
5/ Estimated specific conductance based on data for streams draining undisturbed areas; hardness, sulfate, and dissolved solids concentrations estimated from equations 15, 17, and 18 in table 8, respectively.

Table 10.--Summary of characteristics of the hydrologic response units used in the model.

HRU Number	Area (acres)	Aspect (compass direction)	Slope (percent)	Median altitude (NGVD, 1929)[1/]	Vegetation[2/]	Available soil-water capacity (inches)
			BEAR CREEK BASIN			
1	487	E	12	387	FOREST	6.0
2	1294	S	9	416	FOREST	6.0
3	1315	S	15	483	FOREST	6.0
4	600	NW	14	483	FOREST	6.0
5	401	E	14	491	FOREST	6.0
6	1075	W	13	509	FOREST	6.0
7	591	SW	16	491	FOREST	6.0
8	1012	NE	18	475	FOREST	6.0
9	567	N	13	448	FOREST	6.0
10	421	NW	11	417	FOREST	6.0
11	295	N	19	400	FOREST	6.0
12	626	SW	19	463	FOREST	6.0
13	798	SW	12	394	FOREST	6.0
			BLUE CREEK BASIN			
1	557	SE	8	486	FOREST	6.0
2	512	SE	6	490	FOREST	6.0
3	352	E	13	547	FOREST	6.0
4	608	W	9	545	FOREST	6.0
5	166	SE	14	535	FOREST	6.0
6	550	NW	10	545	FOREST	6.0
7	659	W	10	486	FOREST	6.0
			YELLOW CREEK BASIN			
1	1235	SE	6	540	FOREST	6.0
2	678	NW	9	520	FOREST	6.0
3	774	SE	7	510	PINE	6.0
4	1338	NW	9	495	PINE	6.0
5	640	E	9	457	FOREST	6.0
6	275	SW	6	492	PINE	6.0
7	294	E	12	472	PINE	6.0

1/ National Geodetic Vertical Datum of 1929
2/ Forest - Mixed Deciduous Hardwoods and Pines

Table 11.--Summary of observed and simulated annual discharge and associated error for the period of simulated record at sites 1, 3, and 7.

Water year	Observed discharge [(ft^3/s)-days]	Simulated discharge [(ft^3/s)-days]	Error [(ft^3/s)-days]	Percent error
		Bear Creek near Samantha (Site 1)		
1978[1/]	4,993.40	4,948.78	-44.62	-1
1979	15,558.80	14,228.90	-1,329.90	-9
		Blue Creek near Oakman (Site 3)		
1978[1/]	1,775.00	1,707.03	-68.17	-4
1979	4,854.50	5,109.70	+225.20	+5
		Yellow Creek near Northport (Site 7)		
1977	5,444.70	5,279.60	-165.10	-3
1978	5,110.60	4,584.80	-525.80	-10
1979	7,033.20	7,068.20	+35.00	+<1

1/ January 1978 - September 1978.

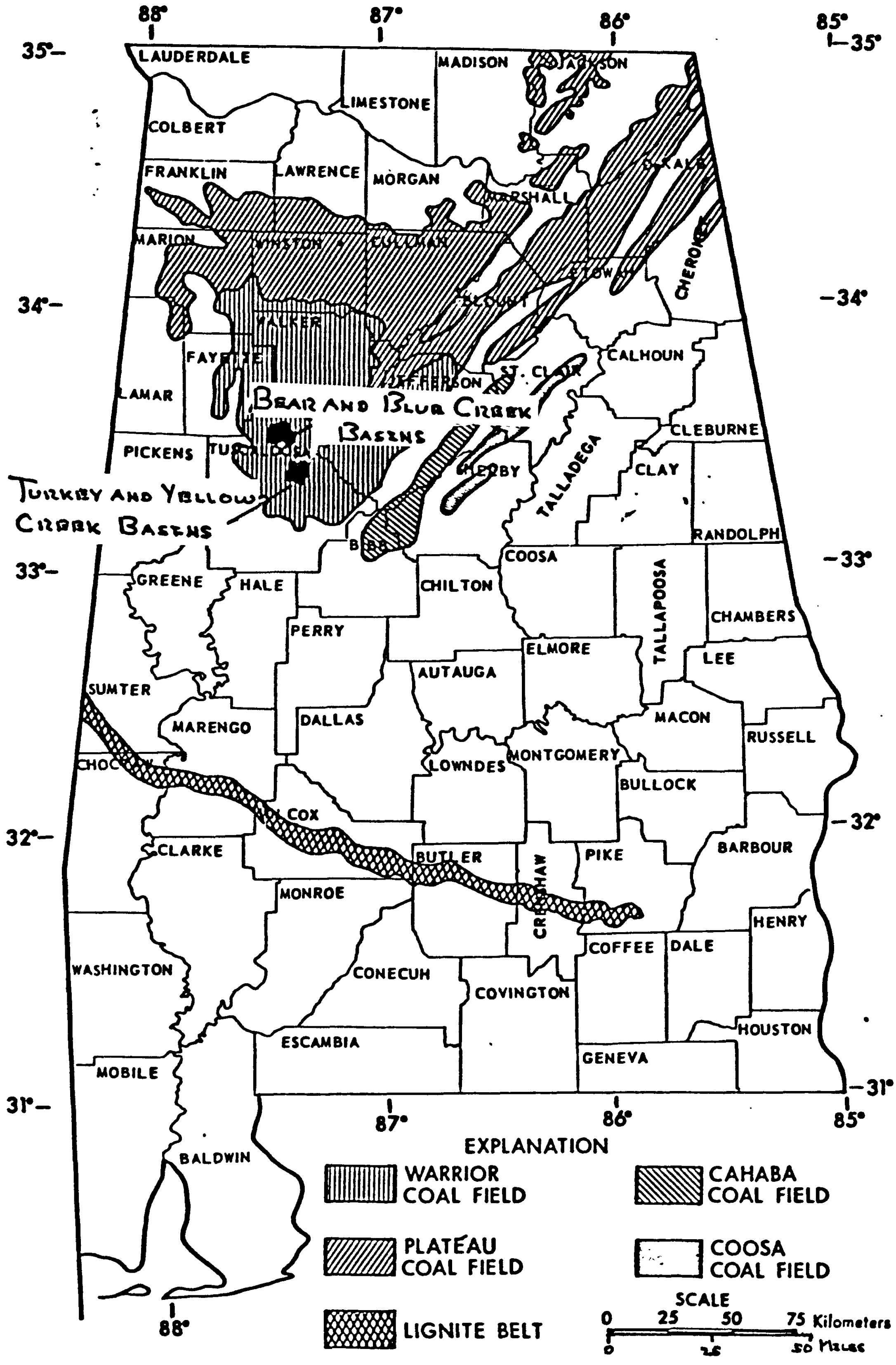


Figure 1.--Areas of study and principal coal fields in Alabama (modified from Ward and Evans, 1975).

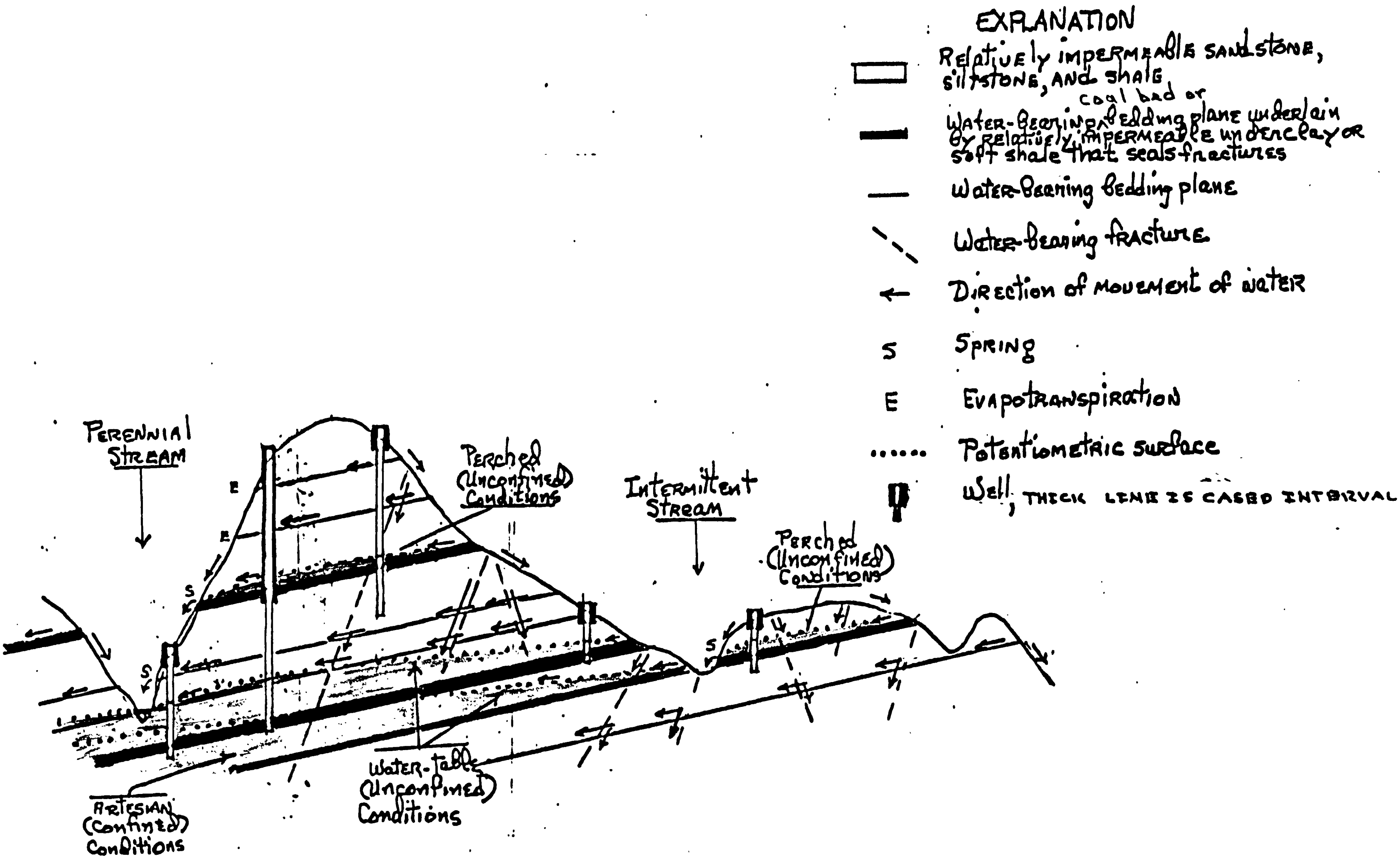


Figure 4. Schematic diagram showing occurrence and movement of water in the Pottsville Formation.

Modified from Puente and Newton (1981)

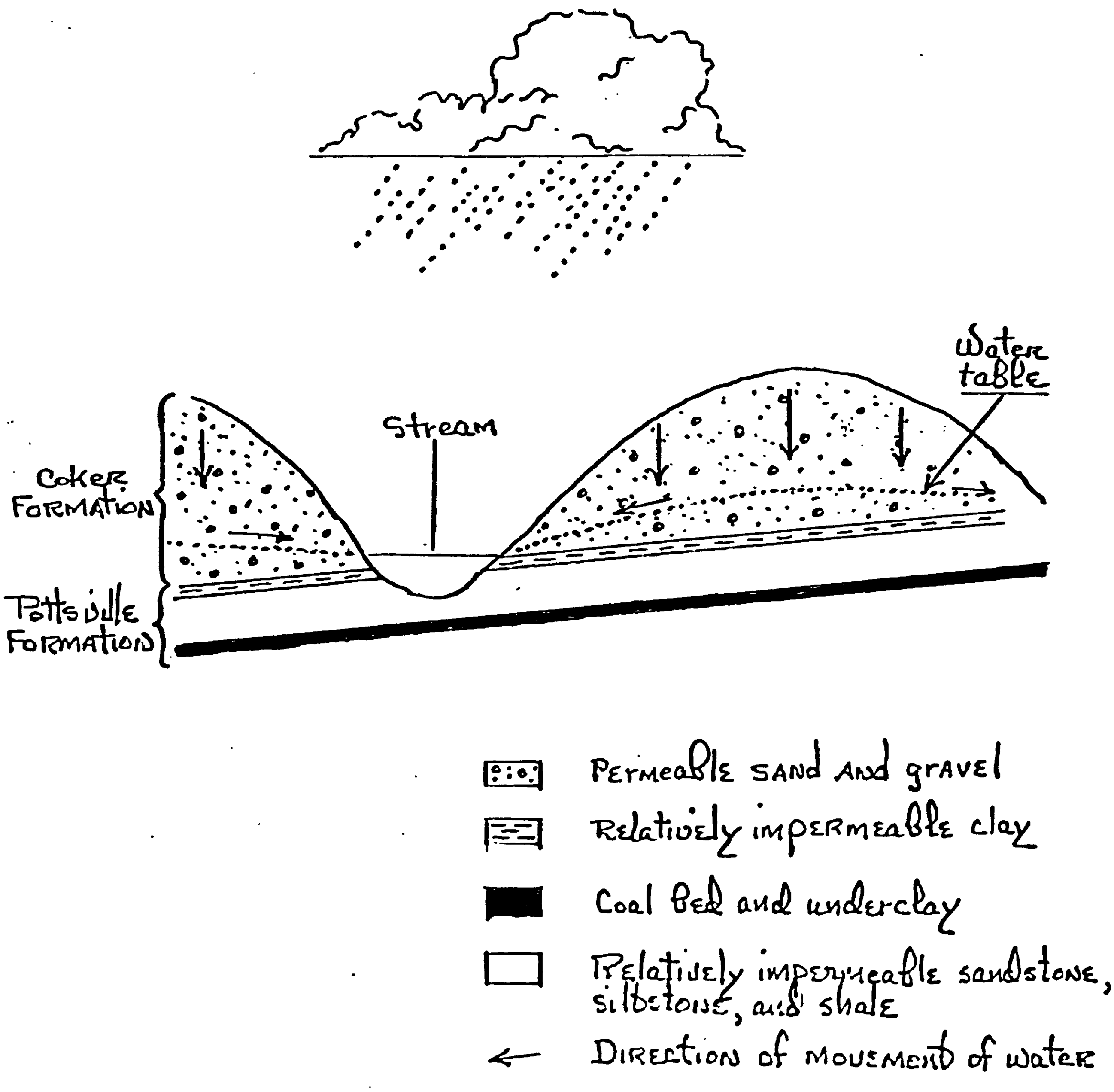


Figure 5.--Schematic diagram showing occurrence and movement of water in the Coker Formation.

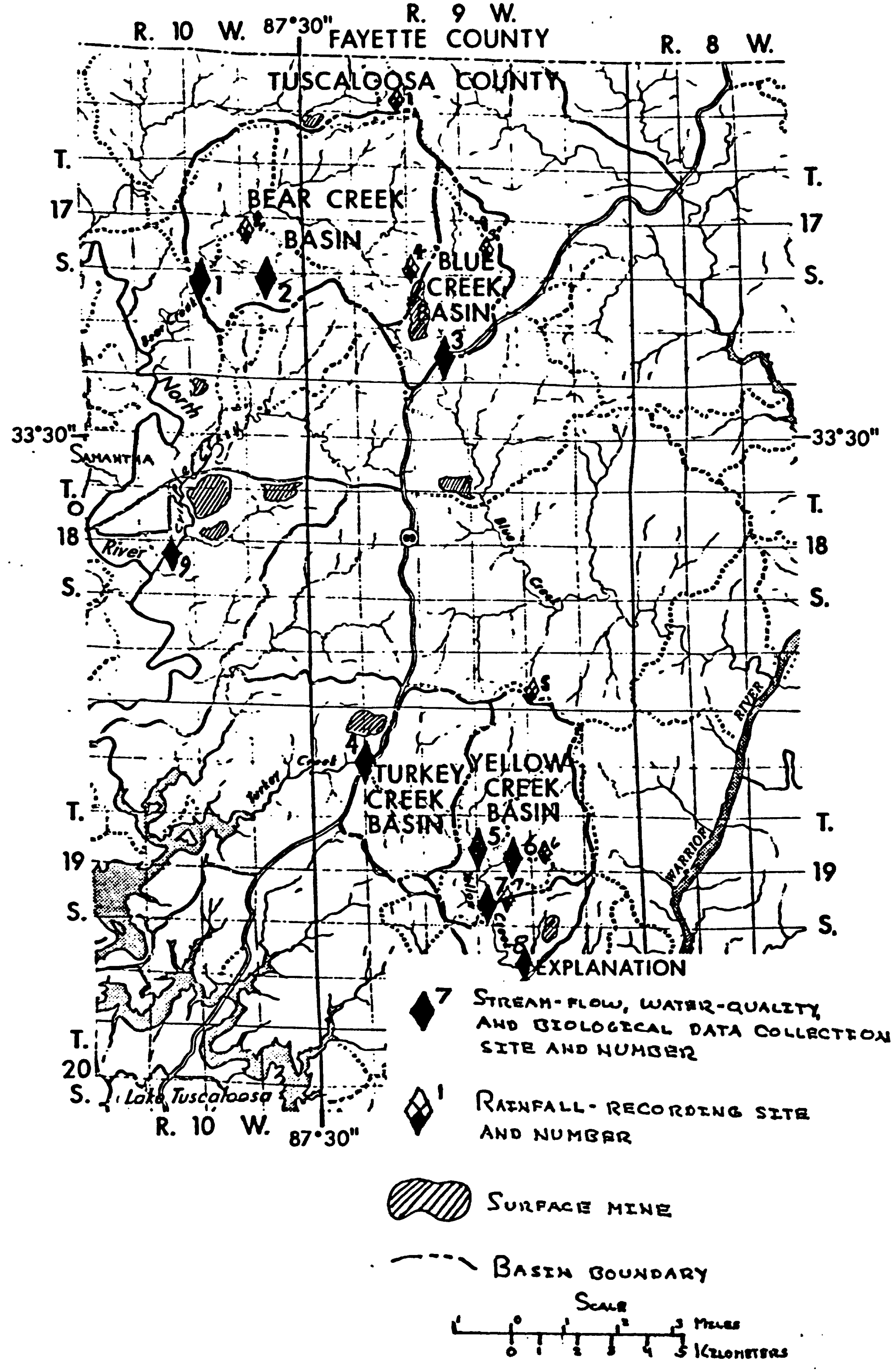


Figure 6.-- Locations of surface-water data-collection sites.

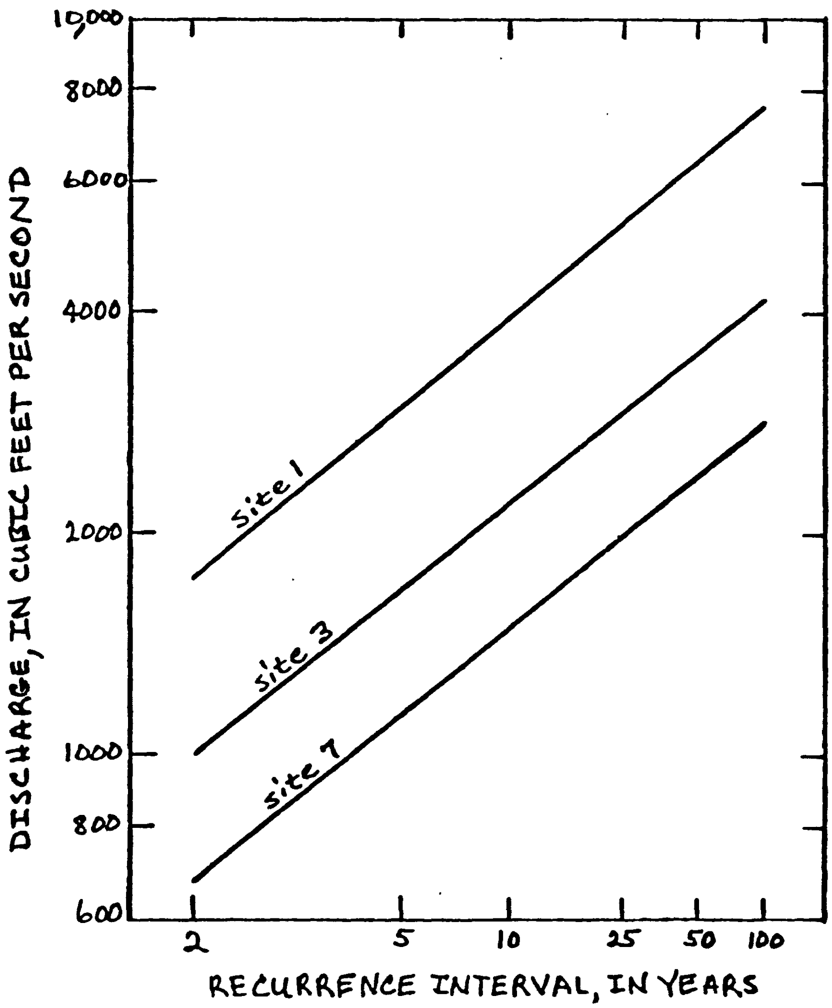
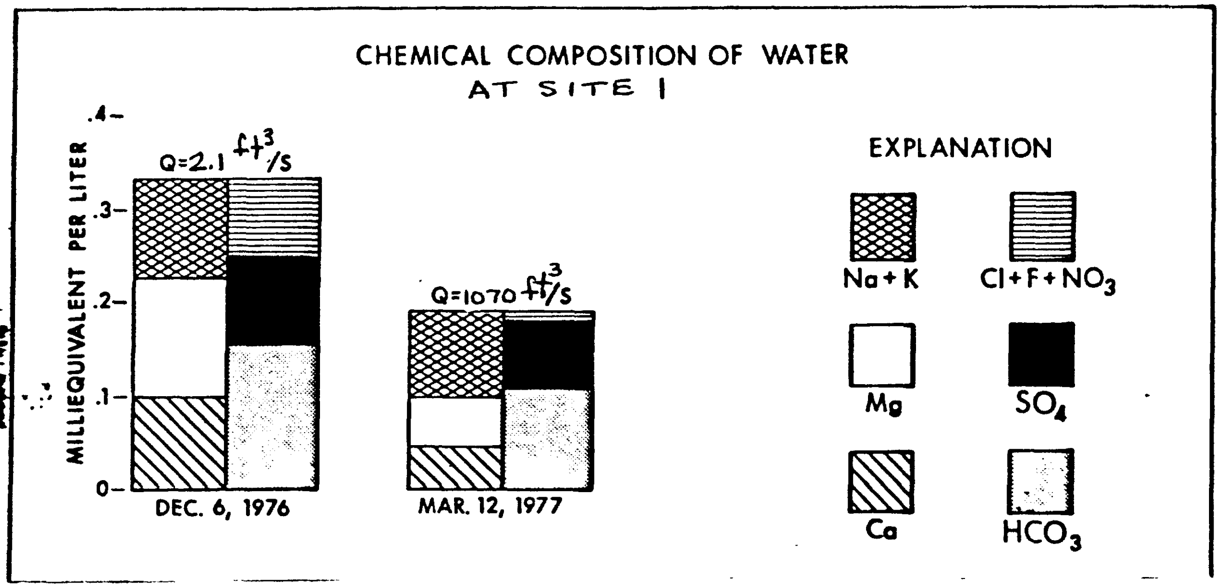


FIGURE 8.--Estimated magnitude and frequency of flood discharges at sites 1 (Bear Creek near Samantha), 3 (Blue Creek near Oakman), and 7 (Yellow Creek near Northport).



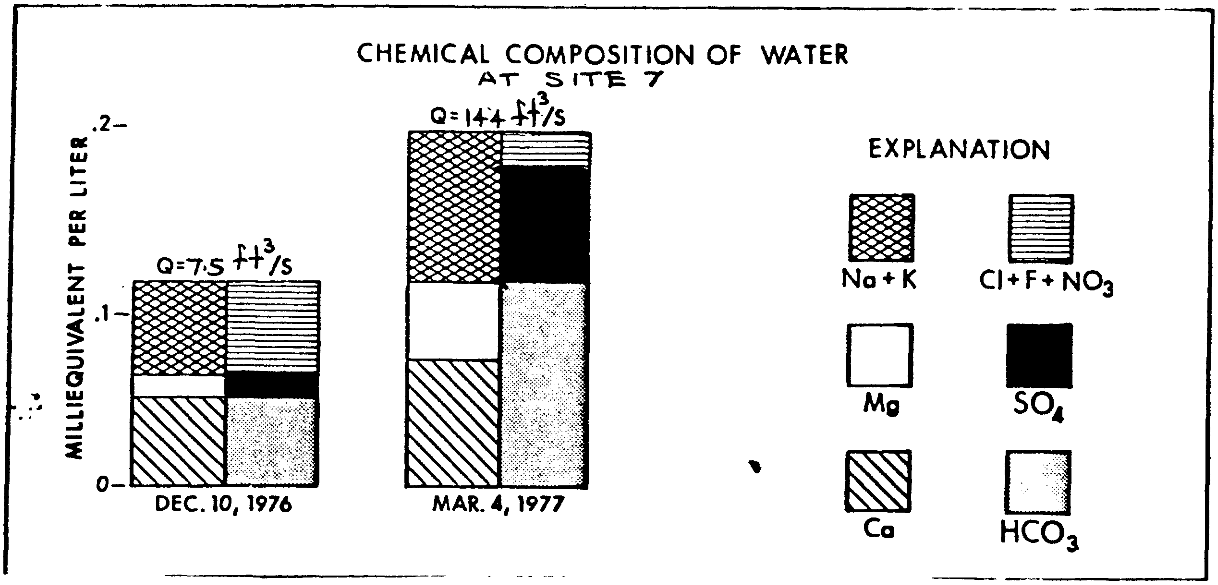


Figure 9.--Chemical composition of stream discharge (Q) at sites 1 (Bear Creek near Samantha), and 7 (Yellow Creek near Northport).

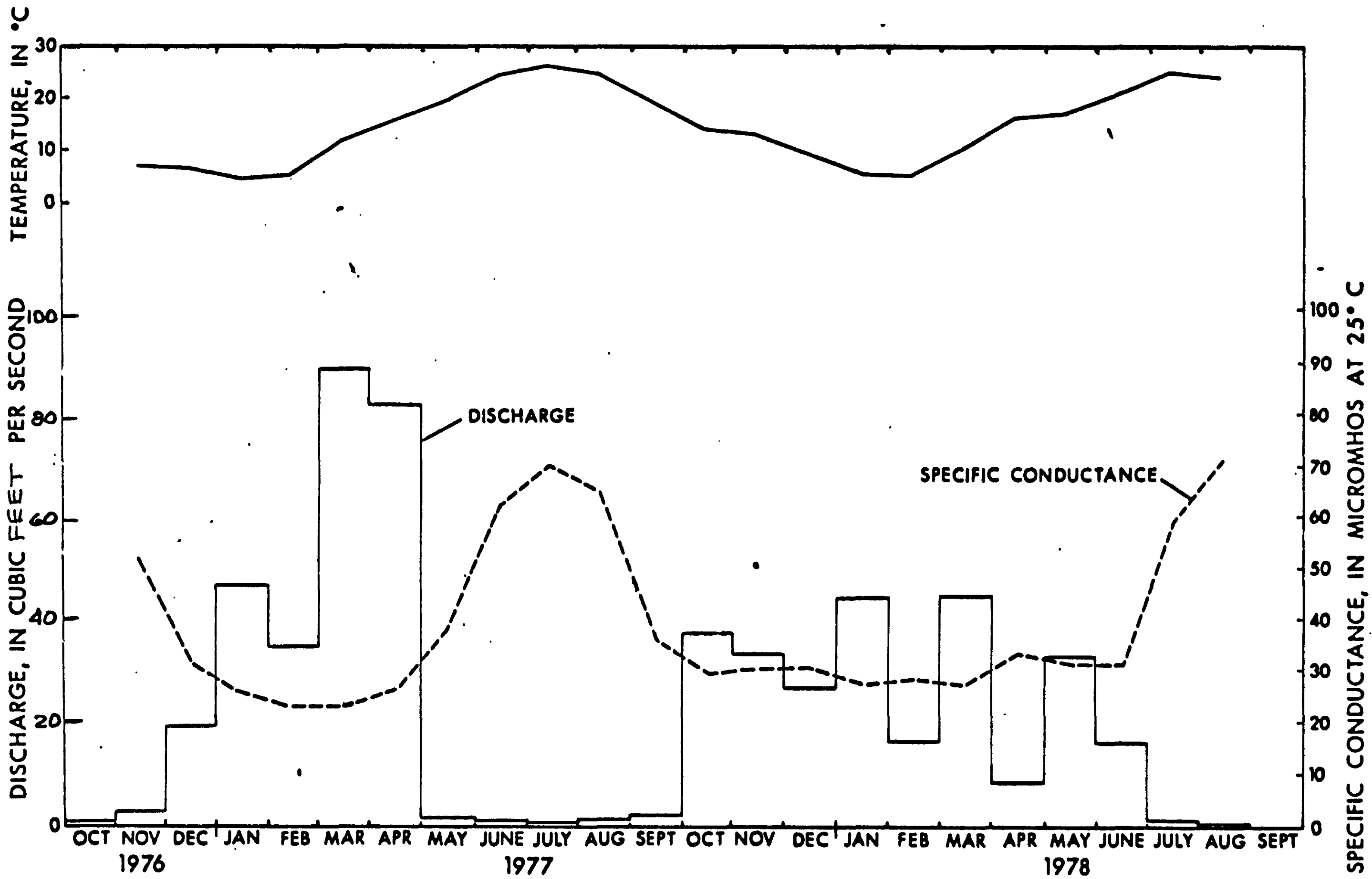


FIGURE 10.-- VARIATIONS IN MONTHLY MEAN DISCHARGE, SPECIFIC CONDUCTANCE, AND WATER TEMPERATURE AT SITE 1 (BEAR CREEK NEAR SAMANTHA).

Modified from Puente, Newton, and Hill, 1980.

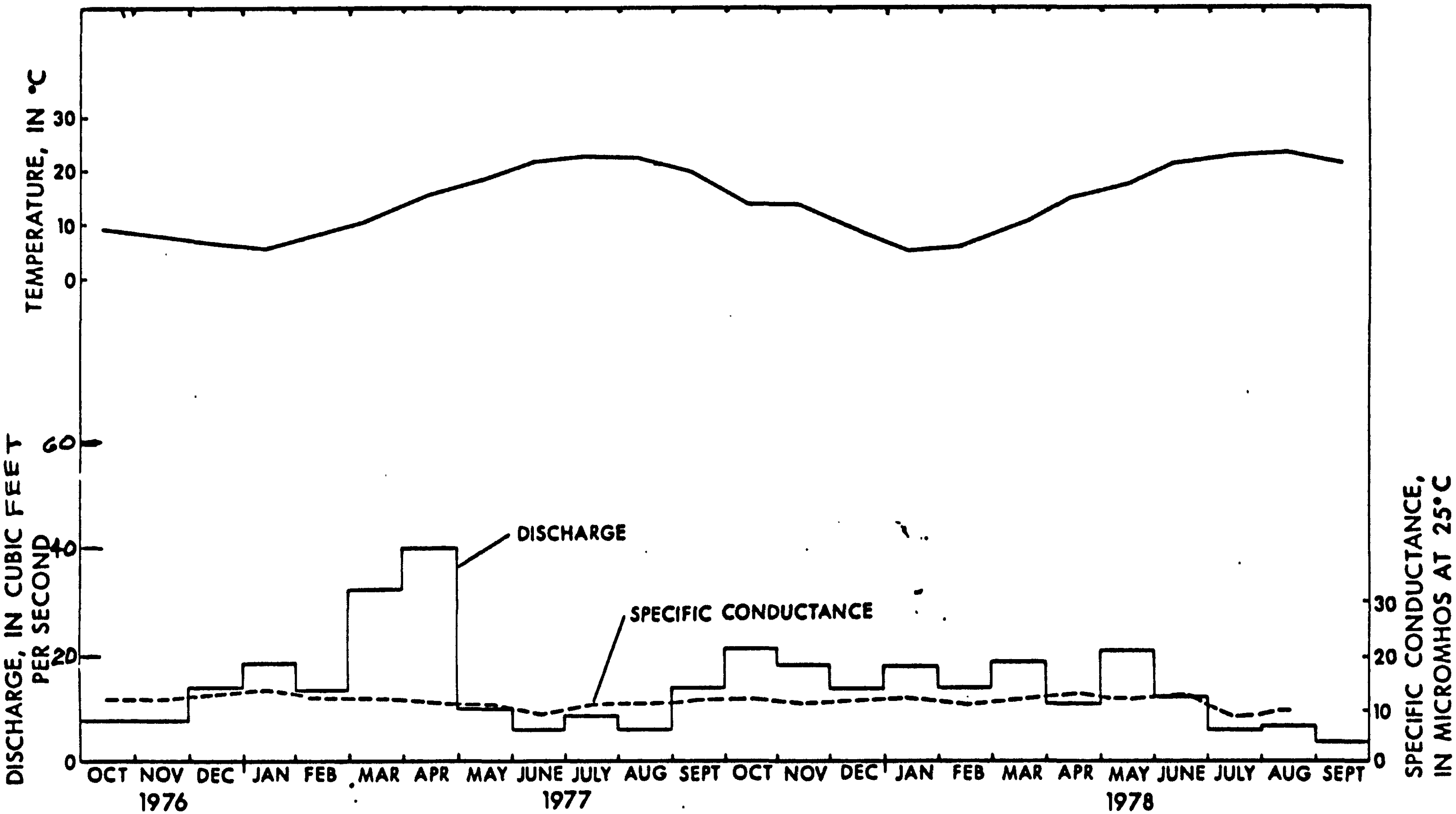


FIGURE 11.-- VARIATIONS IN MONTHLY MEAN DISCHARGE, SPECIFIC CONDUCTANCE, AND WATER TEMPERATURE AT SITE 7 (YELLOW CREEK NEAR NORTHPORT).

Modified from Puente, Newton, and Hill, 1980.

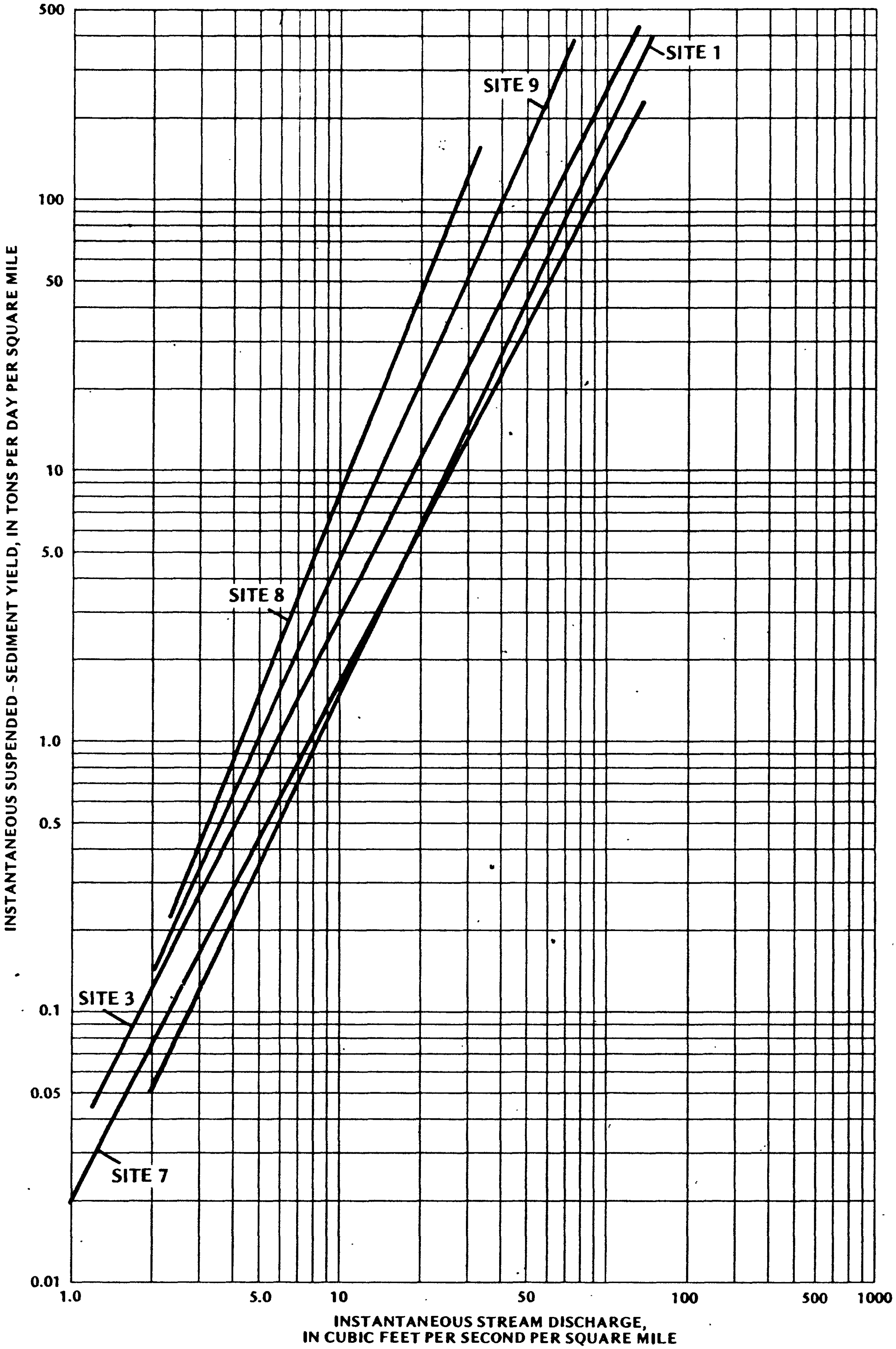


Figure 12. Relation between sediment yield and unit stream discharge for selected sites (locations of sites shown in figure 6).

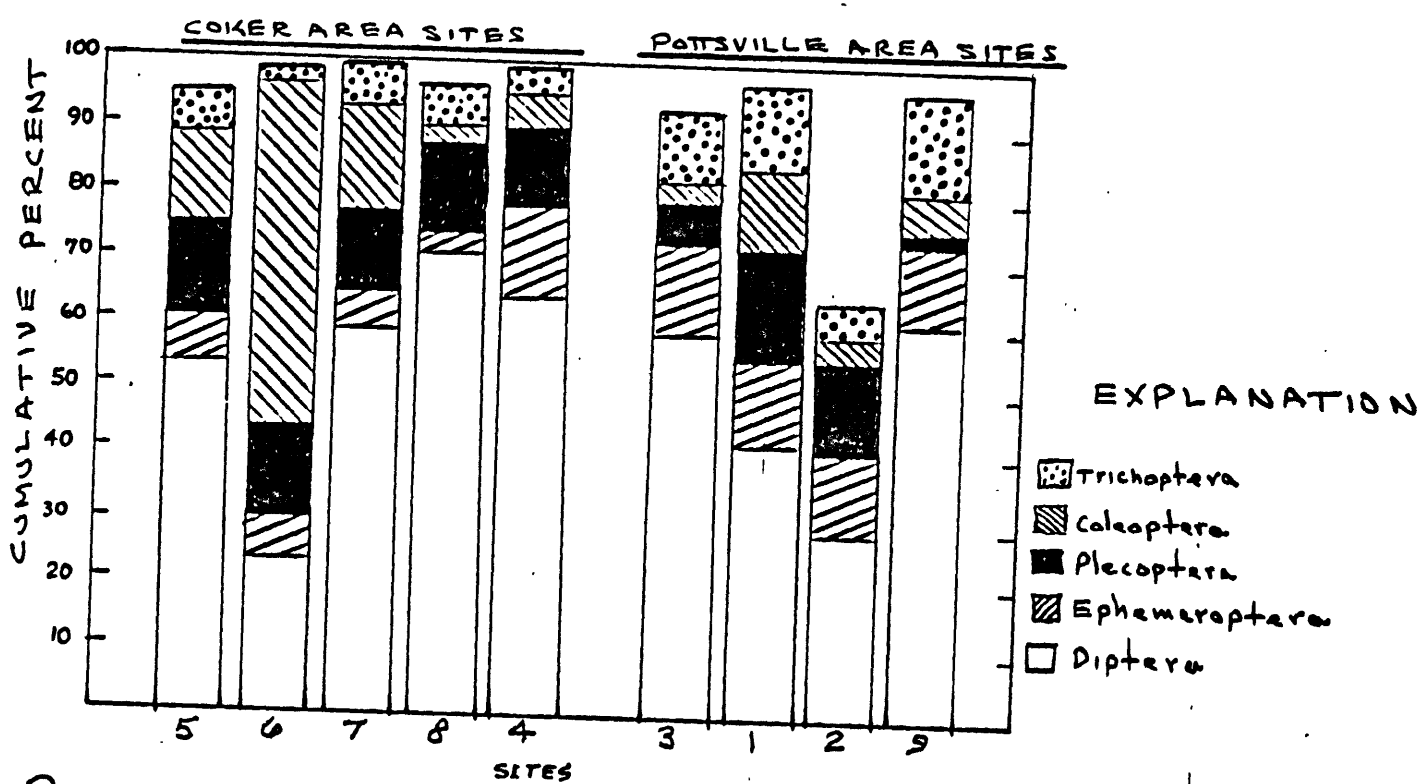


FIGURE 13.-- CUMULATIVE PERCENTAGES OF MAJOR INSECT ORDERS COLLECTED AT SITES 1-9, JANUARY 1977 - JUNE 1979.

MODIFIED FROM HILL (WRITTEN COMMUN. 1981)

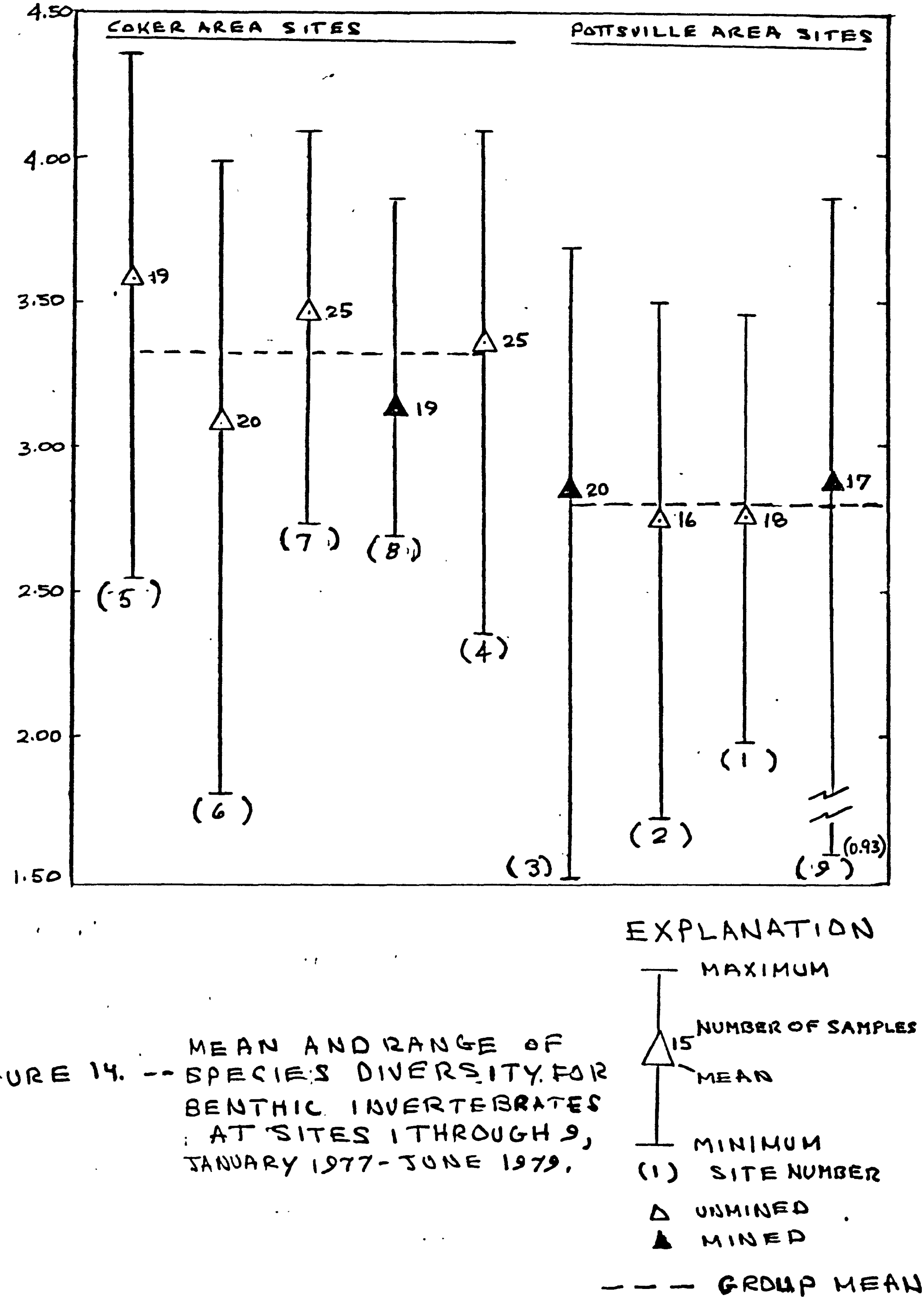


FIGURE 14. -- MEAN AND RANGE OF SPECIES DIVERSITY FOR BENTHIC INVERTEBRATES AT SITES 1 THROUGH 9, JANUARY 1977 - JUNE 1979.

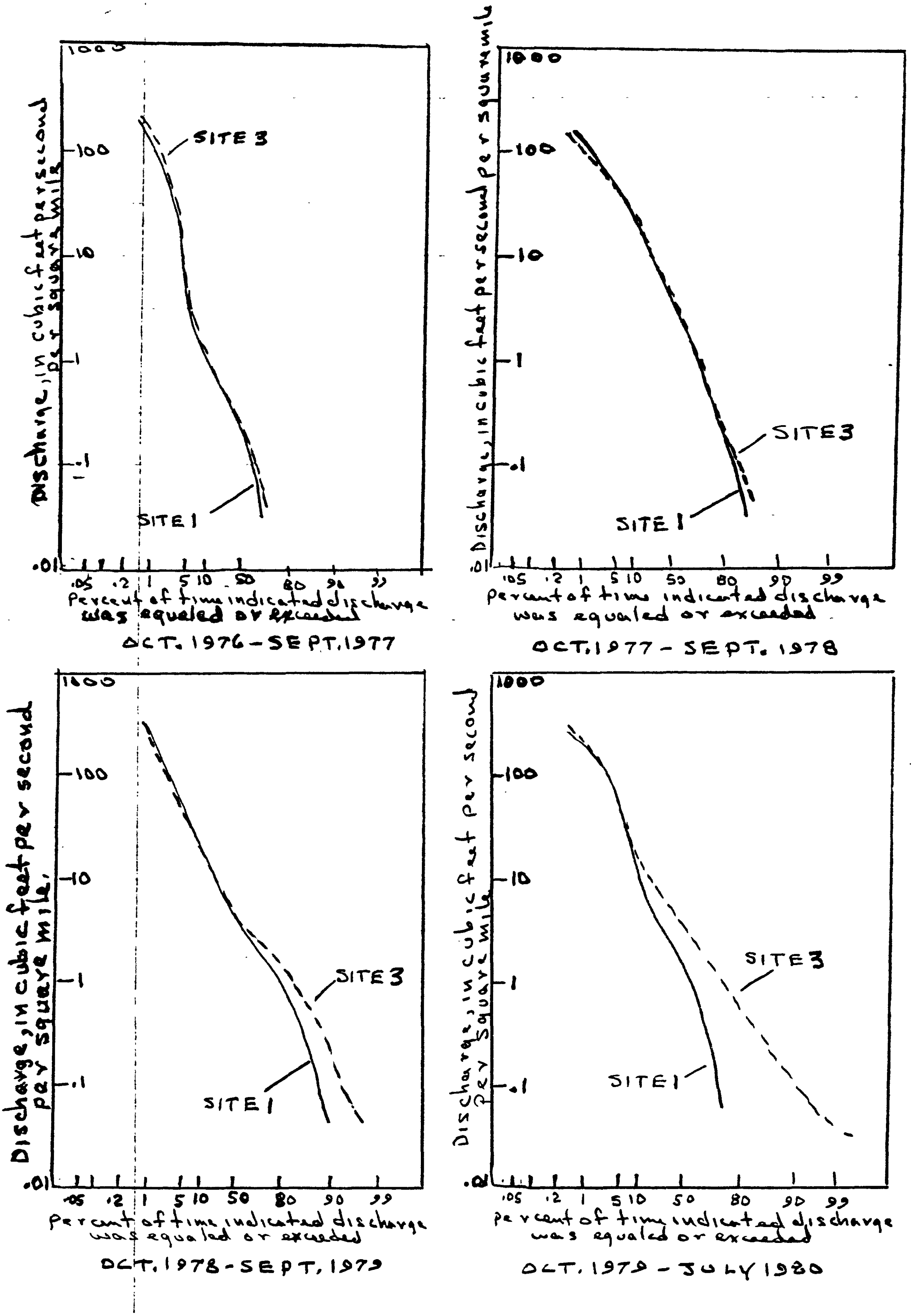


Figure 19.--Annual flow-duration curves for sites 1 (Bear Creek near Samantha), and 3 (Blue Creek near Oakman).

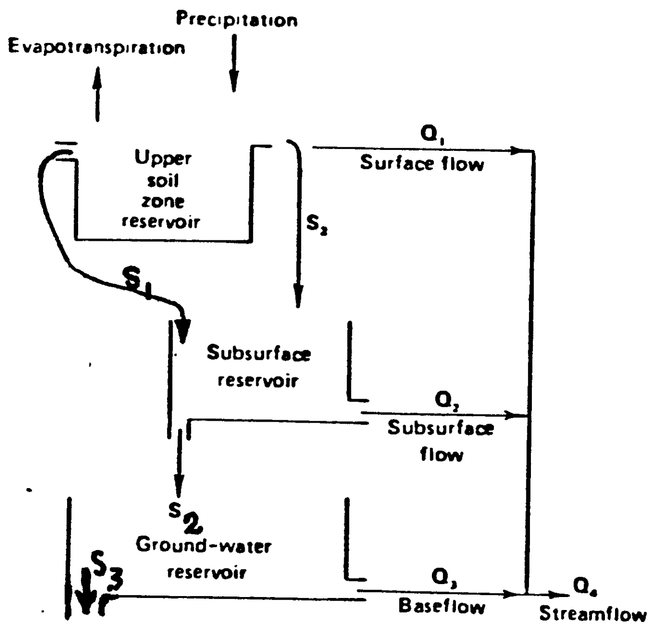


FIGURE 23.-- SCHEMATIC DIAGRAM OF THE WATERSHED MODEL.
MODIFIED FROM LEAVESLEY AND OTHERS, WRITTEN COMMUNICATION, 1981.

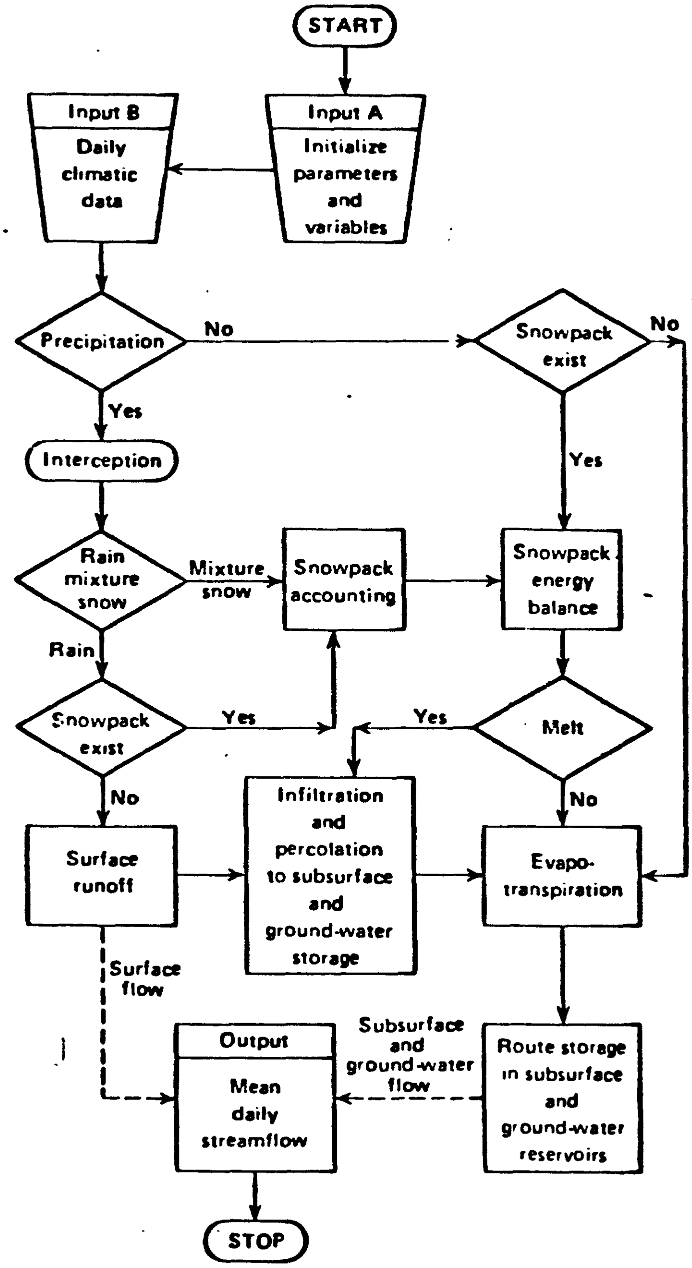


FIGURE 24.-- FLOW CHART OF THE DIGITAL WATERSHED MODEL.
FROM WEEKS AND OTHERS, 1974.

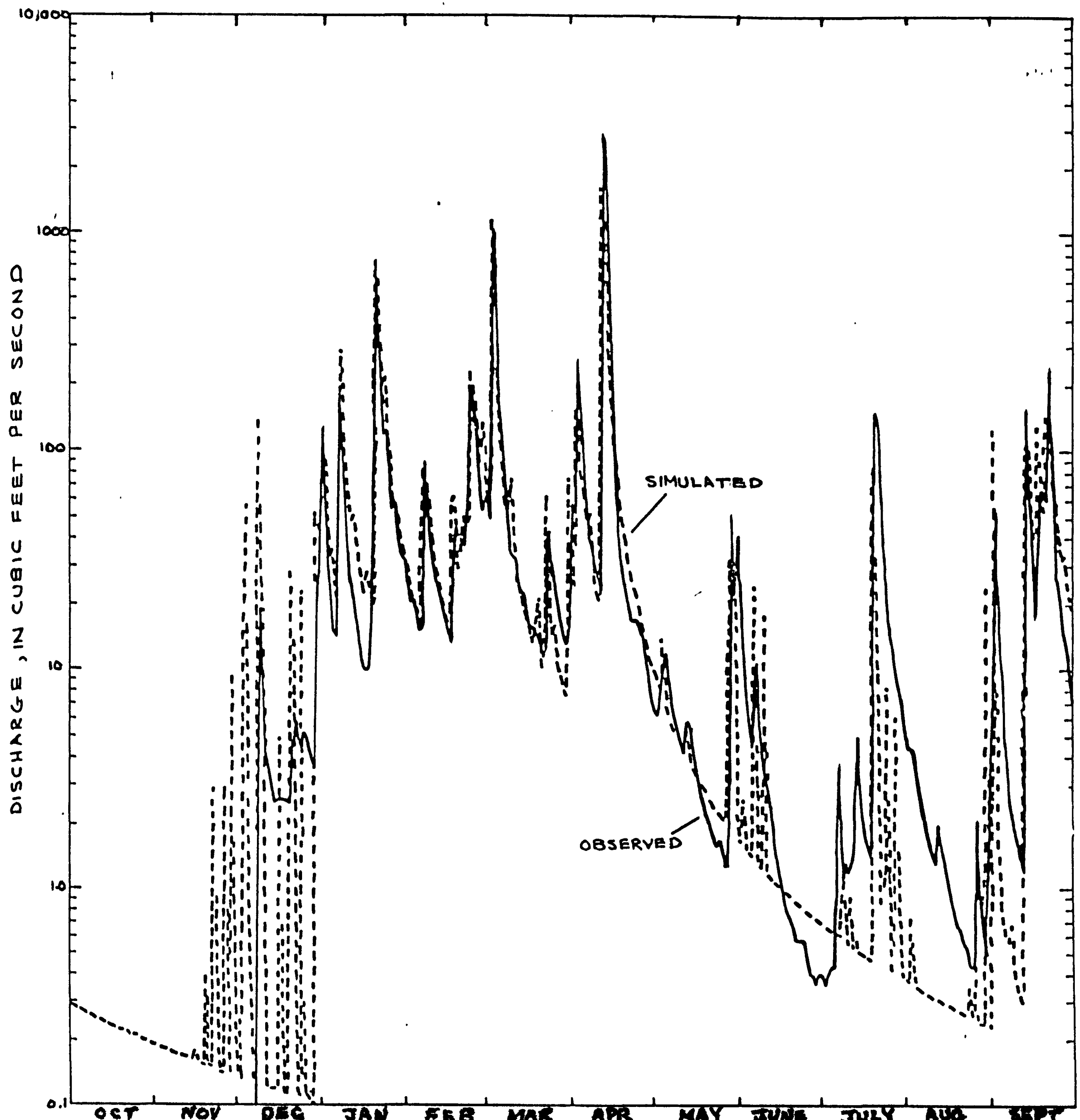


Figure 25.-- Observed versus simulated daily mean streamflow at site 1 (Bear Creek near Samantha), October 1978- September 1979.

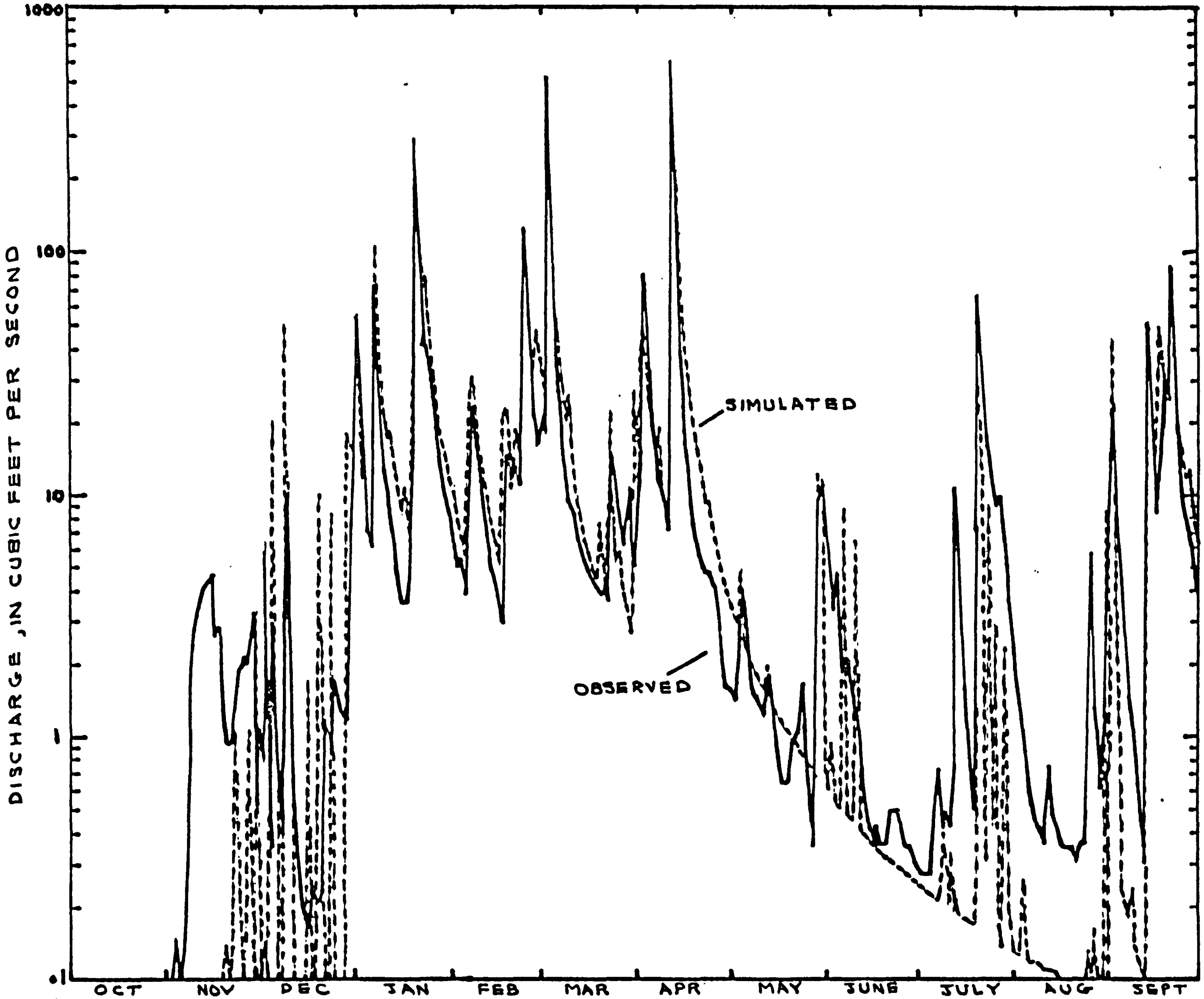


Figure 26.-- Observed versus simulated daily mean streamflow at site 3 (Blue Creek near Oakman), October 1978- September 1979.

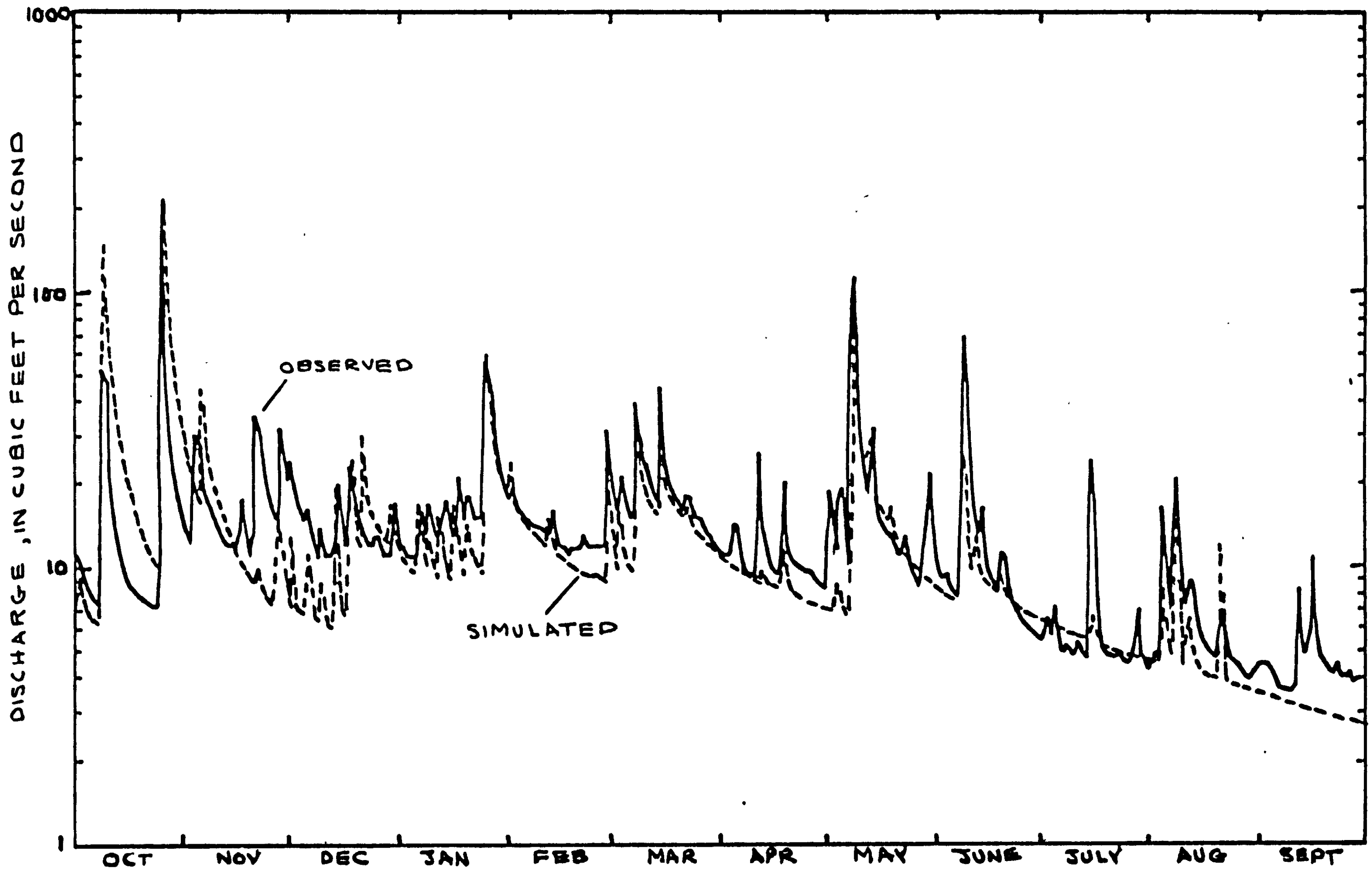


Figure 27.-- Observed versus simulated daily mean streamflow at site 7 (Yellow Creek near Northport) October 1977 - September 1978.