Influences of Strip Mining on the Hydrologic Environment of Parts of Beaver Creek Basin Kentucky, 1955-59

GEOLOGICAL SURVEY PROFESSIONAL PAPER 427-B

Prepared in collaboration with the U.S. Department of the Interior, Bureau of Sport Fisheries and Wildlife and Bureau of Mines; U.S. Department of Agriculture, Forest Service and Soil Conservation Service; Department of the Army, Corps of Engineers; and the Commonwealth of Kentucky, University of Kentucky, Geological Survey, Department of Conservation, and the Department of Fish and Wildlife Resources

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By CHARLES R. COLLIER *and others*

HYDROLOGIC INFLUENCES OF STRIP MINING

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PREFACE

The purpose of this investigation is to determine the effects of strip mining on the natural resources in a watershed. This report presents the results of a study of the influences of strip mining in the Beaver Creek basin during the period 1955–59 in which several Federal and Commonwealth agencies participated. A physical description of the basin pertinent to the investigation is given in U.S. Geological Survey Professional Paper 427–A, entitled "Description of Physical Environment and of Strip-Mining Operations in Parts of Beaver Creek Basin, Kentucky," by J. J. Musser. Base data collected as part of this investigation are too detailed for inclusion in this report. Data on streamflow, precipitation, and chemical and physical quality of water are contained in the annual compilation reports of the Geological Survey. Data on other phases of this investigation are on file in the office of the agency responsible for the collection and evaluation.

This investigation is intended only as a study of the influences of strip mining on the hydrologic environment of the study area. This report does not propose to describe influences as either good or bad, nor weigh adverse effects against benefits of mining. The data and interpretations contained herein pertain only to this specific area and should not be construed to necessarily apply to all strip-mining areas. However, the principles and processes described in this report are valid for all areas.

The technical coordination of the study was by the Beaver Creek Work Group Committee under the chairmanship of E. L. Hendricks, chief, Surface Water Branch, U.S. Geological Survey. C. R. Collier, G. W. Whetstone, and J. J. Musser, of the Quality of Water Branch, assembled the original draft and did the final technical editing for publication.

The study required the services of many consultants who advised on matters pertaining to their respective scientific specialties. Several of these men participated in the development of plans for the study; most of them visited the area at various times during the study to consult with members of the field staff. Consultants within the U.S. Geological Survey, Water Resources Division, included P. C. Benedict, chief, Research Section, and R. A. Krieger, chemist, both of the Quality of Water Branch, and L. M. Brush, staff geologist, General Hydrology Branch.

In the field operations of the Geological Survey, G. W. Whetstone, district chemist, C. R. Collier, engineer, and J. J. Musser and S. Merrin, geologists, were responsible for geochemical and sedimentation studies. F. F. Schrader, district engineer, N. O. Thomas, C. V. Burns and C. H. Minehan, engineers, conducted the streamflow and precipitation surveys. G. E. Hendrickson, district geologist, W. E. Price, Jr., geologist, and D. S. Mull, physical-science aid, made the ground water studies. R. S. Sigafoos, botanist, described the effects of the mining on the forests.

For the U.S. Forest Service, the following men advised on specific studies: N. R. Tripp, chief, Watershed Management, Eastern Region; E. A. Johnson, chief, Section of Watershed Management, Central States Forest Experiment Station; R. F. Collins, forest supervisor, Cumberland National Forest; M. J. Williamson, center leader, Berea Forest Research Center; and R. A. Tobiaski, forester, Watershed Management, Eastern States. D. E. Whelan, formerly of the U.S. Forest Service was an important contributor to the initial conception of the project and advised in the general supervision. H. H. Bush and W. E. Ruziska, district rangers, Cumberland National Forest, assisted in various field activities in the project.

Consultants for Soil Conservation Service included A. B. Rogers, assistant State conservationist; J. W. Roehl, geologist, Engineering and Watershed Planning; L. M. Lackey, work group conservationist, and A. S. Johnson, soil scientist.

Other Federal agency consultants on the Beaver Creek study included the following: H. J. Blazek, chief, Hydraulic Branch, U.S. Army Corps of Engineers, Nashville District; M. A. Smith, fishery management biologist, succeeded by Braden Pillow, U.S. Bureau of Sports Fisheries and Wildlife; J. J. Dowd, research director, Coal Mining Research Center, U.S. Bureau of Mines; and J. Smallshaw, chief, Hydraulic Data Branch, Tennessee Valley Authority.

Consultants for the Commonwealth of Kentucky included: W. W. Hagan, State geologist, and Preston McGrain, assistant state geologist, Kentucky Geological Survey; H. Callis and R. Montgomery, Department of Conservation; O. Chinn and P. P. Gannon, formerly with this department; P. N. Miles, formerly of the Department of Economic Development, and J. M. Stapleton; and B. T. Carter, director, and J. P. Henley, Department of Fish and Wildlife Resources.

The following men advised the Work Group Committee on specific study areas: J. M. Crowl and C. K. Spurlock, Kentucky Reclamation Association; S. A. Braley, Mellon Institute; and D. A. Robertson, Jr., and F. W. Montanari, sanitary engineers, Ohio River Valley Water Sanitation Commission.

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[Plates are in pocket]

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DEFINITIONS

The definitions given below have generally been taken from the following U.S. Geological Survey Water-Supply Papers.

Water Supply-Paper	*Title*	*Year*	*Authors*
494---	Outline of ground-water hydrology.	1923	O. E. Meinzer.
1373--	Sedimentation and chemical quality of surface waters in the Wind River basin, Wyoming.	1956	B. R. Colby, C. H. Hembree, and F. H. Rainwater.
1541-A.	Manual of Hydrology: General introduction and hydrologic definitions, in pt. 1, General surface-water techniques.	1960	W. B. Langbein and K. T. Iseri.

Acidity. The property of a solution caused by the presence of an excess of hydrogen ions over hydroxyl ions; attributable to the presence of dissolved gases, mineral acids, organic acids, and hydrolyzable salts, especially those of iron and aluminum. Acidity is expressed as ppm H^{+1} and may be converted into equivalent ppm H_2SO_4 by multiplying ppm $H^{+1} \times 49.04$.

Acre-foot. A unit for measuring the volume of water, is equal to the quantity required to cover 1 acre to a depth of 1 foot and is equal to 43,560 cubic feet. The term is commonly used in measuring volumes of water used or stored.

Antecedent moisture condition. A general term describing soil moisture conditions I (dry), II (average), or III (wet), usually applied at the beginning of a storm, and based either on antecedent precipitation or streamflow conditions.

Aquifer. A formation, group of formations, or part of a formation that is water yielding.

Base flow. See **Base runoff.**

Base flow recession. See **Base runoff recession.**

Base runoff. Sustained or fair weather runoff, composed largely of ground-water effluent.

Base runoff recession. A hydrograph showing the decreasing rate of base runoff following a period of rain or snowmelt. Composed largely of ground-water effluent.

"Buffered" solutions. A solution whose pH is changed only a relatively small amount by the addition, within limits, of acids and bases.

A water containing carbon dioxide and a carbonate or bicarbonate contains a weak acid (H_2CO_3) and its salt. This is a buffered solution. In most natural waters this combination is the principal pH control.

Chemical dissociation. The splitting of a chemical compound into charged particles or ions that are capable of reforming the original compound upon suitable alteration of conditions. Water, for example, is dissociated into ions to a slight extent. This dissociation simplified takes the form:

$$H_2O \rightleftharpoons H^{+1} + OH^{-1}$$

Mineral salts dissociate into ions when they dissolve in water in the following manner:

$$NaCl \rightleftharpoons Na^{+1} + Cl^{-1}$$

Chemical quality. Refers to the characteristics of water attributable to the presence of dissolved substances.

Concentration. The weight of dissolved solids or sediment per unit weight of solution. In chemical quality terminology, concentration is computed as one million times the ratio of the weight of a dissolved material to the weight of clear water-dissolved solids solution. In sediment terminology, concentration is computed as one million times the ratio of the weight of sediment to the weight of water-dissolved solids-sediment mixture. Concentration is expressed as parts per million (ppm).

Cubic foot per second (cfs). The rate of discharge of a stream whose channel is 1 square foot in cross-sectional area and whose average velocity is 1 foot per second.

Cubic feet per second per square mile (cfs per sq mi). The average number of cubic feet of water flowing per second from each square mile of area drained by a stream, assuming that the runoff is distributed uniformly in time and area. The unit is used with the term **Runoff** for longer periods of time, and in this report where instantaneous flows such as peaks are compared on a unit-area basis, the unit is also used with the term **Discharge.**

Depletion. As used herein, the term is the natural depletion (decrease) of storage with time following a period of rain or snowmelt. **Storage** is that contributing to base runoff recession. See **Base runoff recession.**

Direct runoff. The runoff entering stream channels promptly after rainfall or snowmelt. Superposed on **base runoff,** it forms the bulk of the hydrograph of a flood.

Discharge. The total fluids measured in the stream including base flow and the dissolved solids and sediment mixed with the water, but not including **Underflow.** Also see **Runoff.**

Dissolved solids. Includes any substance dispersed in water by solution and suspended particles that will pass through a filter whose retention rating is 0.5 micron; sometimes referred to as "solutes." The dissolved substances in natural water are principally silica, aluminum, iron, manganese, calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, fluoride, and nitrate.

Dissolved-solids discharge. The rate at which the dry weight of dissolved mineral solids passes a section of a stream, or the dry weight that is discharged in a given time.

Drainage area. Drainage area of a stream at a specified location in that area, measured in a horizontal plane, which is enclosed by a drainage divide.

Drainage basin. A part of the surface of the earth that is occupied by a drainage system, which consists of a surface stream or a body of impounded surface water together with all tributary surface streams and bodies of impounded surface water.

Duration curve. A cumulative frequency curve that shows the percentage of time that specified discharges of water or sediment were equaled or exceeded.

Equivalents per million (epm). A unit for expressing the concentration of chemical substances in terms of the reacting values of the electrically charged particles, or ions, in solution. One equivalent per million of a positively charged ion will react with one equivalent per million of a negatively charged ion. Parts per million are converted to equivalents per million by multiplying by the reciprocal of the combining weight.

Cation	*Factor*	*Anion*	*Factor*
Iron (Fe^{+2})	0.0358	Bicarbonate (HCO_3^{-1})	0.0164
Calcium (Ca^{+2})	.0499	Sulfate (SO_4^{-2})	.0208
Magnesium (Mg^{+2})	.0822	Chloride (Cl^{-1})	.0282
Sodium (Na^{+1})	.0435	Nitrate (NO_3^{-1})	.0161
Potassium (K^{+1})	.0256		

Evapotranspiration. Water withdrawn from land area by evaporation from water surfaces and moist soil and plant transpiration.

Fluvial sediment. Sediment that is transported by, suspended in, or deposited by water.

Gaging station. A cross-sectional plane of a stream at which streamflow, chemical quality, or sediment data are collected continuously or at regular intervals.

Ground-water discharge. Discharge of water from an aquifer, either by natural means such as evapotranspiration and flow from seeps and springs or by artificial means such as pumping from wells.

Ground-water recharge. Addition of water to an aquifer from all sources; in this area, chiefly infiltration of precipitation through the soil, seepage from streams or other bodies of surface water, or flow of ground water from another aquifer.

Hydrograph. A graph showing flow or other property of water with respect to time.

Hydrolysis. The reaction of a salt with water to form an acid and a base. The products of the reaction take up the elements of water in the sense that one product combines with a hydroxyl group and the other with a hydrogen ion to produce two new compounds:

$$FeSO_4+2H_2O \rightleftharpoons Fe(OH)_2+H_2SO_4$$

Lag. As used herein, lag is the time interval from beginning of rise, or when direct runoff began, to occurrence of peak flow at the stream-gaging station and is applied mainly to flood hydrographs resulting from precipitation of relatively short duration and high intensity.

Overland flow. The flow of rainwater or snowmelt over the land surface toward stream channels. After it enters the stream, it becomes **Runoff.**

Partial-duration flood series. A list of all flood peaks that exceed a chosen base discharge, regardless of the number of peaks occurring in a year.

Particle-size classification. As used herein, colloids have diameters smaller than 0.0002 millimeter (mm), clay particles have diameters between 0.0002 and 0.004 mm, silt particles have diameters between 0.004 and 0.062 mm, sand between 0.062 and 2.0 mm, gravel between 2.0 and 64 mm, cobbles between 64 and 256 mm, and boulders have diameters larger than 256 mm. This classification is that recommended by the American Geophysical Union Subcommittee on sediment terminology.

Perched ground water. Ground water separated from an underlying body of ground water by unsaturated rock.

Permeability. The capacity of earth materials to transmit water under pressure. In general, the larger the connected pore spaces or other openings in the material the greater the permeability.

Permeability, coefficient of. The amount of water, in gallons per day (gpd), that will flow through a cross-sectional area of 1 square foot under a hydraulic gradient of 100 percent (loss of 1 foot in head for each foot the water travels) at a temperature of 60° F.

pH. The negative logarithm of the hydrogen ion activity, a convenient scale to measure the intensity

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of the alkalinity or acidity of a water. The general relation between pH and the types of alkalinity or acidity is as follows:

Approximate pH	*Indications*
<4.5	Free mineral acid, free carbon dioxide.
4.5–8.3	Free carbon dioxide bicarbonate alkalinity.
>8.3	Bicarbonate alkalinity, carbonate alkalinity.

Porosity. The ratio of the volume of the openings to the total volume of a rock or soil. A high porosity does not necessarily indicate a high permeability.

Precipitation. The discharge of water, in liquid or solid state, out of the atmosphere, generally upon a land or water surface. The term precipitation is also commonly used to designate the quantity of water that is precipitated, measured in inches of depth, and includes rainfall, snow, hail, and sleet.

Rainfall. The quantity of water that falls as rain only.

Runoff. The part of the precipitation that appears in surface streams. It is the same as **streamflow** unaffected by artificial diversions, storage, or other works of man in or on the stream channels.

Sediment discharge. (a) The rate at which dry weight of sediment passes a section of a stream or (b) the quantity of sediment, as measured by dry weight or by volume, that is discharged in a given time. Sediment discharge consists of both (1) "suspended load", the sediment that moves in suspension in water and is maintained in suspension by the upward components of turbulent currents or by colloidal suspension, and (2) "bed load", which included both the sediment that moves in virtually continuous contact with the streambed (contact load) and the material that bounces along the bed in short skips or leaps (saltation load).

Sediment sample. A quantity of water-sediment mixture that is collected to represent the average concentration of suspended sediment or the average particle-size distribution of suspended or deposited sediment.

Semiperched ground water. Ground water that has a greater pressure head than the underlying body of ground water. The underlying body of water, however, is not separated from the water above by any unsaturated rock.

Sheet erosion. As used herein, the more or less uniform removal of the land-surface material by overland flow, including flow in rills and minor shallow gulleys.

Specific conductance. A measure of the ability of a water to conduct an electrical current, expressed in micromhos at 25°C. Because the specific conductance is related to the number and specific chemical types of ions in solution, it can be used to approximate the dissolved-solids content of water. The following general relation is applicable for the Cane Branch study area:

$$\text{Dissolved solids (ppm)} = \text{Specific conductance} \times (0.53 \pm 0.03)$$

Specific retention. The ratio of the volume of water that a rock will retain against gravity, after being saturated, to its own volume.

Specific yield. The ratio of the volume of water that a rock will yield by gravity, after being saturated, to its own volume.

Storage. Water artificially impounded in surface or underground reservoirs, for future use; or water naturally detained in a drainage basin, such as ground water.

Storm runoff. See **Direct runoff.**

Storm seepage. That part of precipitation which infiltrates the surface soil, and moves toward the streams as ephemeral, shallow, perched ground water above the main gound-water level. Storm seepage is usually a part of the **direct runoff.**

Streamflow. The discharge that occurs in a natural channel. The term "streamflow" is more general than **runoff,** as streamflow may be applied to discharge whether or not it is affected by diversion or regulation.

Study area. That part of a **drainage basin** that is upstream from a **gaging station.**

Subsurface runoff. See **Storm seepage.**

Supplemental sites. Locations within the study area at which stremflow, chemical quality, or sediment data are collected at irregular intervals.

Surface runoff. That part of the runoff which travels over the soil surface to the stream channel and has not passed beneath the surface since precipitation.

Underflow. The downstream flow of water through the permeable deposits that underlie a stream and is more or less limited by rocks of low permeability. Thus, underflow is not measured at a gaging station.

Water loss. The difference between average precipitation over the drainage basin and runoff at the gaging station, even where part of the difference may be due to seepage and changes in soil moisture and ground-water storage.

Watershed. This term is used to signify **drainage basin.**

Water table. The upper surface of the zone of saturation, except where that surface is formed by impermeable material.

Weighted mean concentration. The concentration that would occur if the sediment or dissolved solids load for a given period of time was equally distributed throughout the volume of water discharged during that time.

Zone of saturation. The zone in which the openings in the rocks are filled with water under hydrostatic pressure.

INFLUENCES OF STRIP MINING ON THE HYDROLOGIC ENVIRONMENT OF PARTS OF BEAVER CREEK BASIN, KENTUCKY, 1955–59

By Charles R. Collier and others

SUMMARY OF RESULTS

By Charles R. Collier, George W. Whetstone, and John J. Musser

Strip mining for coal in the Beaver Creek basin, McCreary County, Ky., was started in 1955. Since then, the hydrologic environment of this area has been altered. About 10 percent of the Cane Branch study area has been strip mined and the West Fork Cane Branch area has been prospected. The Helton Branch area has had no mining activity and has remained virtually unchanged.

Mining in the Cane Branch basin has significantly changed the chemical quality of the surface and ground waters, increased the sediment yield of the basin, altered the forest and forest development, and has adversely affected the aquatic life of the streams. This report presents the preliminary results of the Beaver Creek investigations from 1955 to 1959.

A marked difference in the runoff characteristics in Cane Branch and Helton Branch basins has been measured. However, the effects of strip mining on the runoff characteristics are not readily differentiated from other factors in the hydrologic environment which also affect the runoff regimen.

Cane Branch has a greater flow variability than Helton Branch. Comparisons of the flow-duration curves based on unit area show that Cane Branch flows, 0.07 cfs per sq mi, only one-third those of Helton Branch for 84 percent of the time, and even greater differences occur at greater durations. However, at duration of less than 20 percent, which represent flood runoff, the discharges of Cane Branch exceed those of Helton Branch by as much as 60 percent.

Storage-depletion curves and base flow recession analysis show that the Cane Branch basin has less favorable water retention and storage characteristics than Helton Branch basin. The storage for the support of base flows at comparable times after storm runoff is less in the Cane Branch basin. After 12 days, storage contributing to base flow in Cane Branch is only 0.16 inch, or less than half that remaining in the Helton Branch basin. Correspondingly, the base flow of Cane Branch, 0.14 cfs per sq mi after 22 days, amounts to only half that of Helton Branch. After about 50 days, Cane Branch has only about one-fourth of the flow of Helton Branch. In the Cane Branch basin the upper strata are sandstone, siltstone, and claystone; in the Helton Branch basin the upper strata are predominantly sandstone, which provide a greater water-storage capacity. The flow of three perennial springs in the Helton Branch basin is supported by ground water from the sandstone; no perennial springs exist in the Cane Branch basin. Thus, the ground-water characteristics of the Cane Branch basin are less favorable to the support of low and base flow.

Cane Branch has a greater flood potential, the 5-year flood being nearly twice that of Helton Branch. Many brief, but intense, summer storms produced significant increases in water discharge at Cane Branch, but only small increases at Helton Branch. Cane Branch has a shorter lag than Helton Branch; during storms, the maximum discharge occurs, on the average, about 1 hour and 10 minutes sooner at the Cane Branch gage than at the Helton Branch gage. This more rapid runoff in the Cane Branch basin reflects the shorter stream channel system and lack of land cover in the strip-mined areas for retarding overland flow.

Water losses and evapotranspiration losses were slightly less in the Cane Branch basin than in the Helton basin, although precipitation was nearly equal.

These differences in runoff characteristics are apparent even though the period of record is short. The characteristics for Helton Branch are representative for a longer period of time because virtually no changes in land use or cover have occurred in the basin for many years. For Cane Branch the data reflect, to an unknown degree, the effect of changes in cover conditions and land use resulting from strip mining in the basin, for some of these changes preceded the collection of hydrologic records in the basin. Compared with Helton Branch, Cane Branch showed evidence of a greater deficiency in monthly runoff in 1957 and 1958 than in 1956.

Ground water levels in the holes augered in the Cane Branch spoil bank fluctuate from 1 to 3 feet, indicating changes in storage in the spoil bank. Discharge from the spoil bank was calculated to be 10,000 gpd (gallons per day). Recharge is due to the infiltration of precipitation and to seepage from the pools in the strip pit; water is lost by evaporation and by leakage to the surface. The acid sulfate water in the spoil bank may be seeping into the underlying bedrock and contaminating the ground water there. The information available on this possibility suggests that the effect to date has been slight.

The solutes in streams of the study area are a composite of those contained in rainwater and those leached from the rocks and soils. The rate of chemical weathering is slow in the Helton Branch and West Fork Cane Branch study areas because the clastic rocks, including those with iron sulfides, are covered by well-weathered soils and are protected by vegetation.

In the Cane Branch study area, a part of the parent rock has been redistributed by the mining operations to form spoil banks of fresh rock fragments. These unweathered materials are being actively attacked by the agents of chemical weathering. Oxidation of the iron sulfide in the spoil banks, the highwalls, and the pools of the mining areas provide an excess of hydrogen ions. The hydrogen ions react with the mineral matter of the spoil bank, releasing soluble products at a faster rate than in the unmined areas.

The water in Helton Branch and West Fork Cane Branch generally contains less than 30 ppm (parts per million) of dissolved solids and ranges in pH from 5.0 to 7.2. One-third to two-thirds of the dissolved-solids content of these streams is derived from cyclic salts in precipitation and the remainder from solute-solid reactions in the rocks and soils. The principal ions in the waters are calcium, magnesium, bicarbonate, and sulfate. Silica, released from the weathering of silicate minerals, constitutes about 25 percent of the dissolved-solids content of the streams.

The chemical composition of the water in Cane Branch before mining occurred was similar to that presently found in Helton Branch and West Fork Cane Branch. The water in tributaries to Cane Branch not affected by mining has a median dissolved-solids content of 20 ppm, and its pH ranges from 5.2 to 7.6.

After completion of the 1955–56 mining operation in the Cane Branch area, the dissolved-solids content of Cane Branch ranged from 80 to 1,500 ppm and had a median value of 310 ppm, which is 10 to 15 times that of West Fork Cane Branch and Helton Branch. The dissolved solids consist principally of aluminum, iron, manganese, calcium, magnesium, and sulfate. The pH ranges from 2.5 to 4.2 and the acidity from 0.0 to 17 ppm as H^{+1}.

The aluminum concentration in Cane Branch ranges from 0.0 to 85 ppm. The highest aluminum concentrations occur when the pH of the water is less than 3.

Iron sulfide occurs in significant amounts in the Cane Branch area. The oxidation of iron sulfide yields soluable ferrous sulfate and sulfuric acid, which dissolves the relatively insoluable iron oxides and hydroxides. The concentration of iron in Cane Branch water ranges from 0.06 to 48 ppm.

The chemical quality of the water in and on the spoil bank differs from place to place, but the water generally has a low pH and a dissolved-solids content in excess of 400 ppm and contains relatively large amounts of aluminum, iron, manganese, calcium, magnesium, and sulfate. The chemical character of the water is determined by the kind of material composing the spoil bank in any given place and by the rate of recharge for parts of the bank.

Chemical degradation has definitely accelerated in the Cane Branch area, as compared to the rate of degradation in the Helton Branch area. Cane Branch transported 450 tons, whereas Helton Branch transported 100 tons of dissolved solids per square mile of drainage area in the 2-year period, October 1956 to September 1958. The net yields of the Cane Branch and Helton Branch areas due only to chemical degradation during this 2-year period were 380 and 39 tons per square mile, respectively.

Mine drainage from the Cane Branch area has a detrimental effect on aquatic life. In May 1956, 1 year after mining began, collections of aquatic bottom-dwelling organisms revealed similar population complexes in Hughes Fork, Little Hurricane Fork, and Helton Branch. Cane Branch, however, was supporting a much less varied and a smaller population of bottom organisms. In the later collections from Cane Branch, the detrimental effects of mine drainage on the bottom fauna, especially the insect orders, became more apparent. Hughes Fork below the source of pollution contained no mayflies, the insect order used as indicator organisms, and included relatively few other organisms. The Little Hurricane Fork and Helton Branch faunal complexes were similar throughout the study, and mayflies were always abundant. Hughes Fork above the source of pollution contained a bottom faunal complex similar to that in Little Hurricane Fork. Cane Branch at no time contained more than two insect orders, and the aggregate collection from this stream contained only four insect orders.

Since June 1956, fish life has disappeared from Cane Branch and is present only seasonally in lower Hughes Fork. Normal fish populations existed in Helton Branch, West Fork Cane Branch, and upper Hughes Fork throughout the 3-year study period. The disappearance of fish life from the polluted streams is correlated with the discharge of acid mine effluent, which has drastically increased the acidity of the water.

Mortality studies were conducted to determine the relationship of the disappearance of fish life to the discharge of the acid mine effluent. Individuals of each tested species were dead after 150 minutes of exposure to the acid (pH 2.9) water of Cane Branch. Mortalities did not occur in streams that were not receiving acid mine effluent.

Strip mining affects forest resources in several ways. Through the mechanical operation of strip mining, forests are removed, leaving denudated land surfaces. Acid water containing high concentrations of dissolved constituents also affects the forest resources when the water is received by trees downslope from the mine.

As the mine drainage percolates through the forest soils, large quantities of dissolved minerals are added to the soils and become immediately available to the trees. Trees that receive mine drainage generally grow faster than other trees in the study area.

Trees are becoming established on parts of the spoil bank and above the highwall, but the number per unit area is low because parts of the spoil bank are far from the seed source, the spoil bank material was too well compacted when the banks were leveled, and significant amounts of toxic material are at the surface of the banks.

Before strip mining, the sediment characteristics of the three study areas probably were similar. Weathering of the clastic rocks protected by soil and vegetal cover was slow, and little material was made available for erosion. Sheet erosion in the Helton Branch area decreased from an estimated 0.9 ton per acre in 1957 to 0.6 ton per acre in 1958 and 1959, owing primarily to an improvement in pasture cover. In Helton Branch and in the tributaries to Cane and West Fork Cane Branches that do not receive mine drainage, the sediment concentrations are generally less than 500 ppm during storm runoff.

The spoil banks resulting from strip mining and prospecting are the greatest source of eroded materials. These banks contain large quantities of disturbed rock material not protected by vegetation so that weathering and erosion are greatly accelerated. Sheet erosion in the West Fork Cane Branch area was estimated at 0.7 ton per acre for 1957 and 1958. Coal prospecting disturbed only 0.8 percent of the West Cane area but contributed 83 percent of the sheet erosion. In the Cane Branch study area, sheet erosion was estimated at 4.9 tons per acre in 1957 and 1958 and increased to 7.8 tons per acre in 1959. In 1957 the strip-mined part included 6.4 percent of the Cane Branch area but contributed 96 percent of the sheet erosion. An additional 4.0 percent of the study area was disturbed by mining in 1958 and 1959. This resulted in a 61-percent increase in the average rate of sheet erosion.

The repeated transportation and deposition of the eroded spoil material by surface runoff has resulted in the increasingly large sediment discharge of Cane Branch. Cane Branch discharged 1,900 tons of sediment (2,800 tons per square mile) in the 1957 and 1958 water years compared to 42 tons (49 tons per square mile) discharged by Helton Branch during the same period. The weighted mean sediment concentration of Cane Branch has increased each year, from 440 ppm for the period February to September 1956 to 1,600 ppm for the 1959 water year. The weighted mean sediment concentration of Helton Branch ranged from 14 to 17 ppm.

The sediment load and the concentration of Cane Branch vary seasonally; higher sediment discharges occur in winter, and higher sediment concentrations occur in summer. Thunderstorms in the summer provide intense precipitation and rapid surface runoff, which causes considerable erosion on the unprotected spoil banks. The winter storms, although providing more precipitation, are less intense and of longer duration, and cause less erosion for a given volume of surface runoff.

A study of the relation between direct runoff and sediment discharge shows that significant changes have occurred in Cane Branch. In February 1956, the full effect of strip mining in the southwest side of the basin began to be measured at the gaging station. In January 1959, the sediment discharge increased owing to the mining that was started on the northeast side of the basin in late 1958.

The sediment transported by Cane Branch averaged 67 percent clay, 31 percent silt, and 2 percent sand. The sediment is generally finer at low concentrations (three-fourths is clay) and coarser at high concentrations (one-half is clay). Some cobbles and small boulders also have been transported for short distances.

In the channel of Helton Branch, sediment deposition is limited to small deposits of mostly sand and gravel in the pools that occur between the bedrock riffles. The channel of West Fork Cane Branch contains substantial deposits of clay and silt eroded from the small spoil banks and prospect trenches. The pools in

Cane Branch, from the southwest spoil bank to beyond the gaging station, are almost completely clogged with dark gray sediment from the spoil banks. These deposits of clay, silt, and sand are more than 2 feet thick in some places. Sediment deposits in Hughes Fork are similar in character to those in Cane Branch and are apparent for about 4,000 feet downstream from the mouth of Cane Branch.

PRECIPITATION AND RUNOFF

By Nathan O. Thomas, U.S. Geological Survey

METHODS

The primary purpose of this phase of the investigation was to record the precipitation and streamflow events during and after a strip-mining operation. Precipitation and runoff data have been collected on Cane Branch, which includes the strip-mined areas, and on Helton Branch, a drainage basin which is still largely in its natural state.

The various streamflow and watershed characteristics—flow duration and variability, peak discharge, hydrograph shape, base-flow recession, monthly runoff, and basin storage and water losses—have been delineated for Cane and Helton Branches. The characteristics for the two basins are compared. Factors that affect the movement and quantity of water as it passes through the basins and the effects of strip-mining on these factors are discussed.

INSTRUMENTATION

Instrumentation for the measurement of streamflow and precipitation consists of three stream-gaging and six precipitation stations. (See pl. 1 and 2). Two recording precipitation gages are located in each of the three watersheds: Cane, West Fork Cane, and Helton Branches.

The stream-gaging stations, Cane Branch near Parkers Lake and Helton Branch at Greenwood, were equipped with dependent-type tipping-bucket rain gages. A bubble-type stage recorder was used at the gaging station on West Fork Cane Branch, beginning in February 1958. Prior to that time the station was equipped with a crest-stage indicator for recording peak stages.

Instrumentation of the basins was completed during January and February 1956, except for one recording precipitation gage (gage 4, on plate 1) in West Fork Cane Branch, which was installed in May 1956.

DATA AVAILABLE

Records of daily mean flow at the gaging stations Helton Branch at Greenwood and Cane Branch near Parkers Lake, are being published in the annual series of U.S. Geological Survey Water Supply Papers, part 3B, Cumberland and Tennessee River basins, and are not given herein. In view of the short continuous streamflow record available on West Fork Cane Branch, it was not included in the analyses for this report. Brief descriptive information and precipitation data are included, however.

Daily records at the two stations used in this study covered the period from date of establishment of the station to September 30, 1958. Peak-flow data available covered also the subsequent period ending December 1959; thus 4 years of such data were studied. Descriptions of the stream-gaging stations and records of monthly flow are given in tables 1 to 3.

TABLE 1.—*Discharge and runoff at stream-gaging station Cane Branch near Parkers Lake, Ky.*

Location.—Lat 36°52′05″, long 84°26′57″, on left bank 2,100 ft upstream from West Fork, 2.5 miles northeast of Parkers Lake and 2.6 miles east of Greenwood, McCreary County. Datum of gage 979.4 ft above mean sea level.
Drainage area.—0.67 sq mi (428.6 acres).
Station equipment.—Water-stage recorder and dependent-type tipping-bucket precipitation gage; reinforced-concrete control founded on bedrock.
Establishment.—Station established and water-stage recorder installed Feb. 2, 1956.
Extremes.—Maximum discharge February 1956 to December 1959, 198 cfs Jan. 29, 1957 (gage height, 2.43 ft, backwater from ice); minimum discharge February 1956 to September 1958, 0.005 cfs Sept. 7–8, 1957 (gage height, 0.43 ft).

Month	Water year ending Sept. 30, 1956			Water year ending Sept. 30, 1957			Water year ending Sept. 30, 1958		
	Mean discharge (cfs)	Runoff		Mean discharge (cfs)	Runoff		Mean discharge (cfs)	Runoff	
		Cfs per sq mi	Inches		Cfs per sq mi	Inches		Cfs per sq mi	Inches
Oct				0.0728	0.109	0.13	0.147	0.219	0.25
Nov				.0560	.084	.09	1.85	2.76	3.08
Dec				1.57	2.34	2.70	1.66	2.48	2.86
Jan				5.23	7.81	8.99	.898	1.34	1.55
Feb	5.38	8.03	8.66	2.30	3.43	3.57	1.37	2.04	2.14
Mar	2.93	4.37	5.05	1.25	1.87	2.15	1.45	2.16	2.49
Apr	2.19	3.27	3.65	1.51	2.25	2.51	4.11	6.13	6.85
May	.236	.352	.41	.257	.384	.44	1.76	2.63	3.04
June	.132	.197	.22	.284	.424	.47	.113	.169	.19
July	.263	.393	.45	.0727	.109	.13	.159	.237	.27
Aug	.143	.213	.25	.0258	.039	.04	.0687	.103	.12
Sept	.0469	.070	.08	.208	.310	.35	.120	.179	.20
Year				1.06	1.58	21.57	1.14	1.70	23.04

TABLE 2.—*Description of stream-gaging station West Fork Cane Branch near Parkers Lake, Ky.*

Location.—Lat 36°51′49″, long 84°27′08″, on right bank 2,900 ft upstream from mouth and 2.2 miles northeast of Parkers Lake, McCreary County. Datum of gage is 1,122.9 ft above mean sea level.
Drainage area.—0.26 sq mi (165.3 acres).
Station equipment.—Water-stage recorder (bubble gage) and crest-stage indicator.
Establishment.—Established as a gaging station and recorder installed Feb. 21, 1958. Crest-stage indicator installed Mar. 9, 1956, and station operated as a high-flow partial-record station prior to Feb. 21, 1958.
Data available.—Discharge measurements range from point of zero flow, gage height 0.08 ft, to 17.4 cfs, gage height 0.81 ft. Crest stages recorded include the highest: 2.20 ft Jan. 29, 1957.

TABLE 3.—*Discharge and runoff at stream-gaging station Helton Branch at Greenwood, Ky.*

Location.—Lat 36°53′07″, long 84°28′55″, on left bank 250 ft upstream from mouth, 800 ft downstream from un-named tributary, and 1 mile northeast of Greenwood, McCreary County. Datum of gage is 993.8 ft above mean sea level.
Drainage area.—0.85 sq mi (541.0 acres).
Station equipment.—Water-stage recorder and dependent-type tipping-bucket precipitation gage; reinforced-concrete control founded on bedrock.
Establishment.—Station established and water-stage recorder installed Jan. 5, 1956.
Extremes.—Maximum discharge January 1956 to December 1959, 136 cfs Jan. 29, 1957 (gage height, 1.35 ft); maximum gage height 1.46 ft Jan. 30, 1956 (backwater from debris); minimum discharge January 1956 to September 1958, 0.05 cfs Oct. 2, 1956; minimum gage height 0.475 ft Nov. 20–21, 1956, and at times during August and September 1958.

Month	Water year ending Sept. 30, 1956			Water year ending Sept. 30, 1957			Water year ending Sept. 30, 1958		
	Mean discharge (cfs)	Runoff		Mean discharge (cfs)	Runoff		Mean discharge (cfs)	Runoff	
		Cfs per sq mi	Inches		Cfs per sq mi	Inches		Cfs per sq mi	Inches
Oct				0.116	0.136	0.16	0.255	0.300	0.35
Nov				.148	.174	.19	2.12	2.49	2.78
Dec				1.81	2.13	2.46	2.28	2.68	3.10
Jan	1.43	1.68	1.94	5.88	6.92	7.97	1.15	1.35	1.57
Feb	6.76	7.95	8.58	3.15	3.71	3.86	1.72	2.02	2.10
Mar	3.37	3.96	4.58	1.53	1.80	2.08	1.76	2.07	2.39
Apr	2.31	2.72	3.03	1.62	1.91	2.12	4.38	5.15	5.76
May	.382	.449	.52	.336	.395	.46	2.43	2.86	3.29
June	.166	.195	.22	.347	.408	.46	.275	.324	.36
July	.312	.367	.42	.221	.260	.30	.241	.284	.33
Aug	.193	.227	.26	.134	.158	.18	.192	.226	.26
Sept	.101	.119	.13	.286	.336	.37	.214	.252	.28
Year				1.29	1.52	20.61	1.41	1.66	22.57

Descriptions of the eight recording precipitation gages in the study areas are contained in table 4. Monthly-precipitation data from the six independent-type recording precipitation gages are presented in table 5. The average precipitation in each basin is an arithmetic average of the amounts recorded at the two gages in the basin. Precipitation data recorded by the two tipping-bucket gages were not complete during all periods and thus were not listed in the table; however, these data were valuable in establishing the relative timing of precipitation and storm runoff. Total precipitation for water years 1957 and 1958 ending September 30 and for climatic years 1957 and 1958 ending March 31 is included.

TABLE 4.—*Description of precipitation gages in Beaver Creek basin*

No. on plate 1 or 2	Date established in 1956	Location	Elevation above mean sea level (feet)
1	Feb. 21	Lat 36°51′27″, long 84°26′19″, in upper area, Cane Branch basin.	1,285
2	Feb. 16	Lat 36°51′41″, long 84°26′37″, near center of Cane Branch basin.	1,135
3	do	Lat 36°51′15″, long 84°26′53″, in upper area, West Fork Cane Branch basin.	1,255
4	May 31	Lat 36°51′36″, long 84°27′16″, in lower area, West Fork Cane Branch basin.	1,240
5	Feb. 15	Lat 36°52′25″, long 84°29′27″, in upper left area, Helton Branch basin.	1,275
6	do	Lat 36°52′24″, long 84°28′56″, in upper right area, Helton Branch basin.	1,280
	May 4	Tipping bucket, at Cane Branch gaging station.	1,000
	Oct. 31	Tipping bucket, at Helton Branch gaging station.	1,017

TABLE 5.—*Monthly precipitation, in inches, at recording gages, March 1956 to September 1958*

Month and year	Cane Branch basin			West Fork Cane Branch basin			Helton Branch basin		
	Gage 1	Gage 2	Average	Gage 3	Gage 4	Average	Gage 5	Gage 6	Average
1956									
Mar	5.89	6.16	6.02	5.71			5.67	5.77	5.72
Apr	5.37	5.56	5.46	5.40			5.10	5.19	5.14
May	1.66	1.74	1.70	1.60			1.69	1.79	1.74
June	2.77	2.73	2.75	2.71	2.68	2.70	2.77	2.74	2.76
July	7.68	7.80	7.74	7.69	7.24	7.46	7.92	7.76	7.84
Aug	3.76	3.82	3.79	3.64	3.63	3.64	3.42	3.47	3.44
Sept	.57	.46	.52	.55	.47	.51	.54	.54	.54
Oct	3.11	3.07	3.09	2.96	2.99	2.98	3.03	2.95	2.99
Nov	1.46	1.29	1.38	1.30	1.21	1.26	1.28	1.24	1.26
Dec	8.93	8.80	8.86	8.78	8.32	8.55	8.33	8.11	8.22
1957									
Jan	11.69	11.77	11.73	11.72	11.65	11.68	12.19	12.32	12.26
Feb	4.89	4.73	4.81	4.84	4.49	4.66	4.64	4.72	4.68
Mar	2.81	2.73	2.77	2.73	2.62	2.68	2.78	2.84	2.81
Total, climatic year ending Mar. 31, 1957	54.70	54.50	54.60	53.92			53.69	53.67	53.68
Apr	4.59	4.47	4.53	4.53	4.46	4.50	3.79	3.85	3.82
May	3.79	3.80	3.80	4.13	3.48	3.80	2.40	2.54	2.47
June	6.23	5.86	6.04	6.53	5.91	6.22	6.20	6.78	6.49
July	1.92	1.95	1.94	2.05	2.01	2.03	3.17	2.90	3.04
Aug	1.03	.93	.98	.89	.85	.87	.98	1.04	1.01
Sept	6.21	6.30	6.26	6.60	6.61	6.60	6.87	6.53	6.70
Total, water year ending Sept. 30, 1957	56.66	55.70	56.19	57.06	54.60	55.83	55.66	55.82	55.75
Oct	3.13	3.05	3.09	3.11	2.89	3.00	2.71	2.77	2.74
Nov	6.99	6.97	6.98	7.04	7.11	7.08	7.38	7.51	7.44
Dec	5.07	4.99	5.03	5.10	4.70	4.90	4.86	5.00	4.93
1958									
Jan	3.22	3.35	3.28	3.48	3.21	3.34	3.28	3.33	3.30
Feb	1.81	1.76	1.78	1.59	1.59	1.59	1.62	1.65	1.64
Mar	3.89	4.07	3.98	4.21	3.96	4.08	4.03	4.03	4.03
Total, climatic year ending Mar. 31, 1958	47.88	47.50	47.69	49.26	46.78	48.01	47.29	47.93	47.61
Apr	8.29	8.56	8.42	8.81	8.41	8.61	8.12	8.34	8.23
May	4.98	4.89	4.94	5.27	4.83	5.05	5.82	5.57	5.70
June	2.05	2.08	2.06	2.11	2.08	2.10	2.73	2.80	2.76
July	6.15	6.08	6.12	6.68	5.84	6.26	4.68	5.02	4.85
Aug	1.89	1.92	1.90	2.50	2.22	2.36	1.88	1.96	1.92
Sept	4.38	4.47	4.42	4.61	4.40	4.50	4.32	4.45	4.38
Total, water year ending Sept. 30, 1958	51.85	52.19	52.00	54.51	51.24	52.87	51.43	52.43	51.92

RUNOFF CHARACTERISTICS AND EFFECTS

A comparison of average monthly runoff of Cane and Helton Branches and Pitman Creek is shown by the bar charts in figure 1. Pitman Creek records were collected at two sites, having drainage areas of 26.3 and 31.3 square miles, and the two records were combined to produce the graph shown in figure 1. This basin is located about 25 miles northwest of the study area, and its graph demonstrates the distribution expected from longer-term records.

The graphs for Cane and Helton Branches are based on the period February 1956 to September 1958 and compare well. The short-term monthly patterns of Cane and Helton Branches compare favorably with the long-term distribution established on Pitman Creek.

FLOW DURATION AND VARIABILITY

Differences in the amount and variability of flow in Helton and Cane Branches are shown by the flow-duration curves in figure 2. The steep slope and less apparent reverse "S" features demonstrated by the Cane Branch curve are usually characteristic of drainages having great flow variability and low base flows. The curves are based on two complete water years ending September 30, 1958. Water pumped from the drift mine into Cane Branch (Musser, 1963) increased the daily discharges by such small amounts that the effect on the duration curve is considered negligible. To enable direct comparison of the curves for each stream, the flows were converted to cubic feet per second per square mile.

Helton Branch has a larger sustained low flow than Cane Branch. At a duration of 50 percent, daily flow at Helton Branch is approximately 1½ times greater than at Cane Branch. At 84 percent duration, or one standard deviation from the median, Helton Branch has nearly three times the flow of Cane Branch (0.19 versus 0.07 cfs per sq mi). At greater percentages of time the ratio increases to four.

Cane Branch has greater flood discharges than Helton Branch. At durations of less than about 20 percent, which represent flood runoff, Cane Branch discharges exceed those of Helton Branch by as much as 60 percent.

Both Cane and Helton Branches are deeply entrenched, and low-flow characteristics are influenced

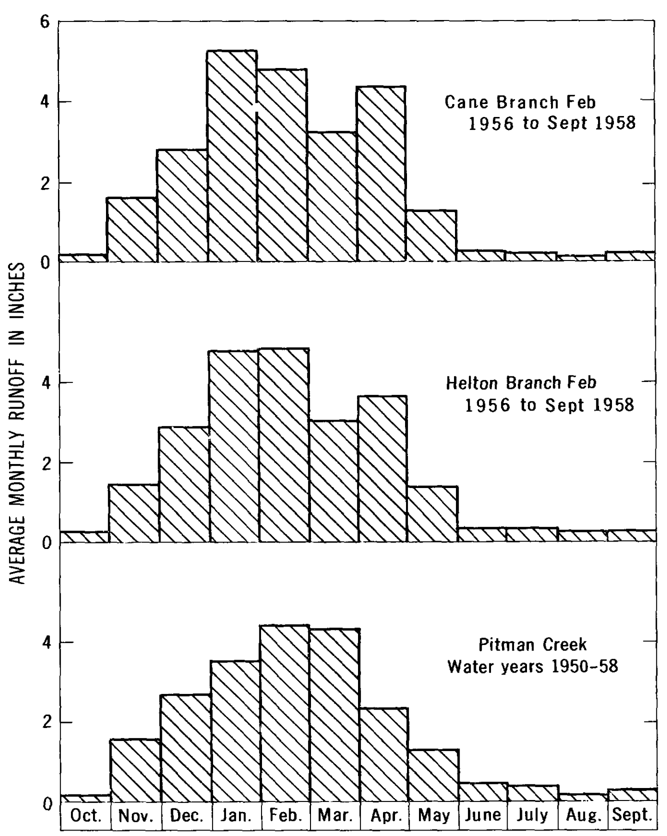

FIGURE 1.—Graph showing distribution of average monthly runoff, Cane and Helton Branches and Pitman Creek.

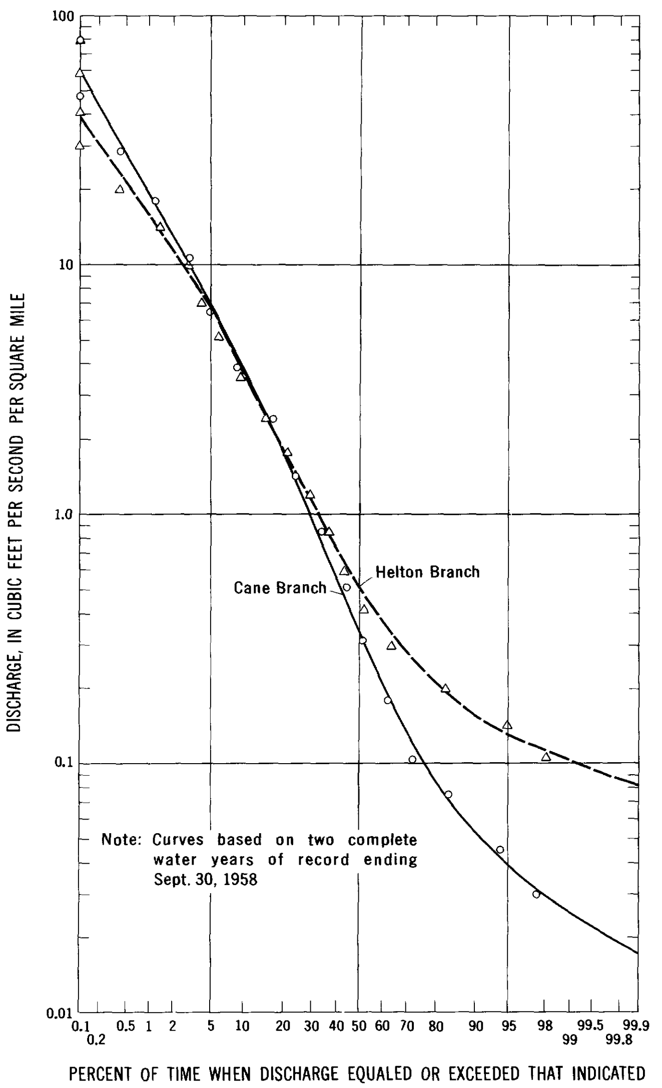

FIGURE 2.—Flow-duration curves, Cane and Helton Branches.

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largely by geology, soils, and land cover and use. High-flow characteristics, or peak flows, are associated more closely with soils, land cover and use, stream slopes, basin shape, channel geometry, and surface storage in strip-mine pools; the effects of these factors are discussed in the subsection entitled "Peak discharges."

The geology of the Cane and Helton Branch areas is dissimilar enough to cause major differences in the low-flow characteristics of the streams. Above the main cliff-forming sandstone, the Cane Branch area has sandstone, siltstone, and claystone, whereas in the Helton Branch area the rock is mainly sandstone (Musser, 1963). In the Helton Branch area, sandstone predominates and provides a greater water storage capacity, which in turn produces the larger dry weather flow of Helton Branch. Three perennial springs issuing from the sandstone in the upper reaches of Helton Branch are visible evidence of the larger dry weather flow.

A soil survey (Musser, 1963) indicates that the Cane and Helton Branch areas contain a similar proportionate area of soils of high permeability. Differences in the soil hydrology are minor and have little influence on the differences in the low-flow characteristics of the streams.

Land use and cover are important factors of the hydrologic environment, and are reported in detail in the section on "Sheet Erosion." The two study areas had a significant difference in percentage of land with vegetal cover; the Helton Branch area was 99 percent covered and the Cane Branch area only 90 percent. The 10 percent of the Cane Branch area with practically no vegetal cover is the strip-mined and spoil areas. The effect of strip mining on the low-flow characteristics of Cane Branch is discussed in the subsection "Base flow and storage."

Climate throughout the Beaver Creek area is inherently the same (Musser, 1963) and therefore is a minor factor in evaluating differences in the flow duration of Cane and Helton Branches. Precipitation during individual storms, particularly summer storms, may vary somewhat from basin to basin, but this would have little effect upon flow-duration characteristics. Precipitation records indicate that the effect of elevation is negligible. The relief, about 400 feet, in both basins is not great, and the storms contributing most of the precipitation move usually from the southwest to the northeast and do not move over any well-defined upslope areas.

Channel geometry has probably little effect on the differences in flow-duration characteristics of the two basins. Generally, bed slopes are steep, and channels are narrow and well defined, although in some short reaches there are overbank or flood plain areas. The narrow, steep channels of Cane and Helton Branches contain pools, which provide minor channel storage for the support of low flow. Changes in channel geometry due to sediment deposition would alter flow conditions hydraulically, but would have little effect on duration of flow.

The relationship between area and elevation in the two basins is shown in figure 3. Elevations above the gaging stations are equivalent to the following ranges in sea-level elevation: 979 to 1,385 feet in the Cane Branch study area and 994 to 1,385 feet in the Helton Branch study area. The elevation at which mining occurred in Cane Branch is indicated on the graph.

The cliffs along Cane Branch account for the small increase in area between elevations of 90 and 170 feet. Only 25 percent of the area lies below an elevation of 190 feet. In comparison, 25 percent of the area in Helton Branch lies below an elevation of 150 feet. At the median-area points, however, there is little difference in elevation: half of the Cane Branch area is below 222 feet and half of Helton Branch area is below 216 feet. The slight differences in the area-elevation relationship of Cane and Helton Branches have little effect upon the differences in the flow duration of the two streams.

PEAK DISCHARGES

Momentary peak discharges are listed for Cane and Helton Branches in tables 6 and 7. The lists of peaks make up a partial-duration series and cover a period of nearly 4 years ending December 1959. The base discharges above which peaks were listed were established so as to include at least one peak for each year.

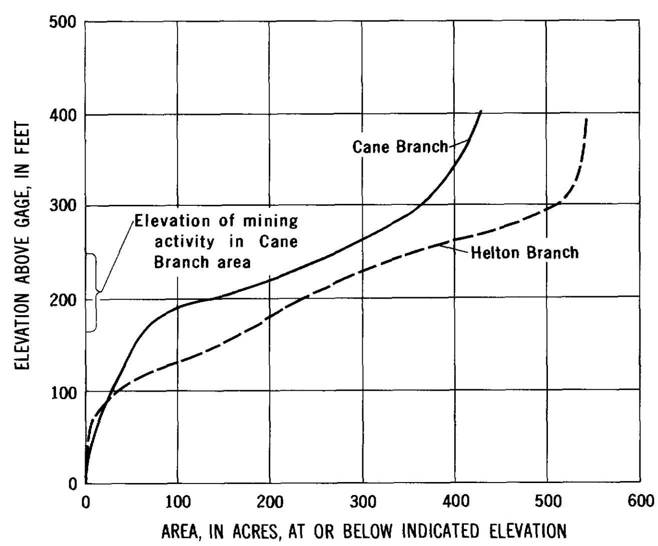


FIGURE 3.—Relationship of area and elevation above the gaging stations on Cane and Helton Branches

The five highest peaks at the gaging stations are listed in order of magnitude in the following table:

Order of magnitude	Cane Branch		Helton Branch	
	Date	Discharge (cfs per sq mi)	Date	Discharge (cfs per sq mi)
1	Jan. 29, 1957	296	Jan. 29, 1957	160
2	Apr. 24, 1958	230	Apr. 6, 1956	122
3	Apr. 6, 1956	146	Feb. 18, 1956	89
4	Nov. 18, 1957	143	Jan. 22, 1957	89
5	Feb. 18, 1956	125	Feb. 17, 1956	85

TABLE 6.—*Flood data for Cane Branch in water years from February 1956 to December 1959*

[Partial duration flood series: peak discharges more than 42 cfs per sq mi]

Date	Time	Gage height (feet)	Discharge (cfs per sq mi)
1956			
Feb. 3	6:15 a.m.	1.21	45
4	9:10	1.29	63
17	7:10	1.41	94
18	1:35	1.51	125
Mar. 14	6:30	1.47	112
Apr. 6	10:30 a.m.	1.57	146
1957			
Dec. 21	11:30 p.m.	1.40	91
Jan. 22	9:00	1.46	109
29	3:30 a.m.	2.43	296
Apr. 8	12:35 p.m.	1.215	46
1958			
Nov. 17	4:15 p.m.	1.43	100
18	8:00	1.56	143
Dec. 20	8:15 a.m.	1.245	54
Apr. 24	10:00 p.m.	1.76	230
1959			
July 19	4:40 p.m.	1.21	45
1960			
Dec. 18	8:50 p.m.	1.23	51

All these peaks, except perhaps those of April 6, 1956, were associated with "winter-type" storms, or storms generally of longer duration during which precipitation intensities were not particularly high. Similarly, practically all the peaks listed in tables 6 and 7 occurred during winter-type storms. By contrast, the "summer-type" storm, usually typified by one or more bursts of rainfall of high intensity, produces lesser peak flows.

TABLE 7.—*Flood data for Helton Branch in water years from January 1956 to December 1959*

[Partial-duration flood series: peak discharges above 21 cfs per sq mi]

Date	Time	Gage height (feet)	Discharge (cfs per sq mi)
1956			
Jan. 29	4:50 p.m.	1.27	34
30	6:45 a.m.	1.465	75
Feb. 4	11:00	1.21	45
17	7:40	1.31	85
18	1:40	1.21	89
Mar. 14	5:00	1.17	71
Apr. 6	10:45 a.m.	1.28	122
1957			
Dec. 22	2:15 a.m.	1.12	48
Jan. 22	10:30 p.m.	1.21	89
29	2:40 a.m.	1.35	160
Feb. 1	6:00 p.m.	1.02	23
Apr. 8	2:30 p.m.	1.03	25
1958			
Nov. 17	8:35 p.m.	1.08	41
18	8:00	1.155	64
Dec. 20	9:30 a.m.	1.07	32
Apr. 21	1:00 p.m.	1.00	24
25	1:55 a.m.	1.10	42
26	9:00 p.m.	.99	23
27	11:00	.98	21
May 7	12:55 a.m.	.995	23
1959			
June 2	3:30 a.m.	.98	21
1960			
Dec. 18	7:00 a.m.	1.14	56

Summer storms generally produce maximum or peak discharges which are less than the base selected for the tabulation in tables 6 and 7 for each gaging station. However, at Cane Branch these storms did result in significant increases in water discharge, whereas Helton Branch had only small increases. Significant increases in Helton Branch discharges are associated with "winter-type" storms.

The small number of summer peaks listed (tables 6 and 7) and the lower peak discharges and small runoff of summer storms show that the retention characteristics—including impediment of overland and subsurface runoff, retention for evaporation and transpiration, and possibly recharge of ground water—are good in both basins during the summer.

Maximum precipitation rates and amounts recorded during selected storms are listed in table 8. Data for noteworthy storms, whose yields totaled 1 inch or more of precipitation and whose durations were 30 minutes or more, are included in the table. The greatest precipitation, recorded during the storm of January 27–29, 1957, totaled 6.59 inches in Cane Branch and 7.39 inches in Helton Branch. Peak discharges for the period of record occurred during this storm. The second-highest precipitation was recorded during the storm of December 12–14, 1956, but the peak discharges reached were less than the respective bases used in compiling tables 6 and 7, owing to the low rainfall intensities. In general, the summer-type storms had more intense rainfall, but were of shorter duration. Winter-type storms were less intense, but had longer durations and therefore produced practically all the peak flows listed in tables 6 and 7.

The flood-peak data were analyzed by the partial-duration-series method. The flood-frequency graphs shown in figure 4 were constructed on the basis of the equation

$$T=\frac{N+1}{M},$$

in which T is the recurrence interval in years, N is the number of years of record (four at both stations), and M is the relative order of magnitude. Peaks were converted to cubic feet per second per square mile to reduce the effect of drainage-area difference. A flood peak was generally considered to be independent and was listed in the partial-duration flood series (see tables 6 and 7) if the lowest discharge reached between rises was 50 percent or less of the lowest adjacent peak.

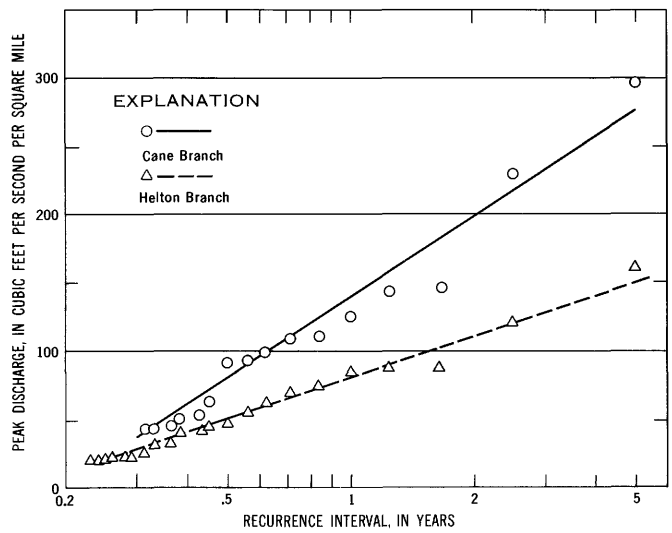


FIGURE 4.—Flood-frequency graphs, Cane and Helton Branches.

Though this rule was a fairly reliable criterion of independency, a more stringent rule, say 25 percent or less between rises, would have affected only the lower ends of the two curves shown in figure 4, with little or no change in their relative position.

The curves in figure 4 might be in error for the rarer events, but their relative position is not expected to change greatly for longer periods of record. The curves show that Cane Branch has a greater flood potential than Helton Branch. For example, the 5-year flood at Cane Branch is nearly twice that at Helton Branch. Relative basin size, 0.67 sq mi for Cane Branch as compared to 0.85 sq mi for Helton Branch, probably has little or no effect on the peaks per unit area.

Peak discharges are not reduced by channel storage.

TABLE 8.—*Maximum precipitation rates and amounts recorded in Cane Branch and Helton Branch basins during selected storms*

[Based on gage that recorded the greater rate and amounts in respective basin]

Date	Cane Branch basin						Helton Branch basin					
	Maximum precipitation rate or amounts (inches per hour) for periods indicated					Storm total (inches)	Maximum precipitation rate or amounts (inches per hour) for periods indicated					Storm total (inches)
	30 min	1 hr	2 hr	4 hr	8 hr		30 min	1 hr	2 hr	4 hr	8 hr	
1956												
Feb. 17–18	1.30	0.75	0.89	1.24	1.68	3.28	2.00	1.14	1.60	1.76	2.00	4.29
Mar. 13–14	1.02	.58	.65	.75	1.40	1.78	.82	.49	.56	.70	1.21	1.68
Apr. 6	.90	.50	.91	1.36	1.71	1.82	.52	.43	.72	1.17	1.56	1.64
July 1							1.10	.90	1.25	1.26	1.69	1.69
2	1.06	.65	.65	.66	.66	.66						
12–14	1.24	.63	.67	.68	1.07	1.88	1.22	.62	.72	.72	.97	2.03
23	1.00	.53	.79	.82	1.39	1.39	1.30	.78	.84	1.10	1.65	1.65
Aug. 19	1.20	1.05	1.30	1.43	1.44	1.44	1.10	.92	1.07	1.15	1.15	1.20
Dec. 12–14	.65	.46	.80	1.27	2.10	4.45	.60	.40	.70	1.20	1.99	4.30
21–22	1.60	1.00	1.30	1.85	1.98	1.98						
1957												
Jan. 27–29	1.00	.95	1.20	2.30	3.70	6.59	1.30	1.10	1.60	2.55	4.55	7.39
Apr. 8	.62	.37	.68	.91	1.20	1.46	.42	.31	.50	.76	1.02	1.30
June 23	1.80	1.24	1.59	1.83	1.85	1.85	.90	.55	1.03	1.21	1.22	1.22
Sept. 13	1.30	.80	1.00	1.14	1.55	2.14	.70	.47	.49	.86	.90	1.72
14	1.00	.70	.92	1.24	1.43	1.46	2.10	1.30	1.36	2.06	2.25	2.33
Oct. 23–24	1.04	.68	.72	.80	1.05	1.29	.60	.44	.45	.59	.84	1.18
Nov. 17	1.20	.84	.89	1.56	2.05	2.21	1.56	.83	.92	1.75	2.17	2.33
18	1.02	.65	1.01	1.58	1.74	2.04	1.10	1.05	1.50	1.75	1.96	2.32
Dec. 19–20	.42	.30	.60	.82	.95	1.83	.60	.42	.60	.87	1.07	1.95
1958												
Apr. 6	.92	.49	.50	.50	.50	.50	1.36	.75	.77	.77	.77	.77
24–25	1.80	.92	1.23	1.50	1.90	2.65	1.60	.86	.87	1.06	1.90	2.38
July 13	1.70	1.14	1.25	1.25	1.25	1.25	1.10	.92	1.10	1.10	1.10	1.10
Sept. 20–21	.60	.45	.65	.85	1.41	2.31	.82	.48	.60	.90	1.47	2.49

Stream slopes are steep in both basins (Musser, 1963) and the relatively small overbank areas provide little storage to attenuate peaks.

Surface storage in strip-mine pools can greatly reduce peak runoff rates, particularly where large subareas drain into such pools. The extent of these subareas, extent of surface areas of the pools, and the pool fluctuations were not determined. There were, however, times during the mining operations when the pools were drained and the released water was measured at the Cane Branch gaging station. Of a total of 23 releases, several of the larger ones (after subtracting base flow) were computed, in acre-feet, as follows:

1956		*1958*	
Feb. 7	0. 40	Oct. 27–28	0. 56
Feb. 8	. 34	*1959*	
Mar. 15	. 60	Jan. 24	0. 67
Mar. 19–22	5. 16	Jan. 30–31	. 38
Apr. 11	1. 11	Apr. 15	. 60
June 18–19	2. 56	Aug. 17	. 77

These releases are not large in volume; however, depending upon the nature of the subareas and the length of the storm period, their effect on peak runoff rates could become magnified. For example, 1 acre-foot stored during a 2-hour storm might reduce the peak by as much as 12 cfs, or 18 cfs per sq mi from the Cane area. If it is assumed that the pools are filled to their outlets, which probably was the case during winter storms, the effect on the peak at the gaging station would be negligible.

Comparisons of time intervals from beginning of increasing discharge to maximum discharge at the gaging stations during winter-type storms are given in figure 5, and during summer-type storms in figure 6. The winter-type storms usually occurred from November to about the middle of April, and the summer-type storms occurred during the remaining months. Precipitation during the storms was generally continuous. The relationship shown in figures 5 and 6 indicates that the lag at Cane Branch is about 1 hour and 10 minutes less than at Helton Branch. The few winter storms during the 1959 water year suggest that the relative lag may be even greater. This is equivalent to a progressive shortening of the lag of Cane Branch runoff and may be attributable to the additional strip mining started during September 1958 in the northeastern part of the study area. This strip mining took place closer to the gaging station than earlier operations. The flow-duration curves and peak discharges indicate that Cane Branch has a greater direct runoff and greater flood potential than Helton Branch. The greater direct runoff and greater peak flows of Cane Branch are due in part to a difference in land cover resulting from strip mining in the Cane Branch area and in part to differences in basin shape. The stream channel system of Cane Branch is shorter than that of Helton Branch, so

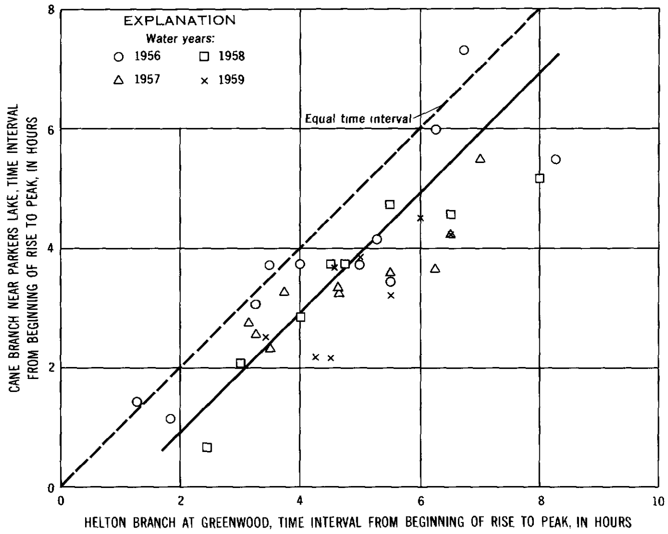


FIGURE 5.—Comparison of time intervals from beginning of rises to peaks during winter storms, Cane and Helton Branches.

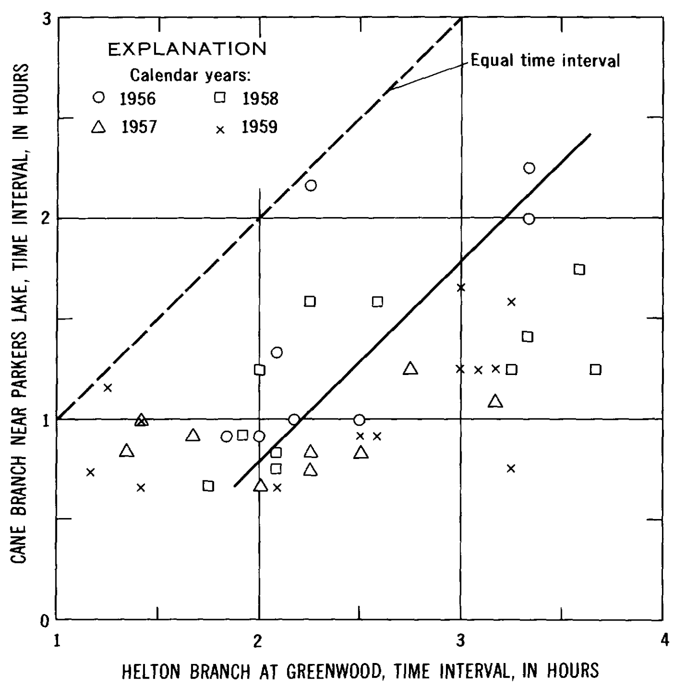


FIGURE 6.—Comparison of time intervals from beginning of rises to peaks during summer storms, Cane and Helton Branches.

flow in defined channels reaches the Cane Branch gage with less delay.

FLOOD HYDROGRAPHS

The shape of the hydrographs and the magnitude of peak discharges are related to season, antecedent moisture conditions, and storm duration and intensity. Because the Cane Branch and Helton Branch basins are small, the effect of these parameters on a flood hydrograph can be recognized.

Graphs of discharge, in cubic feet per second per square mile, and accumulated precipitation during selected storms are plotted in figure 7. Accumulated

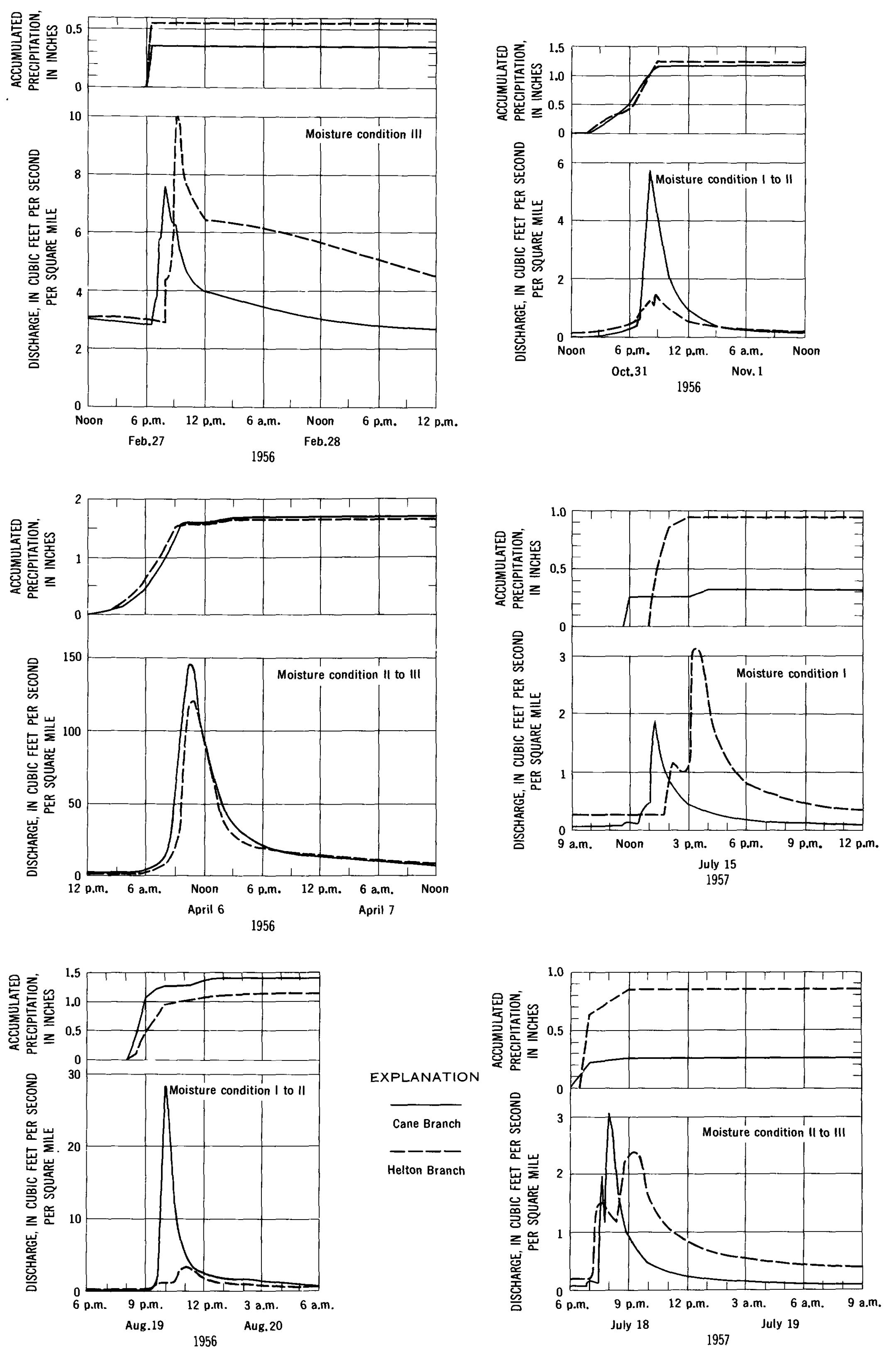
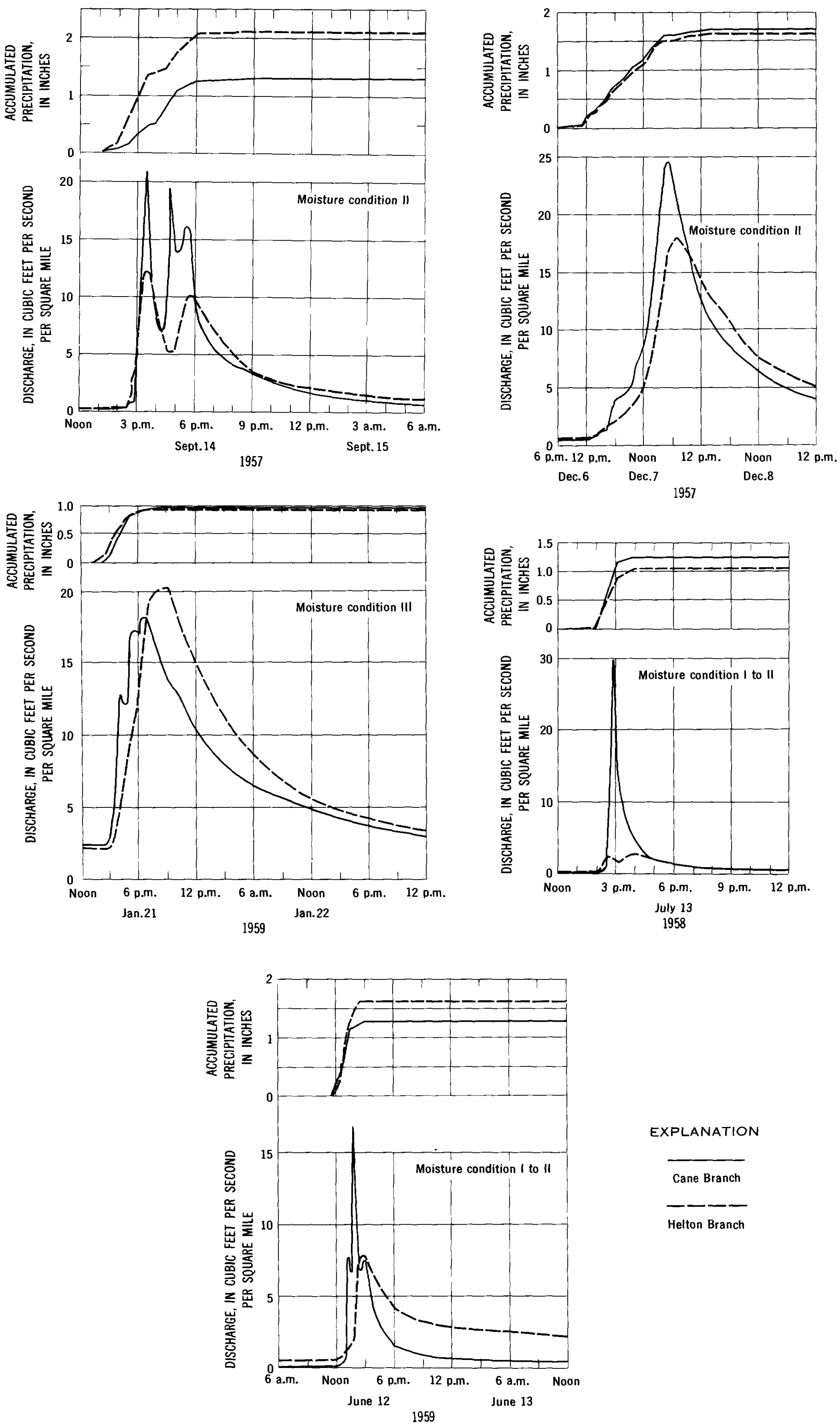


FIGURE 7.—Graphs of discharge and



accumulated precipitation.

precipitation is the average of accumulations at the two recording gages in each basin.

The graphs cover the seasons of the year and a variety of storm and antecedent conditions. Storms during the period November to about the middle of April are classed as "winter-type." During such storms, precipitation is usually of longer duration and lower intensity than at other times of the year. The summer-type storm, as previously stated, is usually characterized by one or more short bursts of precipitation of high intensity.

Antecedent moisture conditions in the basins at the beginning of each storm are indicated on the graphs. These correspond with soil moisture conditions I, II, and III as outlined in the "Hydrology guide for use in watershed planning" (Mockus, 1955), and were assigned on the basis of the direct runoff that occurred rather than the 5-day antecedent precipitation.

The graphs for April 6–7, 1956, October 31–November 1, 1956, December 6–8, 1957, July 13, 1958, and June 12–13, 1959 (fig. 7) show that Cane Branch had higher peak flows than Helton Branch when precipitation in the basins was about equal. Storms of February 27–28, 1956, July 15, 1957, July 18–19, 1957, and September 14–15, 1957 (fig. 7), are examples of heavier precipitation in the Helton Branch study area and show that, during summer storms particularly, two to four times as much precipitation is required in the Helton basin to produce a discharge equal to that of Cane Branch.

The rises of August 19–20, 1956, and July 13, 1958 (fig. 7) occurred under similar conditions. The Cane Branch peaks were many times greater than the Helton Branch peaks, although differences in precipitation do not altogether account for the disparity.

The discharge graphs for the storm of January 21–22, 1959 (fig. 7), is one example when the Helton Branch peak was greater than the Cane Branch peak. Discharges during this rise were intensified to some degree by snowmelt. The lowest winter temperatures occurred earlier in the month and most of the precipitation fell as snow. This rise is noteworthy because the greater direct runoff and peak rate of Helton Branch indicate retention of a greater proportion of the antecedent precipitation.

Rises at Cane Branch are sharper and are more responsive to changes in precipitation rates. The Helton Branch area retains a greater part of the initial precipitation, particularly in the summer, than does the Cane Branch area. In addition to the storms shown on the graphs for August 19–20, 1956, October 31–November 1, 1956, and July 13, 1958 (fig. 7), there were many brief but intense summer storms that produced well-shaped hydrographs at Cane Branch but only perceptible rises at Helton. Significantly, bare or strip-mined areas with well-defined channels to Cane Branch allow precipitation due to summer storms to become runoff almost immediately.

BASE FLOW AND STORAGE

Low and base flows represent an integration of the various ground-water factors of a basin. As a direct measure of the rate of release of ground-water effluent, low and base flows of surface streams are related closely to the geologic features and land-use practices of the area drained and are indicative of the quantities stored and the recharge characteristics. Base flow supported by ground-water effluent from a relatively deep-seated source generally will be more constant, and possibly larger, than from perched water bodies of small areal extent. Effluent from coarse materials near the surface, sometimes referred to as subsurface runoff, and from shallow perched ground-water areas which occurs almost immediately after a storm is not considered to be a part of the base-flow characteristics.

Base-flow recessions of Cane and Helton Branches are plotted in figure 8. The curves were based on an analysis of 5-day recessions observed during periods of no precipitation, so as to exclude direct storm runoff. At each station, no difference was noted between recessions for the dormant and growing seasons. This fact indicates that most of the water table is below the

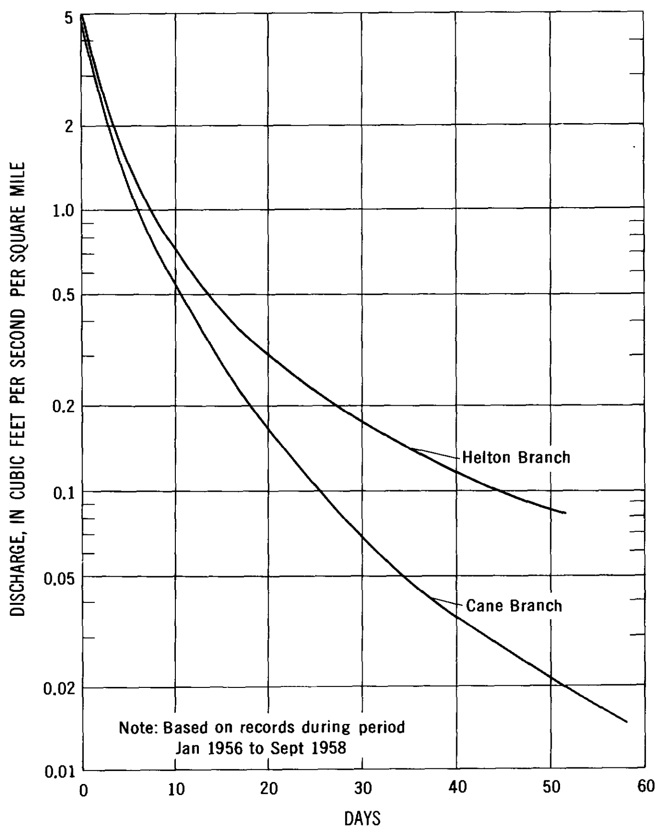


FIGURE 8.—Base-flow recession curves, Cane and Helton Branches.

root zone. The initial point of the recessions is about 5 cfs per sq mi, and the lower limits are equal to the respective minimum daily discharges observed during the period ending September 30, 1958.

The curves indicate that Cane Branch has a lower base flow than Helton Branch. For example, after 22 days the unit discharge of Cane Branch decreased to one-half that of Helton Branch. Near the end of the defined recessions, discharge of Cane Branch amounted to only one-fourth or less that of Helton Branch.

Depletion of storage with time, is shown by the curves in figure 9. The curves define the storage remaining in the basins and include the storage equivalent of flows greater than the end-point discharges of the base-flow recessions. The storage equivalent of lesser discharges is minor and is not included. The storage depletion curves illustrate not only the comparative deficiency of ground waters stored in the Cane Branch basin, but the small equivalent depth of such waters in both basins. For example, 5 days after the end of direct surface runoff from a moderately high rise, storage in Cane Branch basin decreased sharply to 0.37 inch as compared with 0.58 inch in Helton Branch. After about 12 days, storage in Cane Branch amounted to only 0.16 inch, or less than one-half that remaining in Helton Branch basin.

The curves in figure 10 show the relationship of base-flow discharge and storage in the two basins. These curves were constructed from the data used in figures 8 and 9.

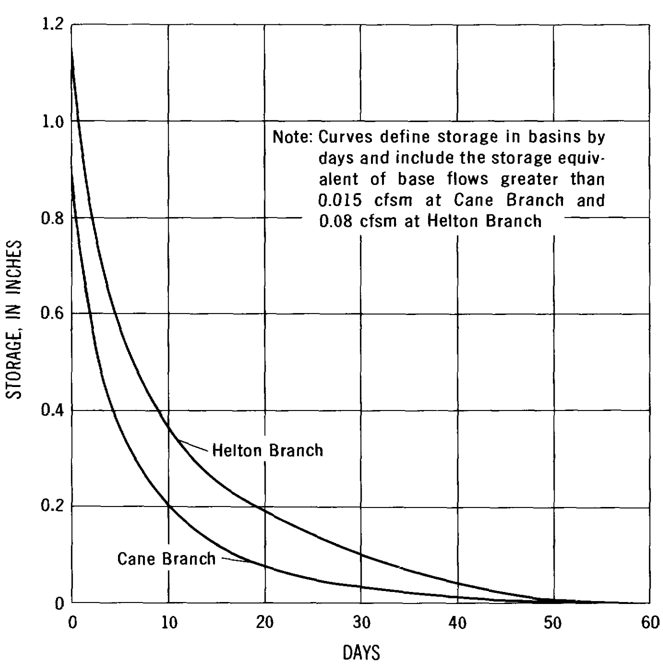


FIGURE 9.—Curves showing depletion of storage with time, Cane Branch and Helton Branch basins.

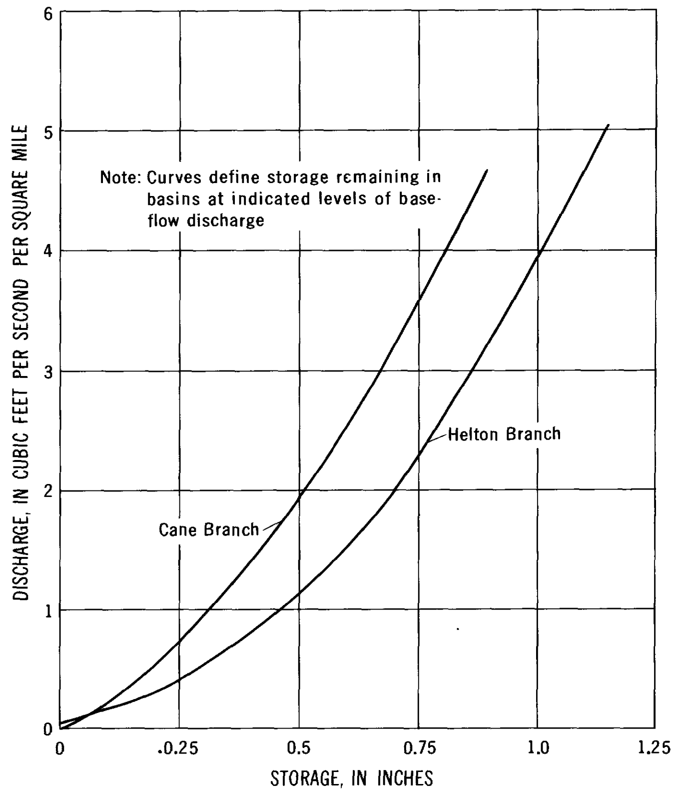


FIGURE 10.—Relationship of base-flow discharge and storage in basins, Cane and Helton Branches.

The large difference in base-flow recession and storage characteristics of Cane and Helton Branches (see figs. 8–10) cannot be accounted for by chance or by the shortness of the flow records. Geology probably has the greatest effect on these characteristics. However, soils may provide additional capacity for ground-water storage and affect the rate of recharge of the deeper ground waters. Land cover and use also affect the opportunity for recharge.

Differences in the geology of the two areas could account for the differences in the base flow and storage. The Helton Branch area has proportionately more sandstone and less siltstone and claystone than the Cane Branch area. The sandstone has better water-bearing qualities and thus is able to support the base flow of Helton Branch. A greater part of the water stored in the sandstone is probably released through fractures.

Both study areas contain similar proportionate areas of soils of high permeability. These permeable soils probably contribute little water to the long-term base flow because much of the water drains to the streams shortly after recharge. However, some water is contributed to the underlying sandstone and is available for the support of base flow.

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The strip-mine spoil banks in Cane Branch basin have little vegetal cover and are clayey and relatively impervious. This material offers little capacity for ground-water storage and thus contributes little to long-term base flow. Moreover, these banks tend to reduce to a minimum the recharge of more porous soils and formations (generally the cliff-forming sandstones) at underlying levels.

MONTHLY RUNOFF AND WATER LOSSES

A relationship of concurrent monthly runoff of two basins in close proximity shows the relative yield at various levels of flow and often reveals time trends that are not apparent in other analyses. Departure of the relationship from equal yield is attributable generally to differences in precipitation, evapotranspiration, and ground-water storage.

A plotting of concurrent monthly runoffs of Cane and Helton Branches is shown in figure 11. Above 1 cfs per sq mi, the runoff of Cane Branch is slightly more than that of Helton Branch. The points for months of low runoff are scattered, but indicate less runoff in Cane Branch than in Helton Branch. Whether the difference in flow is inherent and existed before strip mining began is not known. The scatter can be accounted for only in part by differences in precipitation.

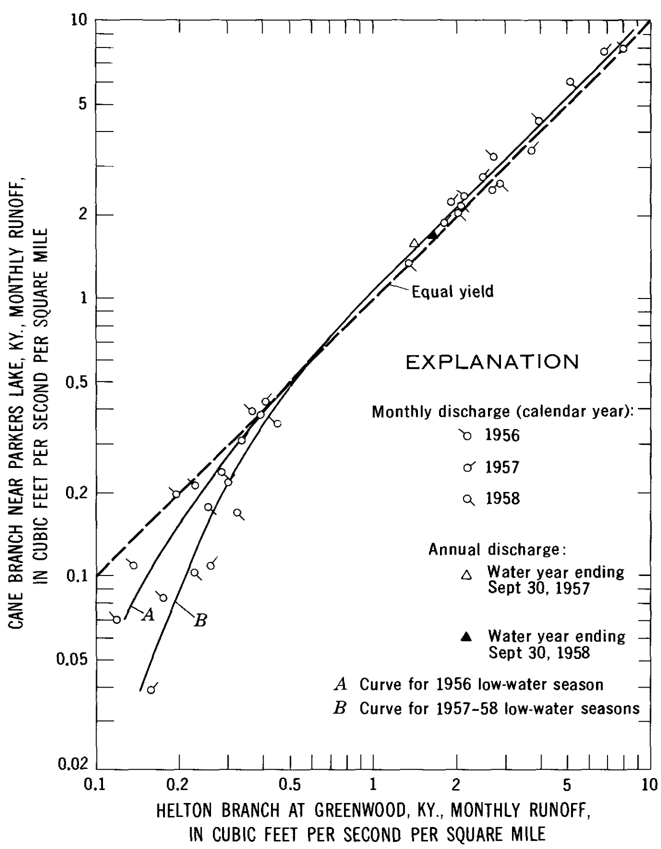

FIGURE 11.—Comparison of concurrent monthly runoffs, Cane and Helton Branches.

Two curves were drawn for the low-runoff months; curve A is based on the points for 1956 and curve B on the points for 1957 and 1958. Both streams had more runoff during the 1957–58 low-flow seasons than during the 1956 low-flow season, but the 1957–58 curve is shifted to the right because Cane Branch had a proportionately smaller increase.

The change in the low-flow relationship from 1956 to 1957–58 cannot be definitely evaluated because of the short period of record available. However, some possible causes are known. The increase in the Helton Branch runoff during the 1957–58 low-flow seasons was a natural increase as there were no activities of man to change the runoff characteristics of that basin. Although strip mining ceased in the Cane Branch area in 1956, the physical changes caused by mining probably affected the runoff of Cane Branch. The effects of these physical changes are complex and can result in either a reduction or increase in runoff.

Storage of water in artificial pools in the mine area tends to keep evaporation losses high and would reduce direct runoff and thus reduce the water yield from Cane Branch. Similarly, impervious spoil banks would tend to reduce ground-water recharge and storage for the support of base flow. Conversely, the removal of vegetation reduces the water loss by evapotranspiration and increases the amount of runoff.

The comparative runoffs of the two basins during low-runoff months corroborates studies of flow duration (fig. 2) and base flow and storage (fig. 8–10). Statements on geologic features given earlier in the section are applicable generally to the monthly runoffs.

Monthly precipitation-runoff differences in the two basins are plotted linearly in figure 12. These differences, commonly called water loss, are equal to storage changes plus evapotranspiration losses. It is assumed that underground flow out of the basins is negligible owing to the low permeability of the bedrock. (See section on "Ground Water.") The trends of high losses during the growing season and during months when higher temperatures prevailed and of small losses during winter months are subject, of course, to the availability of moisture for evapotranspiration. Small losses in May, September, and November 1956, August 1957, and February and August 1958 are attributable for the most part to precipitation which totaled less than 2 inches. Approximately half of the precipitation during February 1958 fell as snow and contributed little to runoff; hence, most streamflow came from ground-water storage. A slow thaw began near the end of the month, and snow of February appeared as runoff in March.

Monthly changes in ground-water storage, based on month-end base flows and graphs shown in figure 10, are plotted in figure 13. Actual month-end storage in Cane Branch basin ranged from practically zero in August 1957 to 0.76 inch in January 1957, whereas Helton Branch storage ranged from 0.034 inch in September 1956 to 1.09 inches in January 1957.

Evapotranspiration losses are estimated by adjusting the water-loss values (fig. 12) for changes in ground-water storage (fig. 13). A further adjustment for changes in soil moisture would provide a better estimate of evapotranspiration, but these changes were not defined. Monthly evapotranspiration in the two basins is plotted in figure 14. Differences in evapotranspiration in the basins during January, May, and July 1957, and May, June, and July 1958 are attributable to precipitation differences.

Precipitation, water loss, and evapotranspiration, in

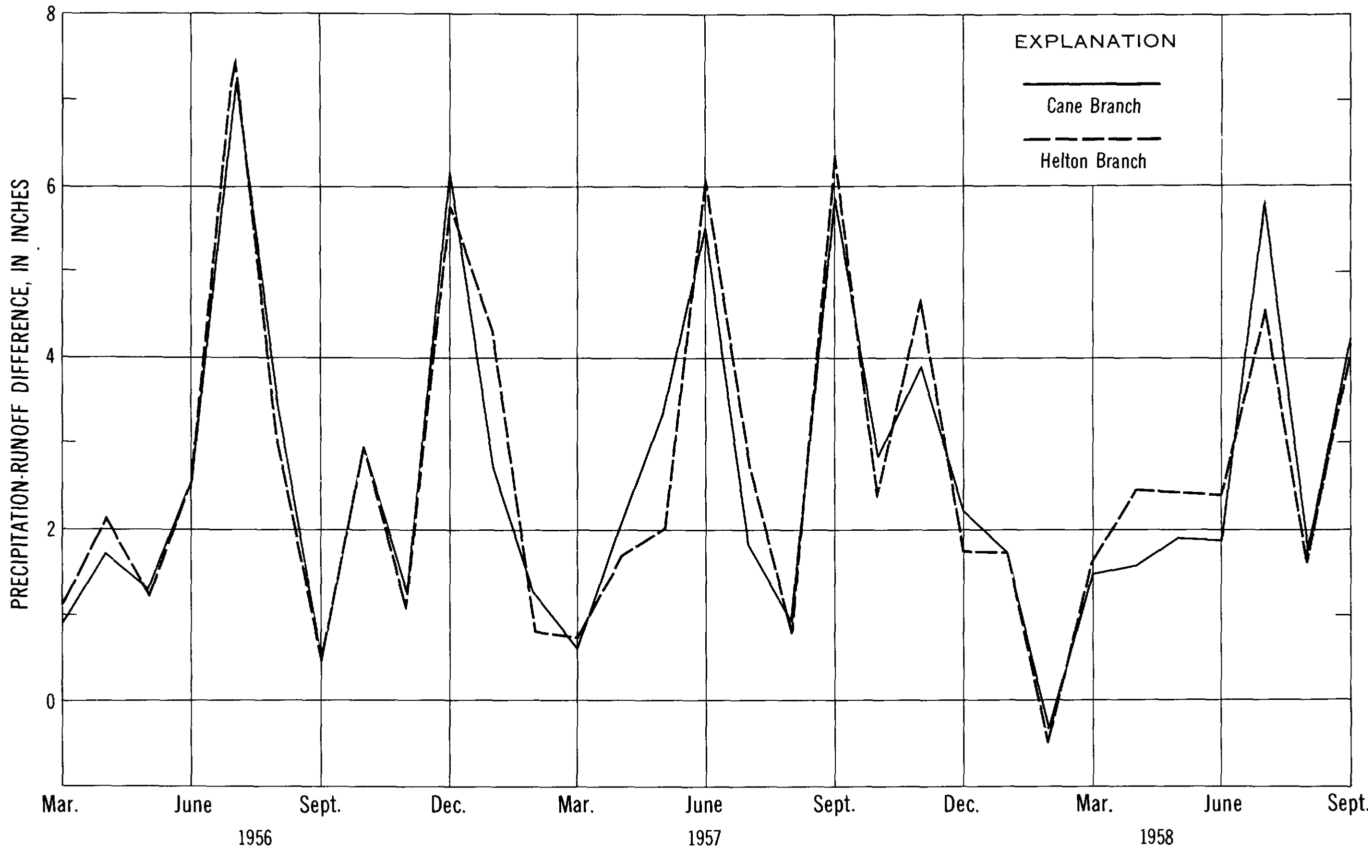

FIGURE 12.—Monthly precipitation-runoff differences, Cane Branch and Helton Branch basins, March 1956 to September 1958.

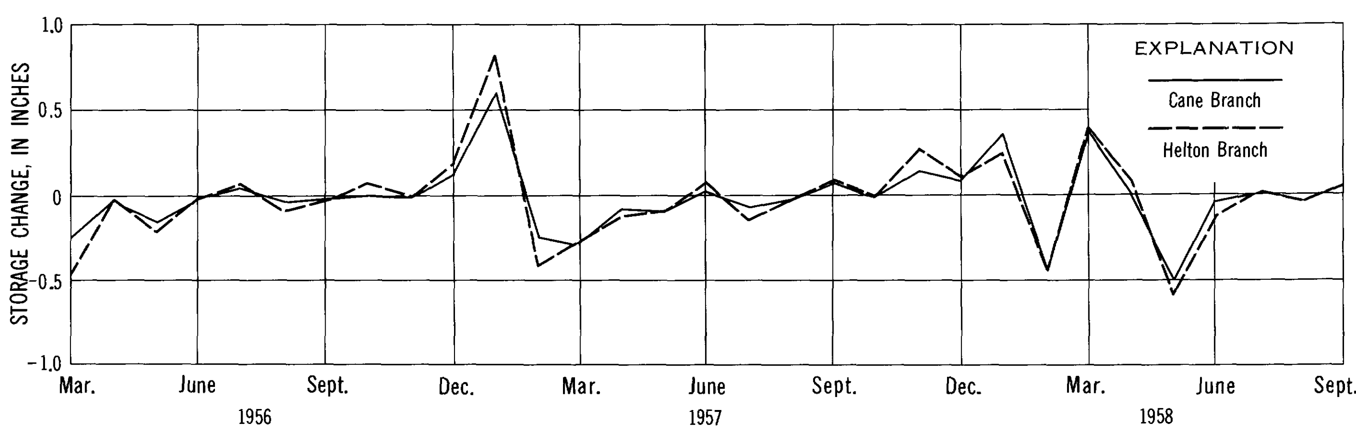

FIGURE 13.—Monthly change in ground-water storage contributing to base runoff, Cane Branch and Helton Branch basins, March 1956 to September 1958.

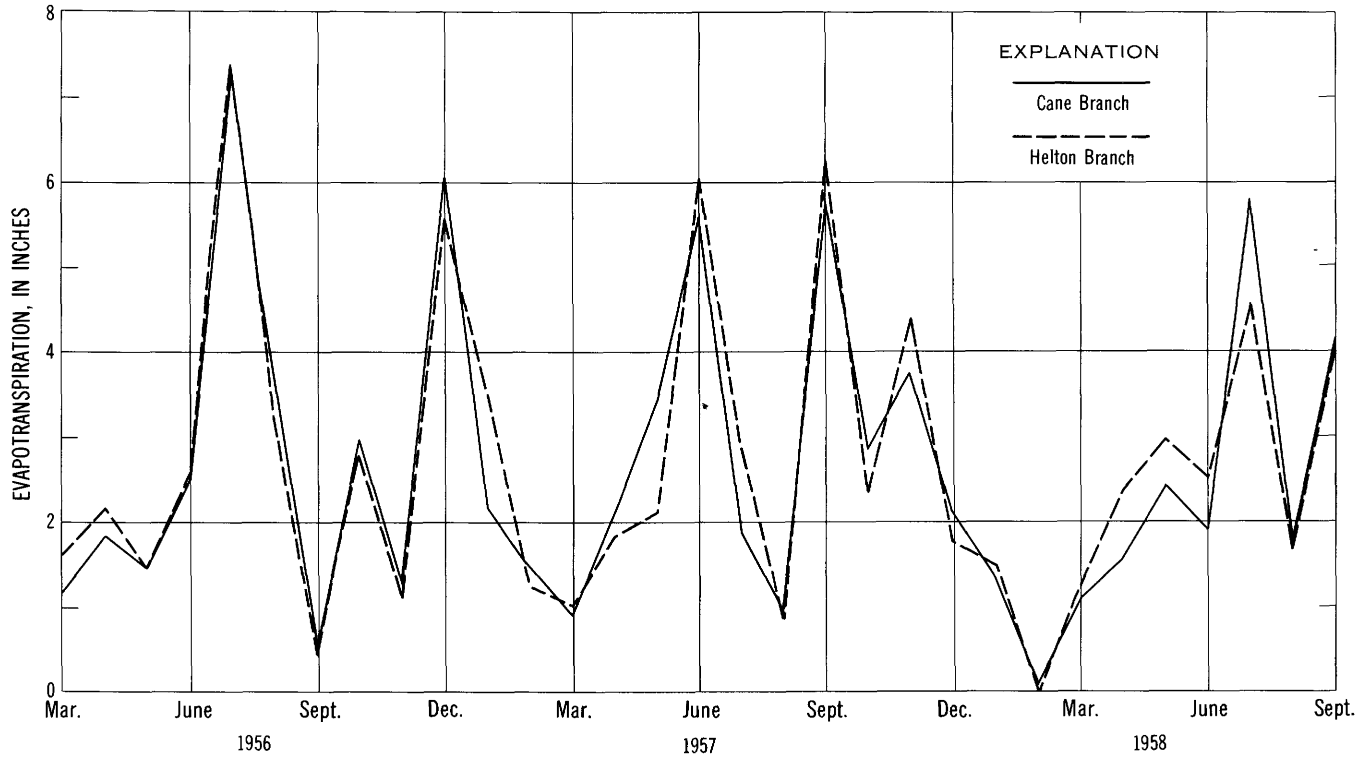

FIGURE 14.—Monthly evapotranspiration in Cane Branch and Helton Branch basins, March 1956 to September 1958.

inches, during the period March to September 1956, and the water years 1957 and 1958 are listed in the following table for comparison:

	Cane Branch			Helton Branch		
	Precipitation	Water loss	Evapotranspiration	Precipitation	Water loss	Evapotranspiration
Mar. to Sept. 1956	27.98	17.87	18.28	27.18	18.02	18.79
Water year:						
1957	56.19	34.62	34.58	55.75	35.17	35.05
1958	52.00	28.96	28.96	51.92	29.35	29.34

Adjustments for ground-water storage contributing to base flow were relatively minor except for the period March to September 1956. During each period, evapotranspiration in Cane Branch basin was slightly less than in the Helton Branch basin, even though precipitation was greater. These smaller evapotranspiration amounts may be due to loss of vegatal cover in the Cane Branch mining area, but this interpretation is only conjecture. A longer period of record and a wider range of precipitation and evapotranspiration would permit a more conclusive interpretation.

CONCLUSIONS

Studies of streamflow data collected since strip mining began show marked differences in the runoff characteristics of the Cane Branch and Helton Branch basins. These differences are apparent even from the short period of record.

Cane Branch has a much greater flow variability than Helton Branch. The studies show that conditions in Cane Branch basin are less favorable toward the retention of runoff during both winter and summer storms. The flood potential of Cane Branch is nearly twice that of Helton Branch. Moreover, Cane Branch has a much shorter lag than Helton Branch. Many brief but intense summer storms produce significant increases in water discharge at Cane Branch but only small increases at Helton Branch.

Base-flow-recession and storage-depletion curves corroborate the lower discharge of Cane Branch at greater percentages of time, as indicated by Cane Branch's flow-duration curve. Similarly, the study of concurrent monthly discharges substantiates further the comparative flow-duration characteristics of the two basins. Water loss and evapotranspiration are slightly less in the Cane Branch basin.

The effects of land cover and use changes brought about by strip mining are not readily separable from other factors of the hydrologic environment—such as climate, geology, soils, basin shape, and stream slope—which affect the runoff regimen. The runoff characteristics of Helton Branch are representative of the characteristics over a much longer period of time because no major changes in land cover and use have occurred in the basin for many years. On the other hand, Cane Branch data probably reflect, to an unknown degree, the changes in land cover and use resulting from strip mining in the basin.

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Musser, J. J., 1963. Description of physical environment and of strip-mining operations in parts of Beaver Creek basin, Kentucky: U.S. Geol. Survey Prof. Paper 427–A, 25 p.

GROUND WATER

By WILLIAM E. PRICE, JR., U.S. Geological Survey

METHODS OF STUDY

The objectives of the ground-water study are to determine how much, if any, ground water seeps from the spoil banks and, if it does, where it goes. The study is also concerned with the effect of the ground water in the spoil banks on the natural ground water and the surface water in the area; this effect is discussed in more detail in the section on "Geochemistry of water." An inventory was taken of one water well, six coal-test holes, and three springs in the area. In addition, 14 holes were augered in the spoil banks. The coal-test and auger holes were cased so that water-level measurements and samples of water for chemical analysis could be collected periodically from them.

Each auger hole, coal-test hole, well, and spring inventoried during this investigation was numbered consecutively from 1 to 24 and also given a number based on the Kentucky plane-coordinate system. These numbering systems are listed in table 9 and the locations of the holes and springs are shown on plates 1 and 2.

TABLE 9.—*Sources of ground-water data*

Hole or spring	*Description*	*Kentucky plane-coordinate number*
1	Auger hole in spoil bank, Cane Branch area	S–2,381.48–194.55
2	do	S–2,381.47–194.59
3	do	S–2,381.44–194.62
4	do	S–2,381.41–194.68
5	do	S–2,381.39–194.72
6	do	S–2,381.37–194.77
7	do	S–2,381.36–194.79
8	do	S–2,381.31–194.68
9	do	S–2,381.32–194.69
10	do	S–2,381.43–194.75
11	do	S–2,381.48–194.77
12	Well at toe of spoil bank, Cane Branch area	S–2,381.84–194.62
13	Auger hole in spoil bank, Cane Branch area	S–2,382.28–194.63
14	do	S–2,382.33–194.64
15	do	S–2,382.42–194.66
16	Coal-test hole above spoil bank, Cane Branch area.	S–2,381.29–195.12
17	Coal-test hole, West Fork Cane Branch area	S–2,380.17–195.21
18	do	S–2,380.02–195.09
19	do	S–2,379.47–194.63
20	do	S–2,379.28–194.52
21	do	S–2,379.15–194.43
22	Spring, Helton Branch area	S–2,368.95–198.33
23	do	S–2,367.69–199.18
24	do	S–2,367.97–199.38

GROUND-WATER HYDROLOGY

NATURAL CONDITIONS IN THE AREA

Ground water is derived almost entirely from local precipitation. Part of the water that falls as rain or snow runs off directly over the land surface to streams; part of it percolates downward into the soil where it is stored and later transpired by plants or evaporated. The water that does not become runoff or that escapes transpiration and evaporation percolates downward through the soil and underlying strata until it reaches the water table, where it joins the body of ground water in the zone of saturation.

In the Beaver Creek area, as in most of the Eastern Coal Field, the boundaries of ground-water drainage are approximately the same as the boundaries of surface drainage. The slight dip of the beds and the orientation of fracture openings cause some variation in ground-water drainage, but the variations probably are of small magnitude. Slow movement of water at great depth is more or less independent of local topography, and the water at this depth is probably not significantly affected by strip mining.

Water levels in coal-test holes in the valley of West Fork Cane Branch (fig. 15) indicate that shallow ground water moves from topographically high areas to discharge into streams, as is normal in humid regions. Water-table conditions are shown in figure 15; actually, the water table is much more irregular than shown, owing principally to variations in the permeability of the aquifer.

The position of the water table in the area also varies with the season. Figure 15 shows that the water table was much higher on May 8, 1958, than it was on Novem-

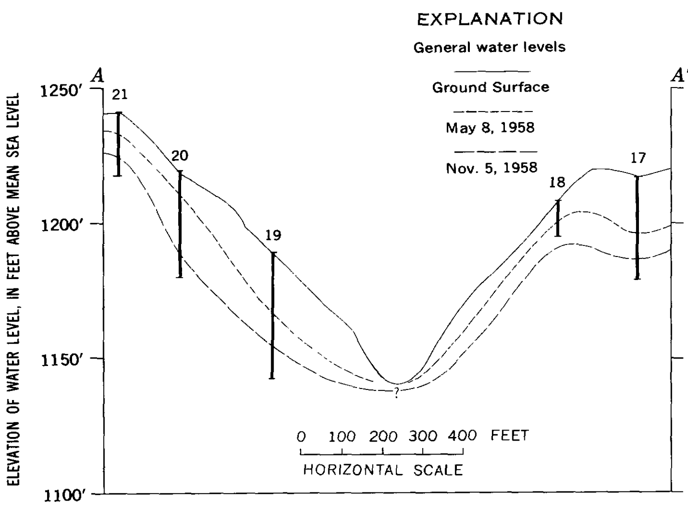

FIGURE 15.—Section *A–A'* on plate 1 across West Fork Cane Branch basin, showing water levels in coal-test holes.

ber 5, 1958; these dates represent the approximate times when the water table was at its highest and lowest for the period of record. Generally, water levels in the coal-test holes are lowest in the late fall or early winter and highest in the spring. These seasonal variations are caused primarily by changes in the rate of ground-water recharge. Because nearly all plants draw their water from the soil zone, and because water must pass through this zone before it reaches the ground-water reservoir, less water reaches the zone of saturation in the Beaver Creek area during the summer when plants are growing than during the winter when plants are dormant.

Seasonal water-level fluctuations are shown in more detail in the hydrographs of coal-test hole 20 and auger hole 6 in figure 16. The large fluctuations in coal-test hole 20, in bedrock, are due in part to the presence of nearby vegetation. Auger hole 6, in spoil bank material, is relatively far from vegetation and shows little or no seasonal variation.

In the Beaver Creek area, ground water undoubtedly moves through both intergranular and fracture openings, but the relative amounts of water moving through the two types of openings have not been determined. The distinction may be important in the present study because the water moving through fractures generally moves faster than that in intergranular openings, and, therefore, contamination from strip-mining operations would spread faster through the fracture openings.

The bedrock of the Beaver Creek area belongs to the Lee Formation of Pennsylvanian System (Musser, 1963). Waters from the coal-test holes are chemically similar so those in the Lee Formation elsewhere in the Cumberland Plateau of the Eastern Coal Field (Otton, 1948, and G. W. Whetstone, written communication, 1961) but they are less highly mineralized. The smaller degree of mineralization is due to the recharge and discharge of ground water in a high topographic

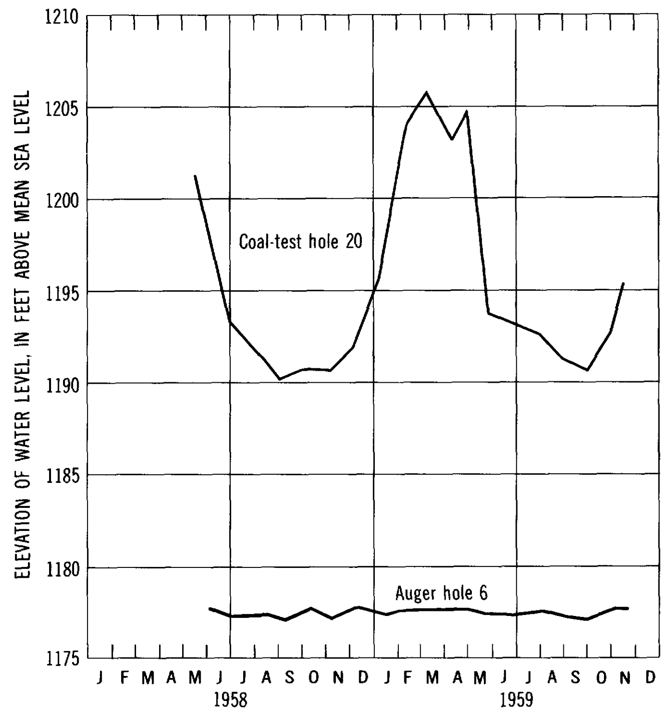

FIGURE 16.—Hydrographs showing elevations of water levels in a coal-test hole and an auger hole in the Beaver Creek area.

position and at shallow depth. Water from the springs is less highly mineralized than that from the coal-test holes probably because the water from the springs has moved through relatively insoluble formations. Waters from the springs in Helton Branch are similar to those collected from the Lee Formation elsewhere in the Cumberland Plateau of the Eastern Coal Field. The chemistry of the ground waters in the Cane Branch, West Fork Cane Branch, and Helton Branch study areas is discussed in the section on "Geochemistry of water." The maximum, median, and minimum values of some of the constituents and properties of these waters are presented in table 10.

TABLE 10.—*Maximum, median, and minimum values of selected chemical constituents and properties of ground water from the Beaver Creek area, March 1958 to November 1959*

[Results given in parts per million except as indicated]

Type of hole or spring	Number of holes or springs	Number of analyses	Range	Silica (SiO_2)	Aluminum (Al)	Iron (Fe)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Immediate acidity (H^+)	Specific conductance (micromhos at 25° C)	pH
Water well	1	11	Maximum	26	0.3	3.1	28	51	0.7	387	7.0
			Median	22	.1	.61	6	44	.1	357	5.8
			Minimum	9.1	.0	.20	4	29	.1	259	5.1
Auger holes	14	69	Maximum	67	102	380	395	2,220	13	3,720	7.0
			Median	22	5.5	84	0	803	7.0	1,640	2.80
			Minimum	4.0	.0	.04	0	4.6	.8	91	2.40
Coal-test holes	6	71	Maximum	25	2.3	27	82	308	1.2	649	7.5
			Median	11	.1	1.3	16	16	.3	105	6.1
			Minimum	6.5	.0	.05	0	5.4	.0	23	3.80
Spring 22	3	3		6.6		.25	3	1.2		11	5.8
23				6.2		.38	7	6.6		43	5.8
24				8.2		.20	9	2.2		25	6.0

EFFECT OF STRIP-MINING OPERATIONS

Strip mining affects the ground-water regimen above, at, and below the strip-mined area. Because strip mining alters the shape of the hillside on which the mine is located and the water table bears some relation to the hillside topography, strip mining alters the shape of the water table. The movement of ground water in the area has a strong horizontal component, especially where impermeable beds, such as the underclays of coal, are present. Exposure of a fresh rock face by removal of the overburden may cause ground water to flow freely to the surface. The drift mine in Cane Branch functioned as an infiltration gallery, yielding water, some of which had to be pumped out during the time the mine was operating. On September 30, 1958, and November 17, 1958, discharge from the mine was measured with a flume and found to be 6 and 4.5 gpm (gallons per minute), respectively.

The water table above the level of the strip-mine and drift-mine workings was probably lowered. However, this lowering could not be determined because no observation wells were available immediately above the mined area.

An attempt was made to determine the effects of mining on the ground-water hydrology at and below the stripped area by data from 14 holes augered in the spoil bank. These holes were cased so that water-level measurements could be made and water samples collected from them. Holes 1 to 6, 9, 10, 13, and 14 were drilled until resistance prevented further deepening. Probably most of the holes penetrated the entire thickness of the spoil bank and were bottomed in bedrock. Some, however, may have been stopped by a large rock imbedded at depth in the spoil material. The character of this material, which is described in the field logs in table 11, is clay intermixed with smaller amounts of sand, silt, coal, or shale. Sandy clay was found a short distance above rock in holes 2, 3, and 4. Auger hole 8 was not logged but penetrated only a thin cover of spoil; most of the hole was in rock mantle. Chemical analyses of the spoil-bank materials are discussed in the section "Geochemistry of water."

TABLE 11.—*Field logs of nine auger holes in the main spoil bank of the Cane Branch area*

Material	Thickness (feet)	Depth (feet)
Auger hole 2		
Shale, black	3	3
Clay, tan	1	4
Clay, brown	1	5
Clay, brown, silty	3	8
Clay, dark brown	2	10
Clay, gray-green	2.5	12.5
Clay, brown	4.5	17
Clay, tan, trace of fine sand	.5	17.5

TABLE 11.—*Field logs of nine auger holes in the main spoil bank of the Cane Branch area*—Continued

Material	Thickness (feet)	Depth (feet)
Auger hole 3		
Shale, black	1.5	1.5
Clay, brown	10.5	12
Clay, green	5	17
Silt, gray, fluid	1	18
Clay, green, trace of fine sand, moist	4	22
Clay, dark brown	2	24
Auger hole 4		
Shale, black	3	3
Clay, brown	2	5
Clay, dark brown	3	8
Clay, buff	4	12
Clay, brown	5.5	17.5
Clay, gray, silty	1.5	19
Clay, gray-green, trace of medium sand	1.5	20.5
Auger hole 5		
Shale, black, and coal	1	1
Clay, brown, and coal	4	5
Clay, buff, ironstone nodules	3	8
Clay, green	2	10
Clay, mottled orange and tan	5	15
Shale, black	3	18
Auger hole 6		
Shale, black	4	4
Clay, dark gray	7	11
Clay, black, soft	3	14
Clay, black, soft, fluid	2	16
Clay, black; on top hard black shale	2.5	18.5
Auger hole 9		
Shale, black, and coal	2	2
Clay, brown	2.5	4.5
Clay, gray, green	2.5	7
Clay, green, lighter than sample above	3	10
Clay, dark brown	1	11
Clay, black, hard	6.5	17.5
Auger hole 10		
Shale, black, and coal	2.5	2.5
Clay, brown, and coal	3.5	6
Clay, buff	4	10
Clay, dark brown	4	14
Clay, black, hard	5	19
Auger hole 13		
Shale and coal	1	1
Clay, brown	2	3
Clay, red	4	7
Clay, reddish-brown, silty	4	11
Auger hole 14		
Shale, black, and coal	2	2
Clay, gray-green, and coal	5	7
Clay, brown, trace of coarse material	1	8
Clay, green	6	14

Thirteen of the test holes were cased with 2-inch plastic casing slotted in the bottom 10 feet; one test hole was cased with 4-inch plastic casing slotted in the same manner. Sand from crushed local Lee sandstone was packed around the slotted part of each casing, and the upper part of the holes were backfilled with clay and silt brought up by the auger. Local sand was used to pack the screens because the material would be expected to have little effect on the quality of water obtained from the holes.

During the period of study, water was found in all auger holes except hole 15. Probably some of the water was in the material when it was bulldozed into its present position, but this water now is only a part of the ground water in the spoil pile. The shape of the water table and its seasonal fluctuations indicate that water is recharging and is being discharged from the spoil bank.

Water may be moving into the spoil bank from beneath by way of the underlying bedrock, but there is no information concerning this possibility.

Precipitation may directly recharge the ground water in the spoil bank. The amount of recharge from this source is probably small, however, because the spoil is tight, runoff is high, and infiltration is slow. Seepage of rainwater and snowmelt is aided, however, by the temporary impounding of water on the uneven surface of the spoil bank.

The slope of the water table near the margins of the main spoil bank suggests that the pools and drainage ditch may be sources of ground-water recharge because a water table slopes from an area of recharge down to an area of discharge. The water level in the pool adjacent to auger hole 13 was 1,178.20 feet above mean sea level on April 14, 1959, or slightly above the average elevation of the water in hole 13. More information on the relation of the water levels in the pools to the water levels in the auger holes is needed, however, before the source of recharge definitely can be determined.

Hydrographs of the water levels in the auger holes indicate that the movement of water in and out of the main spoil bank is seasonal. These hydrographs are similar to those of the coal-test holes except that the range in fluctuation is much less. The difference between the highest and lowest water levels in each of the auger holes for the period of record ranges from about 1 to about 3 feet. The average seasonal rise in water levels in auger holes 2 to 6, 9, 10, 13, and 14 for the period November 5, 1958, through April 29, 1959, was a little more than 1 foot, and the average seasonal decline from April 29, 1959, to September 30, 1959, was a little less than 1 foot. (See fig. 17.) The difference in amount between the rise and decline may be due to a normal seasonal variation or to continued filling of the ground-water reservoir within the spoil bank.

Samples of spoil material were collected from auger hole 5 for hydrologic analysis. The results of the determination of specific yield and coefficient of permeability are given in table 12.

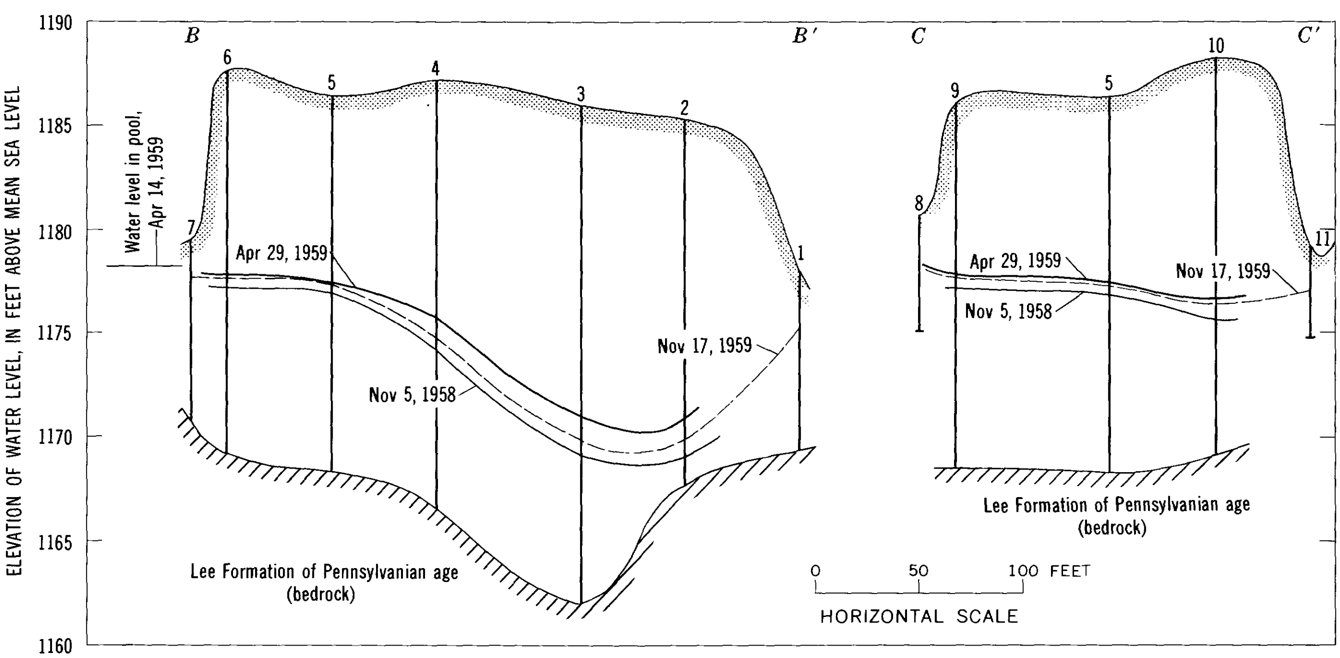

FIGURE 17.—Sections *B-B′* and *C-C′* on plate 1 across the upper part of the main spoil bank, Cane Branch area, showing auger holes and water table.

TABLE 12.—*Specific yield and coefficient of permeability of undisturbed samples from auger hole 5, Cane Branch area*

Depth (feet)	Specific yield *Wy* (percent)	Coefficient of permeability (gpd per sq ft)
0.5–1.0	20.4	0.008
1.0–1.5	19.8	.02
1.5–2.0	13.9	.005
3.0–3.5	15.8	.1
3.5–4.0	17.0	.002
4.0–4.5	13.0	.002
4.5–5.0	13.9	.009
7.5–8.0	3.3	.001
12.0–12.5	14.4	.001
12.5–13.0	9.3	.002
13.0–13.5	17.2	.004
13.5–14.0	21.0	.002
16.0–16.5	35.2	.04
16.5–17.0	15.8	.02
17.0–17.5	13.4	.003
17.5–18.0	.6	.003

The average specific yield of spoil samples collected from auger hole 5 is about 15 percent. If this figure is representative of the spoil-bank material, about 0.15 foot of water was added to and discharged from storage in the spoil banks during the period of record. Because the area of the spoil banks in Cane Branch (as of May 1959) is about 1,643,000 square feet, seasonal changes account for the movement of approximately 246,500 cubic feet or 1,844,000 gallons of water in or out of the banks during a 5- to 6-month period. Computed on a daily basis, the amount is about 10,000 gpd.

The sections in figures 17 and 18 indicate that ground water in the spoil bank generally moves from a source of recharge located along the margins of the bank adjacent to the hills to a line of discharge at the foot of the spoil bank. Calculations based on Darcy's law give a rough measure of the quantity of water discharged. Darcy's law may be expressed as $Q=PIA$, in which Q is the quantity of water discharged in a unit of time, P is the constant, which depends on the character of the material, I is the hydraulic gradient, and A is the cross-sectional area through which the water percolates.

The data in table 12 indicate that coefficients of permeability range from 0.001 to 0.04 gpd per sq ft for the material below a depth of 8.5 feet, the average depth of the water table for the period of record. An average of six of the samples of lower permeability is 0.002, and an average of the two samples of higher permeability is 0.03. In order to calculate the value of Q for each of these two groups of samples, a hydraulic gradient (I) of 0.06 and a saturated thickness of 5 feet are assumed. Because the total linear extent of the spoil banks is about 1.3 miles, the total cross-sectional area, A, is 5 by about 7,000 feet, or about 35,000 square feet. Therefore, for the samples of lower permeability:

$$Q=0.002(0.06)\ 35{,}000$$
$$\approx 40 \text{ gpd}$$

for the samples of higher permeability:

$$Q=0.03(0.06)\ 35{,}000$$
$$\cong 600 \text{ gpd}$$

The above calculations based on Darcy's law indicate that only very small quantities of water are discharged from the spoil banks.

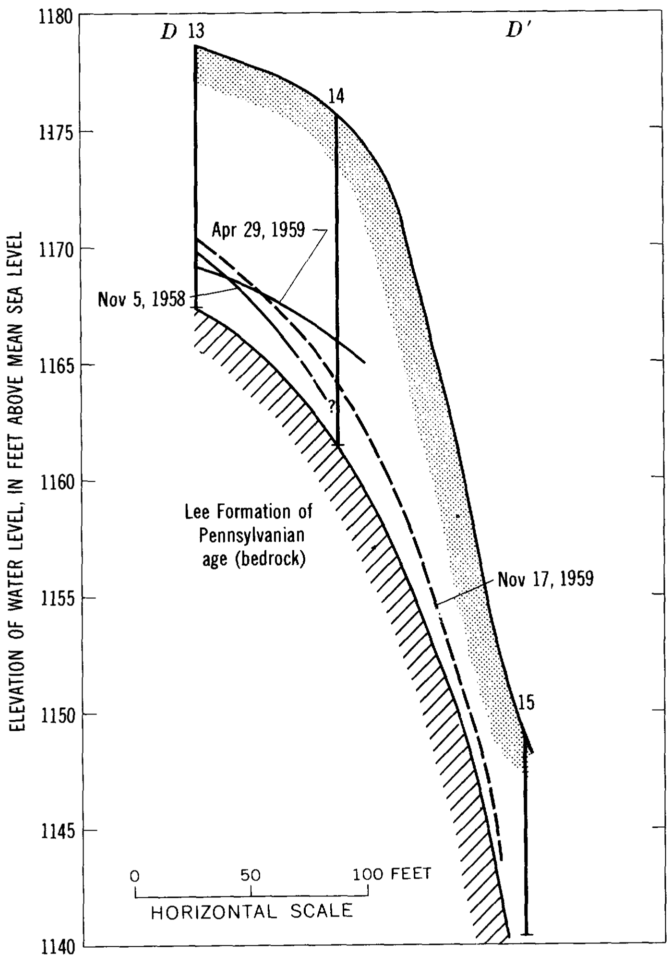

FIGURE 18.—Section *D-D'* on plate 1 across the lower part of the main spoil bank, Cane Branch area, showing auger holes and water table.

To obtain more information on the ground-water yield of the spoil materials, a bailing test was made on auger hole 5 on April 14, 1959. A total of 35 gallons of water was bailed at irregular intervals, and the recovery of the water level in the bailed auger hole was measured. Recovery of the water level was much more rapid at the end of the test than at the beginning. This fact indicates that silt and clay had partially clogged the perforations in the 4-inch plastic casing. Water levels were also measured in auger hole 4 in an attempt to determine the effect of the bailing test on water levels in this hole. A record of the bailing test on auger holes and water-level measurements in auger holes 4 and 5 are shown in figure 19.

SUMMARY AND CONCLUSIONS

The quantity of water discharged from the spoil banks as determined by using calculations based on Darcy's law is very much smaller than that determined on the basis of seasonal changes in storage. Probably the figure 10,000 gpd, obtained by the changes in storage method, is the more accurate because it is based on a longer period of time and a larger area. The wide difference in discharge obtained by the two methods may indicate relatively rapid ground-water movement along zones of higher permeability within or beneath the spoil pile. Even so, the total amount of water moving in and out of the banks is small. Probably some of the water seeps into the bedrock and streams, but most of it probably is discharged by evapotranspiration.

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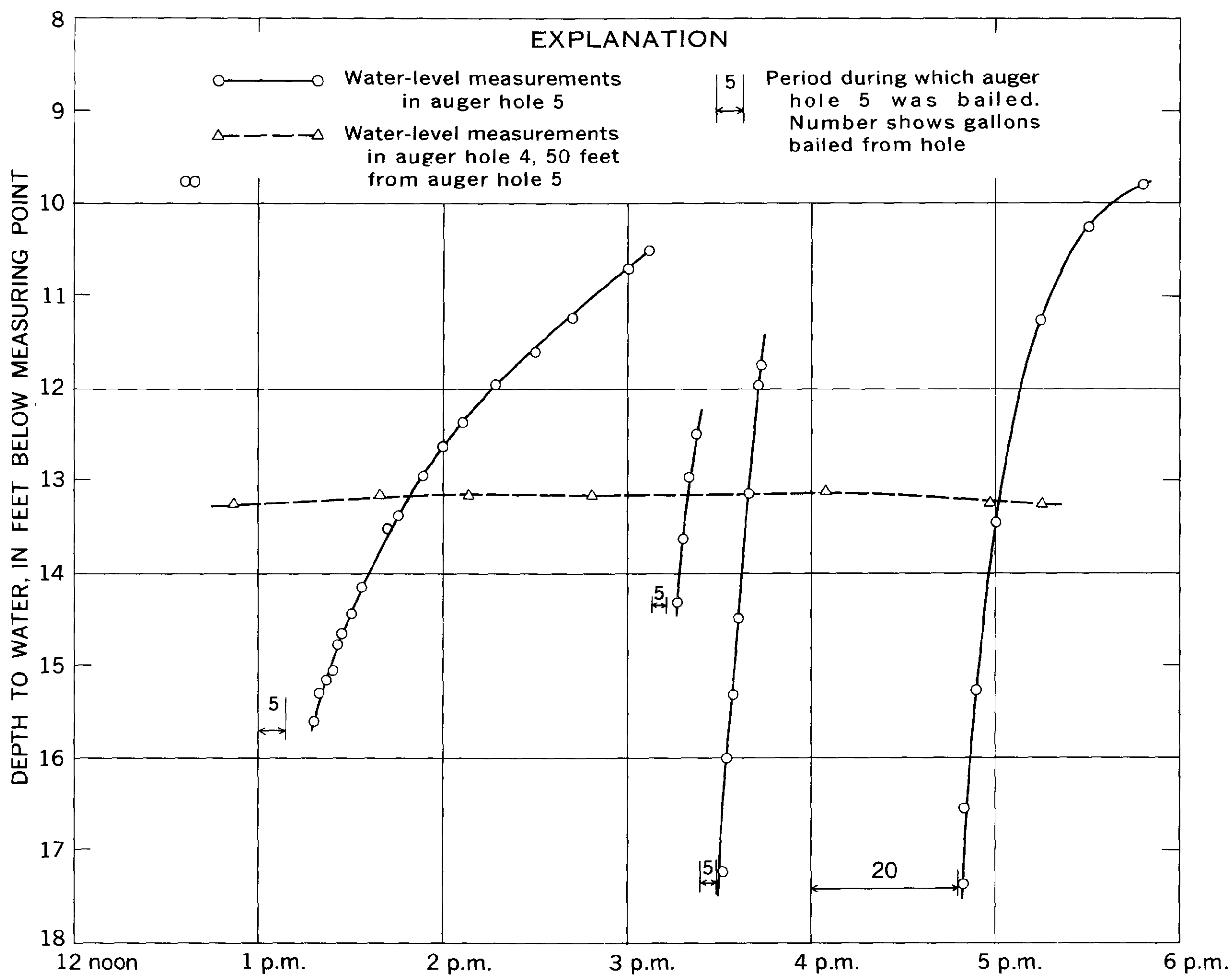

FIGURE 19.—Results of a bailing test on auger holes 4 and 5, Cane Branch area.

GEOCHEMISTRY OF WATER

By JOHN J. MUSSER and GEORGE W. WHETSTONE, U.S. Geological Survey

METHODS OF STUDY

A study of the relationship between geology and the dissolved minerals in the water provides an understanding of the changes in chemical quality of water which take place during and after strip mining. The purpose of this paper is to describe and evaluate the variation in constituents and properties of the water in the strip-mined area, including pools and streams on the spoil bank, at the gaging station on Cane Branch below the strip mine, and in the undisturbed study areas in Helton Branch and West Fork Cane Branch. The effect of precipitation, soils, geology, topography, and streamflow on the solute concentrations and loads in the study areas is also explained.

Since January 1956, data on the chemical quality of surface water have been collected in the Beaver Creek basin. This report includes the data for scheduled stations and information from unscheduled sampling points through the 1959 water year. The periods of record and the sampling frequency at the scheduled sampling stations are shown in figure 20. In addition, 245 water samples from 53 other sites have been collected and analyzed. The locations of the sampling sites are shown on plates 1 and 2.

Dissolved-solids discharge computations were made for all sampling sites whenever streamflow was measured. Annual and monthly dissolved-load calculations were made only at the scheduled sampling stations on Cane Branch and Helton Branch. From the relation between specific conductance and dissolved solids, a daily mean concentration of dissolved solids in parts per million was obtained. The daily mean dissolved-solids content and water discharge were then used to calculate the dissolved load.

In August 1957, a conductivity recorder was installed at the Cane Branch gaging station. This recorder has provided a continuous record of the specific conductance of the water at this point. The relation between specific conductance and many of the dissolved constituents has been used to compute variations in the concentrations of the constituents with time and in the calculation of dissolved solids loads.

PROCESSES AND FACTORS CONTROLLING CONCENTRATIONS OF MINERAL CONSTITUENTS

Except for material carried away by the wind and removed by mining, the materials from the Beaver Creek basin are stream transported. The solutes in the streams are a composite of those contained in rainwater and those leached from the rocks and soils.

The weathering of rocks and soils is not unlike any solvent-solid relationship. The composition of the two

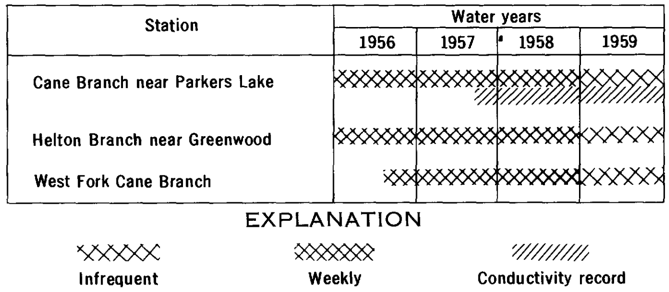

FIGURE 20.—Duration of chemical-quality records and sampling frequency at scheduled stations.

phases, solvent and solid, and the external factors of temperature and precipitation are the effective forces of weathering. In an undisturbed area, weathering may be considered as affected only by the external forces, which are primarily seasonal.

In the Cane Branch study area a part of the parent rock has been redistributed by the mining operations, exposing new solid-phase materials to the same solvent phase and the same external factors.

The bedrock in the area drained by Cane and Helton Branches is composed of conglomerate, sandstone, siltstone, and claystone. In the Cane Branch area, coal belonging to the upper part of the Lee Formation of the Pennsylvanian System is also found. The coal seam was not found in Helton Branch; the stratigraphic position of the coal seam is represented by a series of dark claystone beds containing pyritic material. In the Cane Branch area, the coarser sandstone is generally found below the coal seam and the finer grained claystone predominates in the rocks above the coal seam.

The unconsolidated material in the study areas consists of the thin soil overlying the bedrock, the talus piles along the flood plains, and the clay- to boulder-sized fluvial deposits in the stream channels and on the flood plains.

During mining operations the 40-foot sequence of strata lying directly above the coal seam was removed and piled haphazardly on undisturbed ground. The resulting two large spoil banks in the Cane Branch area are composed of a heterogeneous mixture of rocks and soil. In general, the composition of these rock and soil masses is similar to the composition of the rock units in the highwalls.

Thirteen samples of material from the spoil banks were collected for mineralogic, petrographic, and X-ray analysis. All the samples were characterized by fairly uniform color, texture, and composition.

The heavy-mineral fraction in all samples wasi dentified as goethite [FeO(OH)]. The lighter fraction was composed mainly of well-rounded quartz grains, clay, and minute coal fragments with goethite present as a cement or coating on the other minerals.

Clay components of the soil samples were identified as kaolinite ($Al_2Si_2O_5(OH)_4$) and illite (hydrous K Al silicate). The degree of hydration of the hydromicas (illite) showed some variation. This variation was interpreted as resulting from differences in the degree of weathering; the more weathered parts showed the highest degree of hydration. The samples showing the highest degree of weathering were taken from subsurface cores of the spoil bank. Weathering of these samples occurred before formation of the spoil bank; that is, when the rock fragments were parts of the bedding in the active zone of weathering.

Crystalline silicon dioxide (SiO_2), as quartz, makes up most of the clastic rocks in the study areas. For practical purposes, quartz can probably be ignored as a source of silica in natural waters of the study areas. The greater part of the dissolved silica in the water is derived from the chemical breakdown of silicates during weathering. The tetrahedral structure formed by a silicon atom surrounded by four oxygen atoms, SiO_4^{-4}, is the building block of the micas and clay minerals, which are abundant in the zone of active weathering in the study areas.

The chemical reactions involved in silicate decomposition are extremely complex. In a general way, they can be represented as hydrolysis reactions in which hydrogen ions (H^{+1}), hydroxyl ions (OH^{-1}), or even H_2O molecules replace other ions in the silicate lattice. This weakens the bonding of silicon-oxygen groups and makes them more readily available for solution.

The fine-grained sandstone, siltstones, and claystones immediately above the coal in the Cane Branch area contain pyrite and marcasite(?). The results of chemical analysis for the sulfur content of these beds exposed in the highwalls of the mining areas are given in table 13. The unit numbers listed in this table refer to the rock units described by Musser (1963). Units 1 to 9 on the southwest side and units 1 to 5 on the northeast side of the Cane Branch area are composed of well-weathered claystones, siltstones, and sandstones, and they contain negligible amounts of sulfur. The remaining units listed consist of fresh claystones, siltstones, and sandstones that contain as much as 2 percent total sulfur. A cubic yard of these rocks containing about 1.5 percent of disseminated iron sulfide could produce about 60 pounds of sulfuric acid after oxidation of the sulfide occurs.

TABLE 13.—*Sulfur content of highwall samples, Cane Branch basin*

[Concentrations given in parts per million]

Southwest side of basin				Northeast side of basin			
Unit	Total sulfur (as S)	Water soluble sulfur (as S)	Sulfide (as S) [1]	Unit	Total sulfur (as S)	Water soluble sulfur (as S)	Sulfide (as S) [1]
1–9 [2]	(3)	(3)	(3)	1–3 [2]	(3)	--------	--------
10–11	18,400	3,800	14,600	4–5	(3)	(3)	(3)
12–13	9,500	2,500	7,000	6–7	14,500	4,800	9,700
14–15	7,300	1,700	5,600	8–9	21,300	5,900	15,400
16 [4]	[5] 26,000	--------	--------	10–11	1,900	450	1,450
				12 [4]	--------	--------	--------

[1] Calculated by difference: total sulfur minus water soluble sulfur.
[2] Top of cut.
[3] Sulfur concentrations for these samples are within the limits of error of the analytical method. Therefore, these values are less than about 250 ppm.
[4] Coal seam.
[5] Analysis by Georgia Power Co.

The coal seam in the Cane Branch area contains disseminated iron sulfide, and some of the blocks of coal lying near the seam have yellow sulfur crystals along the bedding planes and joints. This residual coal from the mining operations could produce appreciable quantities of sulfuric acid. Oxidation of this sulfide is a weathering process which is important to this study chiefly because of the further effects of the products of oxidation.

The oxidation of pyrite can progress in several ways. The subject has been explored by Hem (1960, p. 65, 71) who stated:

Trial calculations demonstrate that complete oxidation without intermediate species is most probable. The direct oxidation of pyrite * * * in solution can be written:

$$FeS_2+8H_2O \leftrightarrows Fe^{+2}+2SO_4^{-2}+16H^{+1}+14e$$

Many sedimentary rocks contain some iron in the form of pyrite. This iron becomes available for solution above Eh 0.03v at pH 4 * * *. The relative instability of pyrite in the presence of air and water is expected from the Eh value of about 0.40v that is typical of aerated water. Oxidation of pyrite in soil and in water-table aquifers can be an important source of iron in * * * water.

The rapid increase in solubility of pyrite with an increase in Eh suggests that pyrite is likely to be relatively unstable in most * * * water environments.

Water that runs off over the land surface or percolates downward through the soil into the underlying rocks reacts with solid-phase material. The bulk of dissolved constitutents in natural water is contributed by precipitation and soluble products of chemical weathering. The release of elements from primary materials is controlled by chemical equilibrium. When equilibrium between the solute phase and the solid phase is reached, the reactions cease. Only a difference in the temperature or chemical composition of the infiltrating water or in the chemical composition of the solid phase with which the water comes in contact will bring into play a new equilibrium that will affect the solute concentration of the streams.

A part of the parent rock in the Cane Branch study area has been redistributed by the mining operations to form spoil banks of fresh rock fragments. This new environment is being actively attacked by the agents of chemical weathering.

GEOCHEMISTRY OF THE WATER IN STUDY AREAS

Significant changes have occurred in the chemical composition and the physical properties of the surface water in Cane Branch study area since the beginning of strip mining in 1955. These changes in the quality of the water have resulted from mining activities. Although strip or drift mining was conducted throughout the course of this study, the original spoil continues to produce measurable effects on the quality of water in Cane Branch. The nearby study areas in the West Fork Cane Branch and Helton Branch basins have undergone little physical change since 1955, and the quality of the water in these unaffected study areas has remained virtually unchanged.

The solute concentration of water at the measuring sites is an expression of the weathering processes and of the solutes brought in to the area by precipitation. In the weathering processes, precipitation provides moisture and the moisture-mineral reaction releases the elements to furnish solutes. The end product of chemical weathering is the concentration of ions which are determined at the streamflow and ground-water observation points. The quantities of solutes at a particular streamflow site, less those contributed by precipitation, are a measure of weathering upstream.

Much of the basic chemical quality of water data collected as a part of this investigation has been published previously by the U.S. Geological Survey (1956–59) and will not be presented in this paper.

The chemical analyses of selected samples for the study areas in the Beaver Creek basin are presented graphically in figure 21. Each analysis is represented by a vertical bar graph whose height is proportional to the total concentration of anions or cations. The bar is divided into segments to show the concentration of the cations and anions which make up the total. Cations are plotted on the left third and anions on the middle third of the vertical bars. This plot represents only the ionized part of the dissolved constituents. To indicate the importance of silica in these waters, the silica concentration in parts per million is plotted on the right third of each bar graph.

HELTON BRANCH STUDY AREA

The water in Helton Branch is a calcium bicarbonate type in which the sulfate ion is also significant. The concentration of dissolved solids ranges from 14 to 75 ppm, and the median concentration is 30 ppm. About 83 percent of the samples analyzed contained dissolved solids in the range from 20 to 35 ppm. Selected chemical analyses of samples collected from Helton Branch are given in table 14, and the quality of the water is illustrated graphically in figures 21 and 22.

About 65 to 90 percent of the cations is calcium plus magnesium, the calcium-to-magnesium ratio being about 2.5 to 1. Sodium and potassium account for most of remaining cation concentration and together are generally present in the water in amounts less than 4 ppm. Sodium is present in slightly greater concentrations than potassium, the sodium-to-potassium ratio being about 1.5 to 1.0. The slightly higher sodium-to-potassium ratio observed in the water of Helton Branch originates in the weathering and release of sodium through base exchange.

In the low runoff in summer and fall the bicarbonate ion accounts for one-third of the dissolved solids and, when taken together with calcium, makes up two-thirds of the dissociated dissolved-solids content of the water. The sulfate concentration ranges from 1 to 20 ppm. The higher sulfate concentrations are observed during periods of precipitation. Chloride, fluoride, and nitrates together are present in concentrations of less than 2 ppm.

Other dissolved constituents are present in relatively minor amounts, except for silica, which accounts for slightly less than 25 percent of the dissolved-solids content of the water. Manganese concentrations may exceed 0.1 ppm, and concentrations as high as 2.3 ppm have been recorded. Iron concentrations as high as 2.6 ppm have been observed, but they generally range from 0.1 to 0.2 ppm.

TABLE 14.—*Chemical analyses of selected samples of Helton Branch near Greenwood, Ky.*

[Results given in parts per million, except as indicated]

Date of collection	Instantaneous discharge (cfs)	Silica (SiO_2)	Aluminum (Al)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (residue on evaporation at 180° C)	Hardness as $CaCO_3$ calcium, magnesium	Specific conductance (micromhos at 25°C)	pH
Aug. 21, 1956	0.23	8.2	0.0	0.11	0.18	17	1.9	2.4	1.7	44	16	4.1	0.2	0.8	75	50	121	7.1
Nov. 13	.14	7.9	.2	.13	.23	1.7	.5	.5	.0	10	.6	.8	.1	.1	21	6	17	6.8
July 2, 1957	.25	6.8	.1	.15	.00	8.4	1.3	.6	1.2	26	6.0	1.0	.1	.3	46	26	64	7.2
Feb. 7, 1958	6.05	4.4	.1	.06	.01	3.2	.9	.4	.6	7	8.4	2.0	.1	.4	25	12	34	6.7
Mar. 20	1.40	4.6	.0	.06	.03	3.9	.8	.7	.4	9	5.7	.5	.1	.5	24	14	40	6.7

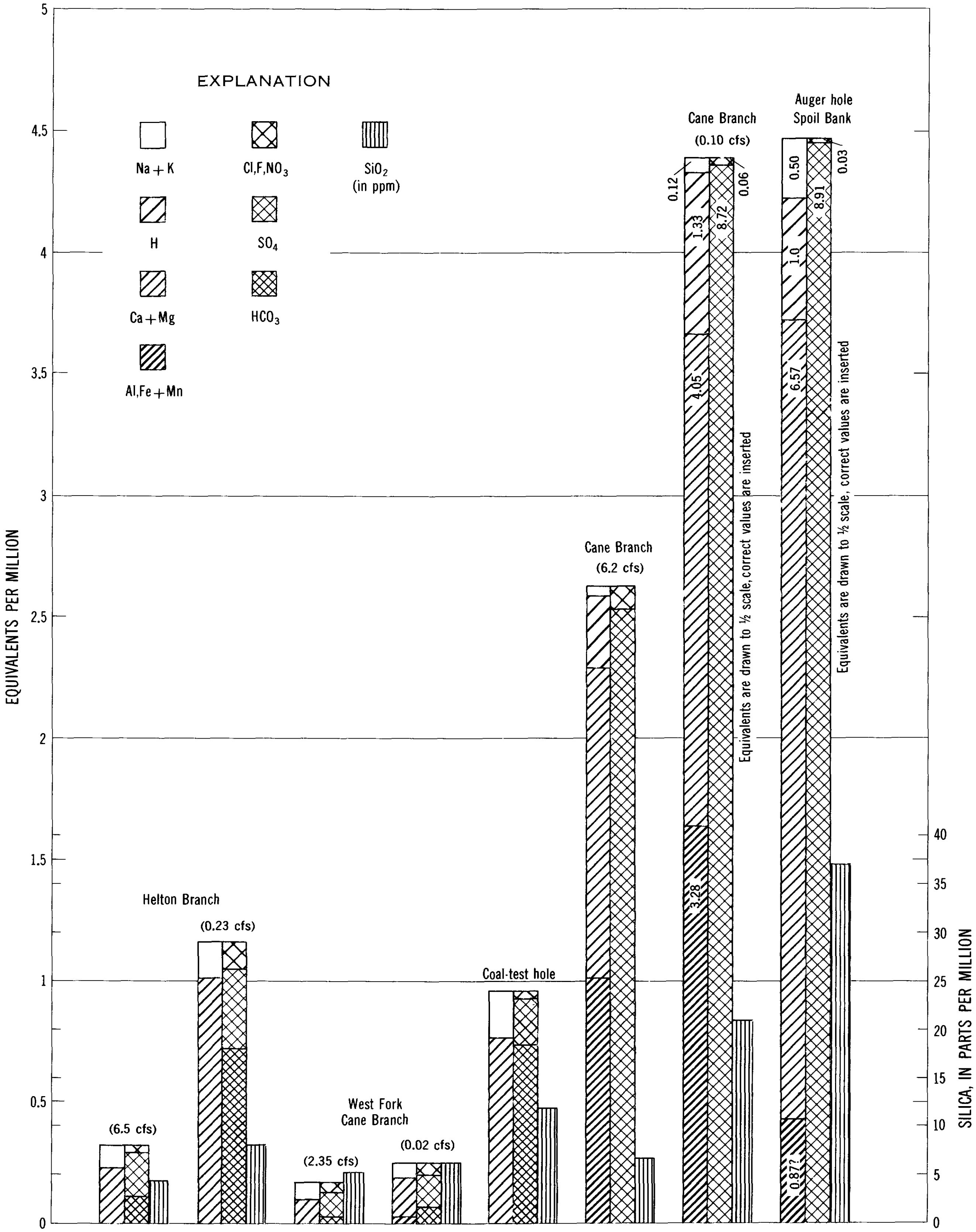

FIGURE 21.—Quality of water in Beaver Creek study areas, June 1956 to September 1958.

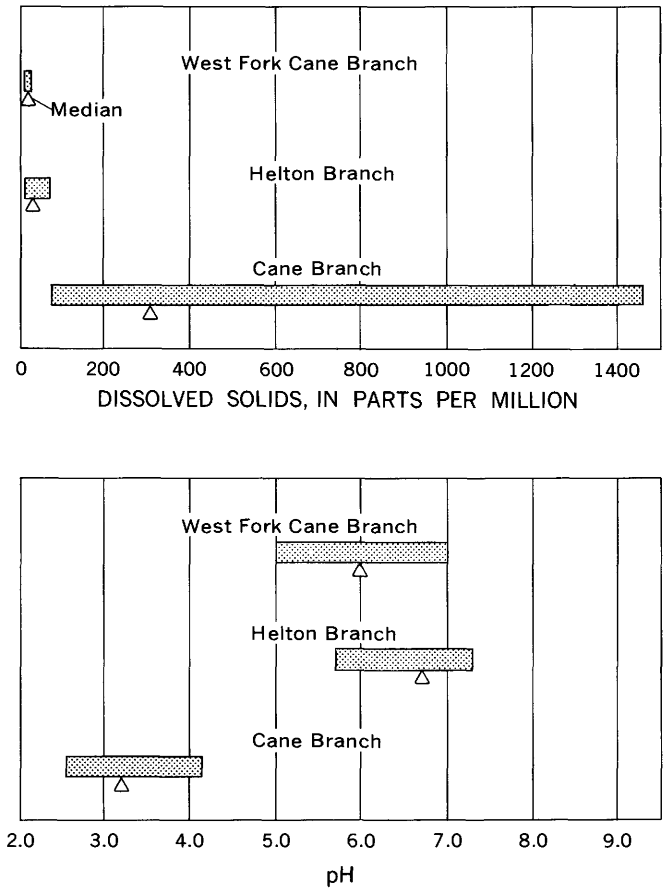

FIGURE 22.—Range of dissolved solids and pH of surface waters in study areas, June 1956 to December 1959.

The pH of the water in Helton Branch generally ranges from 6.0 to 7.0, but during the summer it sometimes exceeds 7.0. The median pH of the water is 6.7 (fig. 22). The water is poorly buffered, and the pH is changed by the addition of small amounts of acidic or basic substances (fig. 23).

Both inorganic and organic matter are dissolved in precipitation. The most prevalent of the dissolved inorganic constituents in precipitation are calcium, magnesium, sodium, potassium, bicarbonates, sulfates, chlorides, and nitrates. The dissolved-solids content of the runoff from Helton Branch is virtually constant (fig. 24) and is controlled by chemical equilibrium between the solutes in precipitation and solid phases.

In the study area, the dissolved-solids content of rainwater ranges from 8 to 10 ppm. Values for the sulfate concentration were found to be 3 ppm. Hendrickson and Krieger (1964), in geochemical studies in the Blue Grass region of Kentucky, found that the dissolved-solids content of rainwater ranged from 6 to 14 ppm and averaged about 8 ppm. The bicarbonate ranged from 3 to 8 ppm, the sulfate from 0.2 to 4 ppm, and the chloride from 0.0 to 2.2 ppm. The pH of the rainwater in the Blue Grass ranged from 5.5 to 6.2, indicating that the water was weakly acid.

The average concentration of dissolved solids for precipitation in the Beaver Creek area cannot be precisely calculated from the limited data available. However, many of the values reported here are in good agreement with the data given by Rankama and Sahama (1950) and by Junge and Werby (1958); so, the average value of 8 ppm reported by Hendrickson and Krieger for the Blue Grass is probably indicative of the mineral content of the precipitation in Kentucky.

These general concentrations indicate that one-third to two-thirds of the dissolved-solids content of Helton Branch is derived from cyclic salts in precipitation. Most of the anions in the stream water are probably derived from this source. A significant part of the calcium, magnesium, and sodium ions in the water may also be attributed to the precipitation.

Few data are available on the chemical composition of the ground water in the Helton Branch area; so, it is difficult to relate the quality of the ground water to the quality of the water in Helton Branch. The only data available on the chemical quality of the ground water were obtained from the analyses of three springs, but these waters, which emanate from the relatively pure quartz sandstones and conglomerates in the southern part of the Helton Branch area, are not an accurate representation of the ground water because they do not show the effect of the impure siltstones and claystones of the area on the quality of the ground water. The spring water is chiefly a calcium and magnesium bicarbonate

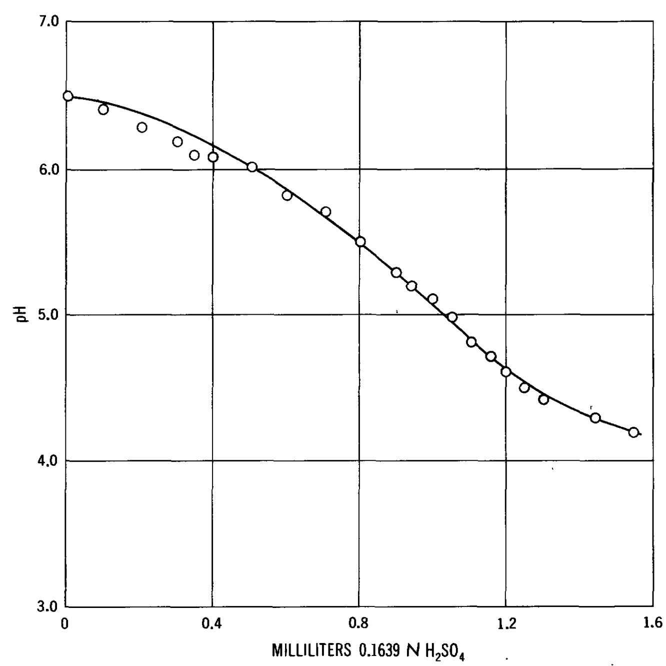

FIGURE 23.—Titration curve for Helton Branch, 6 ppm alkalinity as HCO_3^{-1} and 25 ppm dissolved solids.

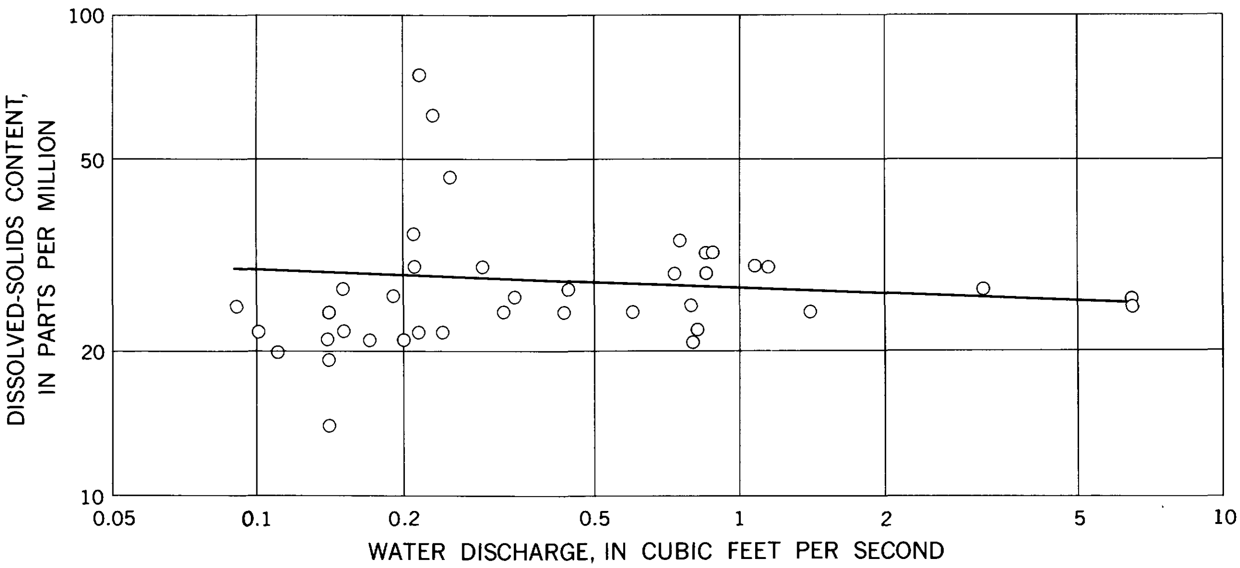

FIGURE 24.—Relation of dissolved-solids content to water discharge in Helton Branch, 1956–58.

type with pH values of about 5.8 (table 10). The dissolved-solids content is generally less than 25 ppm. Much of the silica, iron, and manganese in the water of Helton Branch is probably derived from the springs and shallow ground water through the weathering of the clastic rocks.

WEST FORK CANE BRANCH STUDY AREA

West Fork Cane Branch is an intermittent stream; during extended periods in the summer and fall, no flow is recorded at the West Fork Cane Branch gaging station. The dissolved-solids content of the water at the measuring site during periods of streamflow ranges from 17 to 29 ppm and the median concentration is 20 ppm. This small divergence in concentration is similar to that found in the Helton Branch water and is attributable to the same controls on the solvent-solid chemical equilibrium.

The water in West Fork Cane Branch is principally a magnesium and calcium sulfate and bicarbonate type. These ions make up about three-quarters of the dissociated dissolved solids of the stream (fig. 21).

Calcium and magnesium together are present in amounts generally less than 2 ppm and account for about 60 percent of the cations. Magnesium is present in the water in slightly higher concentrations than calcium, the magnesium-to-calcium ratio being about 1.1 to 1. Sodium and potassium constitute about 30 percent of the cations, and they are present generally in amounts less than 1 ppm. The ratio between sodium and potassium is variable because the concentrations present in the water are small. A rough approximation of a sodium-to-potassium ratio would be 1 to 1.

The sulfate concentration is generally about 5 ppm and remains virtually constant through all ranges of streamflow. The bicarbonate concentration ranges from 3 to 8 pm. Low summer and fall runoff contains the highest bicarbonate ion concentrations. The chloride, fluoride, and nitrate anions together are present in concentrations of less than 2 ppm and represent less than 10 percent of the total mineralization. Most of these latter constituents in the runoff of West Fork Cane Branch are derived from salts brought into the study area by precipitation.

In West Fork Cane Branch and in the other streams in the study area not affected by mining, silica is the most significant dissolved constituent in the water. Silica accounts for about one-third of the dissolved solids content and is derived primarily from the weathering of soils and clastic rocks.

The variation of the pH of the water in West Fork Cane Branch is shown in figure 22. During the winter the pH is generally less than 6.0, due to the increased solubility of carbon dioxide (CO_2) in water at low temperatures. In the summer, assimilation and respiration of CO_2 by aquatic life along with higher water temperature result in an adjustment of the CO_2 concentration, which causes lowering of the hydrogen-ion concentration. During the summer, a pH of about 6.5 is common. Selected chemical analyses of the water in West Fork Cane Branch are listed in table 15.

The topography and geology of the West Fork Cane Branch and Helton Branch study areas control the movement of the water in the soil. In the West Fork Cane Branch area much of the water percolating through the soil moves down the steep slopes of the area and probably remains in the vadose zone until it reaches the stream channels where it becomes surface flow. The stratigraphic section of the West Fork Cane

TABLE 15.—*Chemical analyses of selected samples of West Fork Cane Branch near Parkers Lake, Ky.*

[Results given in parts per million, except as indicated]

Date of collection	Instantaneous discharge (cfs)	Silica (SiO_2)	Aluminum (Al)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (residue on evaporation at 180 °C)	Hardness as $CaCO_3$ calcium, magnesium	Specific conductance (micromhos at 25°C)	pH
Aug. 21, 1956	0.02	6.3	0.0	0.22	0.65	1.6	1.0	0.7	1.3	4	6.3	1.0	0.1	0.3	29	8	26	5.7
May 21, 1957	.08	6.9	.2	.15	.05	.8	.8	.3	.9	5	5.2	.6	.1	.1	21	6	21	6.2
June 11	------	7.4	.1	.16	.20	1.0	.7	.0	.8	5	4.5	1.4	.1	.3	28	6	20	6.2
Dec. 3	.10	5.8	.1	.08	.06	.8	.8	.6	.6	4	5.2	.2	.1	.0	19	6	33	6.2
Feb. 7, 1958	2.35	5.2	.1	.08	.08	.9	.7	.4	.6	2	5.0	1.5	.1	.2	19	5	20	5.2
Mar. 24	.45	5.4	.1	.10	.09	.6	.7	.8	.8	3	4.4	1.0	.1	.2	17	4	34	5.9

Branch area above the gaging station contains many siltstones and claystones. These rocks and their weathered equivalents in the soil inhibit the flow of soil water to the zone of saturation and are instrumental in forming perched water tables near the ground surface. This is not to say that some of the soil percolate does not reach the deeper ground water zone of saturation, for some does, but rather that most of the base flow of West Fork Cane Branch comes from shallow ground water zones and not from the deeper reservoir of ground water.

Aluminum, iron, and manganese are generally present in the water of West Fork Cane Branch in concentrations of less than 0.5 ppm (less than 2 percent of the dissolved solids). These constituents are contributed by runoff that has passed through the shallow well-weathered soils before reaching the stream.

The quality of ground water in the zone of saturation in the West Cane study area is different from the quality of low flows of West Fork Cane Branch and from the quality of the soil water. Data on the quality of deeper ground water was obtained from water in the coal test holes (pl. 1). The water table at the top of the zone of saturation is generally about 25 feet below the ground surface.

The bedrock surrounding the coal test holes is part of the strata above the main cliff-forming sandstone and consists of sandstone, siltstone, and claystone; the bedrock contains significant quantities of iron sulfide and the clay minerals kaolinite and illite.

These minerals are relatively unweathered compared to the soils that have been depleted of most of their reacting minerals. The minerals in the rocks react with the ground water and supply the water with ions of aluminum, iron, sulfate, and bicarbonate.

Differences in the chemical composition of the West Fork Cane Branch water and the water in the zone of saturation are illustrated in figure 21, where the deeper water is represented by the coal test hole. Some of the deep ground water is of the calcium and magnesium bicarbonate type whose pH ranges from 6.1 to 7.5, whereas others are of the acid sulfate type whose pH ranges from 3.8 to 5.6. The dissolved-solids content of these waters ranges from 30 to 200 ppm and is considerably greater than the dissolved-solids content of the low-flow surface runoff at the West Cane gaging station.

CANE BRANCH STUDY AREA

The chemistry of the water in the Cane Branch study area may be divided into two broad categories, the water whose quality is affected by strip mining and the water not affected. Water affected by mining operations includes the pools and drift-mine discharge near the spoil banks, the ground water in the spoil banks, the water in the tributaries emanating from the spoil banks, and the water in Cane Branch. Water not affected by mining includes the ground water other than that in the spoil bank and several small streams tributary to Cane Branch.

POOLS AND DRIFT MINE

During and after the completion of each strip-mining operation in the Cane Branch study area, surface and ground water discharge has flowed into the strip-mining pits and formed pools of water. During periods of storm runoff, surface water flows down the slopes above the highwalls and the inner slopes of the spoil banks and discharges into the strip-mining pits. The greatest contributions of ground water come from the highwalls during periods of low surface runoff when water moves through the sulfide-bearing bedrock and discharges into the strip-mining pits. Some ground water enters the pits from the spoil banks immediately after a storm while water is filtering down through the banks, but generally the flow is from the pools into the spoil banks because the water table in the spoil banks is lower than the water level of the pools.

The pools in the Cane Branch study area are shown on plate 1. Pools 1 to 11 are on the southwest side, and pools 12 to 19 are on the northeast side of the Cane Branch study area.

The pools derive their chemical constituents from the bedrock and soils of the highwalls and from the unweathered rock debris in the spoil banks. Dissolved constituents are carried into the pools from both of these sources by moving water. Also, the pool water reacts with the rocks that form the pool boundaries or that are transported to the pools.

The results of chemical analyses of the pools in the Cane Branch study area are listed in table 16. Pools 1 to 9 are in the strip-mining pit and pool 11 is on the spoil bank of the southwest mining area. The concentration of solutes in these pools is strongly influenced by the oxidation of the pyrite in the highwall and the spoil bank. Soluble products resulting from oxidation are dissolved in water moving from the nearby rocks and spoil debris to the pools, and oxidation may continue further in the pools. The principal dissolved, constituents of the water in these pools are aluminum, iron, manganese, calcium, magnesium, and sulfate. There is no bicarbonate present. The sulfate concentration in these pools ranges from 52 to 3,080 ppm and has a median value of 530 ppm. The iron and aluminum concentrations range from 0.09 to 396 ppm and from 3.6 to 50 ppm, respectively. The pH ranges from 2.50 to 4.10 and has a median value of 2.95. The waters with low pH values generally contain high concentrations of sulfate, iron, aluminum, and acidity.

Pool 10 is south of the spoil bank and strip-mining pit and is surrounded by well-weathered rock and soil. It receives no drainage from the highwall, the strip-mining pit, or the spoil bank, and is therefore representative of the type of water that occurs when the chemical constituents are derived from weathered rock. The principal dissolved constituents are calcium, magnesium, and sulfate, but there is nearly as much bicarbonate as there is sulfate. These latter constituents have concentrations of about 5 ppm, and the pH of the water was 5.9 and 6.5.

Pools 12 and 13 on the northeast side of the Cane Branch study area lie in the strip-mining pit resulting from mining done in the fall of 1958. Although the rocks in the highwall and in the spoil bank surrounding these pools contain iron sulfides, the water in the pools is not as acid as the water in the pools of the strip mining pit on the southwest side of the study area. The principal dissolved constituents are calcium, magnesium, and sulfate; the maximum observed sulfate concentration was 195 ppm. Aluminum and manganese, whose maximum observed concentrations were 2.1 and 8.2 ppm, respectively, are also important constituents in these waters. The pH values of these pools were 4.20 and 6.2. Weathering of the nearby spoil has affected the water in pools 12 and 13, but not to the extent that it has in pools 1 to 9.

Pools 14 to 19 on the northeast side of the Cane Branch study area lie in the strip-mining pit that resulted from mining done from December 1958 to August 1959. The water samples for pools 14, 17, 18, and 19, listed in table 16 for the spring of 1959, were collected while mining was in progress, and the water samples listed for August 1959 were collected after mining was completed.

The changes that occurred in the chemical quality of the water in pool 18 from March to August 1959 are typical of those that occurred in pools 14 to 18. In March 1959, the water in pool 18 contained calcium, magnesium, and sulfate as the principal dissolved constituents. In August 1959, the principal dissolved constituents were aluminum, iron, manganese, calcium, magnesium, and sulfate. Aluminum increased from 0.1 to 12 ppm, iron increased from 0.28 to 7.3 ppm, manganese increased from 0.18 to 15 ppm, and sulfate increased from 12 to 382 ppm. In March the pH was 4.7; in August it was 3.10. These comparisons show how quickly the solute concentration of the pool water changed after unweathered rocks and spoil containing clay minerals and iron sulfides reacted with the spoil-bank water and the pool water.

As of August 1959, the water in pool 19 did not show the changes in chemical composition that had occurred in pools 14 to 18, even though the highwall and spoil bank near this pool are composed of virtually the same rocks as are near pools 14 to 18. The reason for this is not known, but it may be that the sulfide-bearing rocks are buried in a part of the spoil bank where the ground water has difficulty in flowing to pool 19. If this is true, then soluble products from the spoil bank may eventually reach the pool and make the water in it acid.

The water in pool 19 contained calcium, magnesium, and sulfate as the principal dissolved constituents in the spring of 1959 and in August 1959. At both times bicarbonate was present, the pH was at least 5.4, and the sulfate concentration did not exceed 11 ppm. Small changes occurred in the concentrations of aluminum, iron, and manganese, but they were not significant.

Water levels in the pools of the Cane Branch study area fluctuate with the seasons of the year, the highest levels generally occurring in the spring and the lowest in the fall. At the higher levels, some of the pools in each strip-mining pit become connected, and at times the water overflows into drainage ditches and moves down tributaries into Cane Branch.

Two of the pools in the strip-mining pit of the southwest mining area have been drained by mining operators since they were formed. Pool 1 was drained on October 28, 1958, during some prospecting activity. Pool 5 was drained in October 1957 by a mining operator in order to clear a part of the strip-mining pit for a drift entry into the coal seam (pl. 1). From October 1957 to January 1959, acid water was pumped from this drift mine through the strip-mining pit to one of the drainage

TABLE 16.—*Chemical analyses of pools in Cane Branch study area*

[Results given in parts per million except as indicated]

Date of collection	Aluminum (Al)	Iron (Fe)	Manganese (Mn)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Hardness as $CaCO_3$ calcium, magnesium	Potential free acidity (H^+)	Specific conductance (micromhos at 25°C)	pH
Pool 1										
Sept. 25, 1956	----	0.94	0.71	0	324	----	100	4.7	506	3.00
Apr. 30, 1957	----	1.0	1.8	0	120	----	14	1.6	348	3.45
Sept. 2	----	1.1	1.9	0	192	----	62	2.6	558	3.60
Pool 2										
Sept. 25, 1956	----	0.20	0.70	0	209	----	86	2.8	458	3.60
Apr. 30, 1957	----	.32	1.5	0	60	----	13	.6	174	4.10
Sept. 2	----	.97	2.7	0	187	----	84	2.0	428	2.60
Dec. 15, 1958	----	.37	.23	0	91	0.2	18	1.0	229	3.85
Mar. 24, 1959	4.4	.22	1.6	0	63	.0	24	.7	189	4.00
May 23	3.6	.26	1.7	0	61	----	28	.6	173	3.85
Aug. 10	3.8	.09	.97	0	52	----	25	----	174	3.80
Pool 3										
Sept. 25, 1956	----	----	----	0	956	----	289	7.7	1,840	2.80
Apr. 30, 1957	----	0.21	0.25	0	584	----	137	4.2	1,370	2.85
Sept. 2	----	9.8	9.4	0	642	----	189	6.5	1,500	2.75
Dec. 15, 1958	----	28	7.5	0	562	0.0	141	6.0	1,310	2.80
Mar. 24, 1959	27	19	12	0	483	1.5	104	5.2	1,170	2.85
May 23	21	12	11	0	436	----	122	4.4	1,150	2.80
Aug. 10	31	8.1	9.3	0	450	----	126	----	1,090	2.95
Pool 4										
Apr. 30, 1957	----	1.5	0.01	0	138	----	25	1.8	528	3.05
Pool 5										
Sept. 26, 1956	----	28	10	0	613	----	307	8.8	1,420	2.85
Sept. 2, 1957	----	77	16	0	1,440	----	657	13	2,580	2.60
Pool 6										
Sept. 26, 1956	----	----	----	0	2,190	----	1,500	19	3,090	2.70
Apr. 30, 1957	----	9.8	19	0	530	----	227	4.2	1,140	3.00
Sept. 2	----	21	29	0	1,370	----	664	11	2,350	2.75
Pool 7										
Apr. 30, 1957	----	24	33	0	1,060	----	302	10	1,810	2.85
Sept. 2	----	145	41	0	2,420	----	806	27	3,480	2.50
Pool 8										
Sept. 26, 1956	----	396	106	0	3,080	----	900	44	3,540	2.55
Apr. 30, 1957	----	26	42	0	1,100	----	323	10	1,860	2.85
Sept. 2	----	144	30	0	2,050	----	574	26	3,050	2.55

TABLE 16.—*Chemical analyses of pools in Cane Branch study area*—Continued

[Results given in parts per million except as indicated]

Date of collection	Aluminum (Al)	Iron (Fe)	Manganese (Mn)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Hardness as $CaCO_3$ calcium, magnesium	Potential free acidity (H^+)	Specific conductance (micromhos at 25°C)	pH
Pool 9										
Sept. 26, 1956	50	26	32	0	1, 140	0. 7	715	8. 5	2, 000	2. 85
Apr. 30, 1957		5. 0	11	0	402		180	2. 2	936	3. 10
Sept. 2		16	11	0	786		363	5. 7	1, 620	2. 85
Dec. 15, 1958		18	3. 8	0	575	. 5	206	3. 6	1, 310	3. 00
Mar. 23, 1959	22	6. 3	2. 8	0	398	. 5	149	2. 9	908	3. 10
May 23	9. 8	3. 0	6. 7	0	329		177	2. 2	805	3. 15
Aug. 10	19	5. 6	8. 6	0	420		173		1, 010	3. 00
Pool 10										
May 25, 1959	0. 0	0. 01	0. 28	5	6. 4		6		25	6. 5
Aug. 10				4	4. 4		3		17	5. 9
Pool 11										
Aug. 10, 1959	34	12	10	0	516		145	5. 9	1, 180	2. 90
Pool 12										
Aug. 11, 1959	2. 1	0. 04	8. 2	0	195		174	0. 4	438	4. 20
Pool 13										
Aug. 11, 1959	0. 1	1. 4	4. 0	12	116		124		278	6. 2
Pool 14										
Mar. 24, 1959	0. 0	0. 08	0. 22	16	56	0. 0	72		170	6. 3
Apr. 25	. 1	. 15	. 43	20	64		78		184	7. 0
Pool 15										
Aug. 9, 1959	30	58	14	0	1, 100		581	8. 0	2, 220	2. 65
Pool 16										
Aug. 9, 1959	9. 7	3. 6	8. 0	0	776		714	2. 0	1, 470	3. 30
Pool 17										
Apr. 25, 1959	0. 2	0. 13	0. 16	0	21		15	0. 1	63	4. 5
Aug. 9	5. 0	1. 5	11	0	288		244	1. 0	644	3. 60
Pool 18										
Mar. 24, 1959	0. 1	0. 28	0. 18	1	12	2. 0	8		44	4. 7
Aug. 9	12	7. 3	15	0	382		184	2. 4	936	3. 10
Pool 19										
Apr. 25, 1959	0. 7	0. 25	0. 22	2	8. 2		8	0. 0	30	5. 5
May 23	. 4	. 46	. 62	6	7. 8		9		32	6. 2
Aug. 9	. 0	. 90	. 48	4	11		9		47	5. 4

ditches leading to Cane Branch. The mine was abandoned in January 1959, but small quantities of acid water continued to flow from the drift mine.

The results of chemical analyses of the drift-mine water are listed in table 17. The principal dissolved constituents are iron, aluminum, manganese, calcium, magnesium, and sulfate. In January 1958, the water contained 39 ppm bicarbonate and had a pH of 6.0. By July 1958, bicarbonate was no longer present, and the pH had decreased to 2.65. After July 1958, the drift-mine water remained acid and was similar to the water in the pools of the nearby strip-mining pit.

GROUND WATER IN THE SPOIL BANK

The general hydrology of the ground water in the study area is outlined in the section on "Ground Water," but the chemistry of the ground water in the spoil bank is presented here to show the relationship between the pools and the ground water. The chemical quality of the ground water was determined by analyzing the water from the 13 auger holes that penetrate the water table. Hole 15 has always been dry. The auger holes are shown on plate 1.

Ground water in the spoil bank is more highly mineralized than that occurring in the bedrock of the study areas. Compared to the bedrock water, most of the spoil-bank water is relatively high in sulfate, silica, aluminum, iron, calcium, and magnesium (fig. 21), and contains titratable amounts of acidity. The pH and sulfate content of the spoil bank water varies greatly from one hole to another, as shown in figure 25.

The variance in the solute concentrations and physical characteristics of the water in the auger holes is due primarily to the heterogeneity of the spoil bank material and to the source of the recharge water. In the spoil bank, black shale and coal are the principal host rocks for iron sulfide, the chief acid and sulfate-forming mineral of this area. All the auger holes with these rock types, either at or below the water table, contain highly acid water.

Logs of the auger holes (table 11 in section on "Ground-water hydrology") show that holes 2, 3, 4, 13, and 14 do not penetrate carbonaceous material at

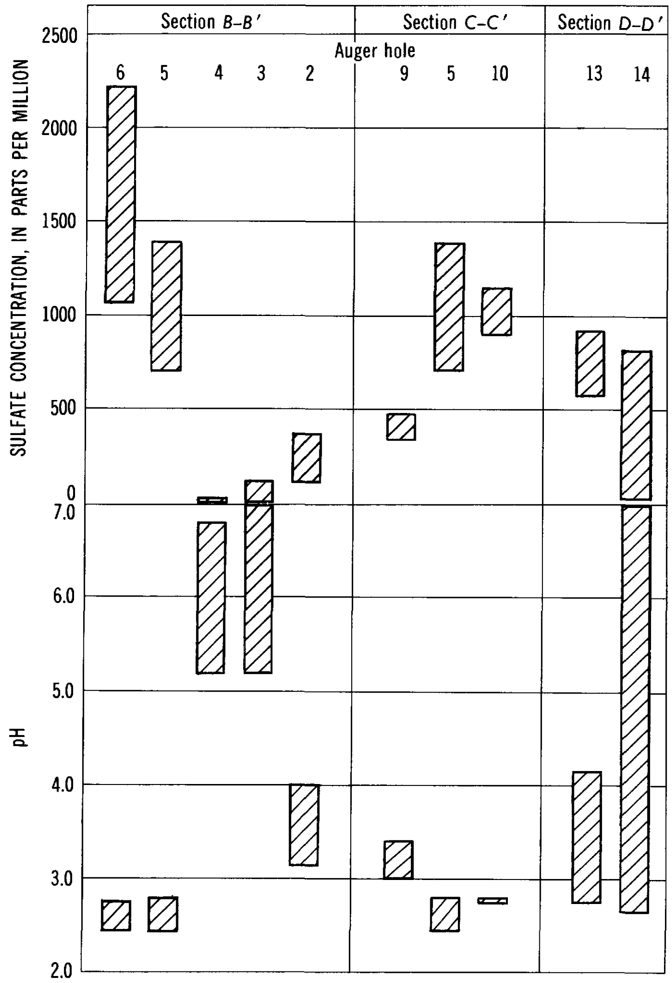

FIGURE 25.—Range of sulfate concentration and pH of water from auger holes on spoil bank, Cane Branch study area, June–December 1958.

depth, but that holes 5, 6, 9, and 10 penetrate black shale or black clay. No logs are available for the other five auger holes. The water in all holes is acid, and the pH ranges from 2.45 to 4.15, except in holes 3, 4, and 14. Holes 2 and 13, although not penetrating black shale at depth, have acid water because they are adjacent to acid pools and are recharged by water seeping from these pools into the spoil bank. The water in holes 3, 4, and 14 is generally only moderately acid and is relatively low in sulfate because these holes

TABLE 17.—*Chemical analyses of water at entrance of drift mine in Cane Branch study area*

[Results given in parts per million except as indicated]

Date of collection	Instantaneous discharge (cfs)	Silica (SiO_2)	Aluminum (Al)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (residue on evaporation at 180° C)	Hardness as $CaCO_3$ calcium, magnesium	Potential free acidity (H^+)	Specific conductance (micromhos at 25° C)	pH
Jan. 30, 1958	--------	21	0.4	24	9.8	144	23	67	4.7	39	636	0.0	0.8	20	960	454	-----	1,220	6.0
July 29	--------	43	23	121	10	144	36	5.5	10	0	908	.0	1.9	1.8	1,300	508	7.7	2,040	2.65
Sept. 9	0.007	34	14	18	--------	152	28	38	5.6	0	832	2.5	1.9	5.0	1,200	494	4.8	1,870	2.80
May 23, 1959	.003	--------	26	176	10	------	--------	-------	-------	0	805	------	------	------	---------	336	9.8	2,220	2.55

are located at some distance from the pools and probably receive only a small part of their recharge from acid pools. Most of their recharge probably comes from the vertical infiltration of rainfall. In filtering through the bank, water from rainfall becomes highly variable in composition, which is determined by the types of rock with which the water comes in contact; this water, however, is probably more dilute than acid pool water.

Hydrogen sulfide gas has been detected in the water from some of the holes. The gas probably is formed by the biochemical reduction of some of the iron sulfide in the spoil bank. After a time, the gas escapes, leaving less acid and sulfate-producing material in the spoil bank.

Ground or surface water in the spoil bank area may be seeping into the underlying bedrock and contaminating the ground water there. Well 12, located below the toe of the main spoil bank, penetrates the underlying bedrock; so, the ground water in this well provides some information on contamination. From April 1958 to June 1959, the pH of water in well 12 ranged from 5.1 to 6.8 and had a median sulfate concentration of 42 ppm. This sulfate content is much lower than that of ground water in the spoil bank, but it is higher than that of the ground water in the coal test holes unaffected by mining. Compared with other water in the Lee Formation from nearby regions of the Cumberland Plateau, the pH of well 12 is slightly lower and the sulfate content somewhat higher. These comparisons indicate that, to date, the water in well 12 has been only slightly affected by mine drainage.

The effects of the seepage of ground water from the spoil bank on Cane Branch are discussed in the following subsection of the paper.

TRIBUTARIES OF CANE BRANCH

The tributary streams of Cane Branch carry the soluble products of chemical weathering into Cane Branch. Some of these tributaries are in subbasins that have not been affected by mining and the waters are dilute, containing only about 10 to 30 ppm dissolved solids. The other tributaries are in subbasins where mining has occurred, and they receive mineralized or acid drainage from the spoil bank and access roads. These tributary streams are not perennial and are sometimes dry during the summer and fall. The locations of these tributary streams and the sites where chemical quality measurements were made are shown on plate 1, and the location and drainage areas are shown in figure 26.

Three tributary streams in the southern part of the study area have not been affected by recent mining activities. The drainage area above site B contains a small spoil bank which was built during 1947, but this bank no longer has any significant effect on the chemical characteristics of the water which flows past site B. The drainage area above sites C and E is forest covered, except for a small area of abandoned brush-covered farmland in subbasin C. The well-weathered soils overlie claystone and siltstone bedrock. The coal seam occurs in the upper part of these subbasins, but it is not exposed. For the purposes of description, the types of water passing sites B, C, and E can be grouped together.

The chemical quality of water in the streams at sites B, C, and E is similar to that of water in West Fork Cane Branch. The dissolved-solids content ranges from 10 to 30 ppm and has a median value of 20 ppm. Silica is the principal dissolved constituent and becarbonate alkalinity is present at all times. The pH ranges from 5.2 to 7.6. The sulfate concentrations are always low, and the maximum observed concentrations at these sites are given in figure 26. The water at these sites contains only minor amounts of dissolved aluminum, iron, and manganese.

Sites A and J receive drainage from roads. In fact, nearly all the drainage area above site A is a dirt road that is built in a well-weathered soil zone. The dissolved-solids content of the water passing site A has not exceeded 25 ppm. The principal dissolved constituents are silica, calcium, magnesium, and sulfate; minor constituents are aluminum, iron, manganese, and bicarbonate. The maximum observed sulfate concentration is 12 ppm, and the pH ranges from 4.5 to 5.2.

The road in the drainage area of site J is covered with limestone gravel, and the dissolution of the limestone adds bicarbonate ions to the water, making it principally a calcium-bicarbonate type. The maximum observed concentrations of dissolved solids, bicarbonate, and sulfate are 41, 34, and 6 ppm, respectively. The pH ranges from 6.5 to 7.9. The dranage at site J enters Cane Branch about 100 feet downstream from the Cane Branch gaging station, so it does not affect the water passing the gaging station.

Sites G, M, P, and R receive surface and ground water drainage from the southwest spoil bank. Site G receives drainage from the area around pool 1. The pool is no longer present because it was drained by a mining operator in October 1958, but water discharging into the strip-mining pit in this area flows through the drainage ditch cut by the mining operator and down a small tributary to site G. Site M receives acid mine drainage from the overflow of pools 3, 6, and 7 and also from the drift mine. The drainage passing sites P and R comes directly from the spoil bank.

The principal dissolved constituents of the water at these sites are aluminum, iron, manganese, calcium, magnesium, and sulfate. The water at sites G, M, and

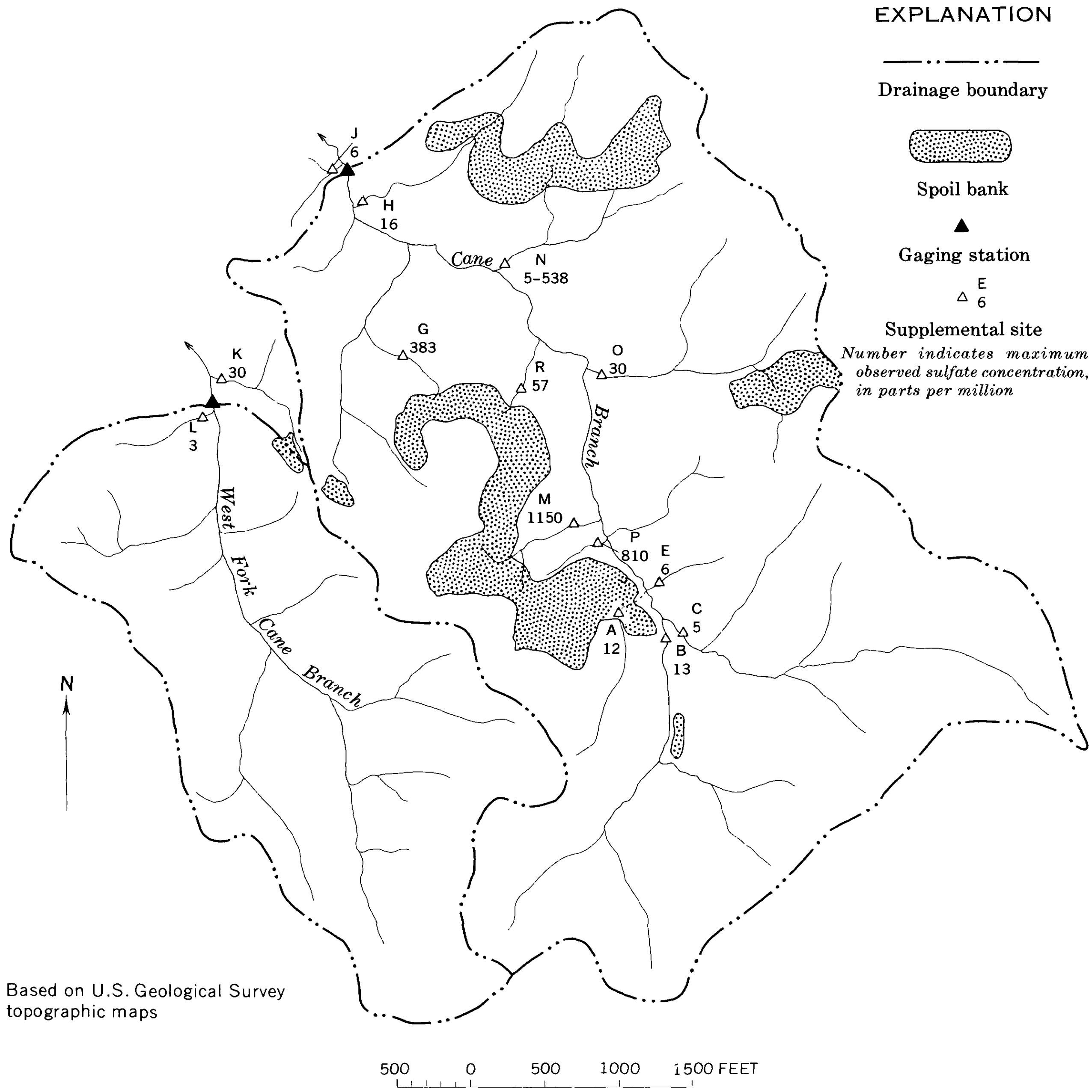

FIGURE 26.—Map of Cane Branch and West Fork Cane Branch study areas, showing maximum observed sulfate concentrations in selected subbasins, 1958–60 water years.

P have pH values of less than 3.0, and the acidity ranges from 0.3 to 12 ppm. The maximum observed dissolved-solids content is 1,800 ppm, and the maximum observed sulfate concentrations are given in figure 26. The water at site R is higher in pH and lower in concentrations of dissolved constituents than that at sites G, M, and P. The chemical quality of the water at site R is described in detail in the section on "Forest and forest development," where the relationship between this water and the growth of trees is discussed.

Supplemental site O receives drainage from the area mined in the fall of 1958 on the northeastern side of the Cane Branch area. The principal dissolved constituents in the water at site O are aluminum, iron, manganese, calcium, magnesium, and sulfate. The maximum observed sulfate concentration is 30 ppm, which is lower than the concentrations observed at the supplemental sites on the southwest spoil bank. The pH ranges from 6.2 to 7.2. The pools in the strip-mining pit in the site O drainage area had a pH greater than 4.1. This spoil bank contains smaller amounts of iron sulfide than the spoil banks in the Cane Branch area, and therefore the acidity of the water leaving the bank is not as great. Surface water and ground water from other parts of the site O subbasin dilute the spoil bank drainage; so, the pH of the water is higher and the concentration of the dissolved constituents lower by the time the water passes site O.

In December 1958, the water at site N had a sulfate concentration of 5 ppm and a pH of 6.9. Strip mining began in the drainage area in this same month, and during the mining operation the water at site N had a maximum observed sulfate concentration of 42 ppm and the pH decreased slowly to 5.5. At the completion of the mining operation in August 1959, a drainage ditch was cleared in the eastern part of the spoil bank, and the overflow from pools 14 and 15 entered the drainage system above site N. The dissolved-solids content increased immediately, and the pH value decreased. From August 1959 to September 1960, the maximum observed sulfate concentration was 538 ppm, the maximum acidity was 2.8 ppm, and the lowest pH was 2.85. In December 1958, calcium, magnesium, and bicarbonate were the principal dissolved constitutents. After August 1959, the principal dissolved constituents were aluminum, iron, manganese, calcium, magnesium, and sulfate. The effects of mining are very evident in these comparisons of the waters at site N.

The drainage at site H comes from the part of the northeast spoil bank near pool 19. The spoil in this part of the bank consists mainly of weathered material and was described during the discussion of the water in pool 19. The water at site H contains calcium, magnesium, and sulfate as the principal solutes. Bicarbonate is also present. The maximum observed dissolved-solids and sulfate concentrations are 30 and 16 ppm respectively. The pH ranges from 5.3 to 6.2.

Five of the twelve subbasins in the Cane Branch study area are contributing acid mineralized water to Cane Branch. Of these five subbasins, four receive drainage from the southwest spoil bank and one drains a part of the northeast spoil bank. These five subbasins make up about 10 percent of the Cane Branch basin above the gaging station.

The seven subbasins not affected by the debris from mining are contributing cyclic salts from precipitation and silica from the weathering of the clastic rocks.

CANE BRANCH

Before strip mining began, the dissolved-solids content of Cane Branch probably was greater than that of West Fork Cane Branch and less than that of Helton Branch. This assumption is based on the analyses of samples collected during the construction of measuring facilities in the Cane Branch study area in January 1956 and the analysis of chemical quality data obtained from tributary streams in Cane Branch not affected by strip mining.

Water from Cane Branch in January 1956 apparently was not affected by the mining operations going on at that time. The chemical quality of the water was similar to the chemical quality of water in Helton Branch.

The sample collected on January 18, 1956, is listed in table 18. The water discharge at the time the sample was collected was 0.1 cfs and consisted mainly of shallow ground water. The dissolved-solids content of the water was 31 ppm, of which about 20 percent was silica. The remaining 80 percent of the dissolved-solids content was principally calcium, magnesium, and bicarbonate ions.

The water in the subbasins above supplemental sites B, C, and E has not been affected by the recent strip mining and gives some indication of the quality of the water in the Cane Branch study area before the April 1955 mining. The water in these subbasins has been described previously, but it should be noted that the median dissolved-solids content is 20 ppm and that the pH ranges from 5.2 to 7.6.

From January to June 1956, the mine debris affected the chemical character of the Cane Branch water, changing it to a calcium and magnesium sulfate type, as shown in figure 27. The dissolved-solids content increased from 31 to 195 ppm. The sulfate concentration increased from 5 to 123 ppm, making sulfate the principal dissolved constituent. The concentrations of aluminum, iron, manganese, calcium, magnesium,

TABLE 18.—*Chemical analyses of selected samples of Cane Branch near Parkers Lake, Ky.*

[Results given in parts per million except as indicated]

Date of collection	Instantaneous discharge (cfs)	Silica (SiO_2)	Aluminum (Al)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (residue on evaporation at 180° C)	Hardness as $CaCO_3$ calcium, magnesium	Potential free acidity (H+)	Specific conductance (micromhos at 25°C)	pH
Jan. 18, 1956	[1] 0.10	6.3	0.3	0.24	0.05	3.7	1.6	0.8	1.1	17	5.6	1.0	0.1	0.2	31	16	-------	44	6.8
July 10	.05	14	33	1.1	14	37	23	1.4	2.2	0	451	1.5	-------	.4	602	187	4.6	1,040	2.95
Dec. 4	.04	10	7.4	2.4	12	23	15	1.2	1.4	0	199	1.8	.6	.1	293	119	1.5	555	3.30
Feb. 5, 1957	4.1	5.9	8.6	5.1	.8	14	10	.6	.8	0	135	1.8	.4	.4	187	76	1.3	367	3.45
July 16	.06	-------	85	48	26	51	28	1.0	3.0	0	1,050	.0	-------	.4	1,290	242	14	2,010	2.55
Feb. 7, 1958	6.2	6.8	6.0	6.3	2.8	11	8.8	.5	.9	0	123	3.0	.4	.4	154	64	1.0	317	3.55
May 3	1.6	7.2	2.6	2.2	2.7	8.6	5.9	.7	.8	0	73	6.0	.3	.4	110	46	.6	231	3.60
July 10	.10	21	17	24	12	48	19	1.3	2.3	0	442	.5	1.0	1.4	629	198	4.3	1,140	2.90

[1] Estimated.

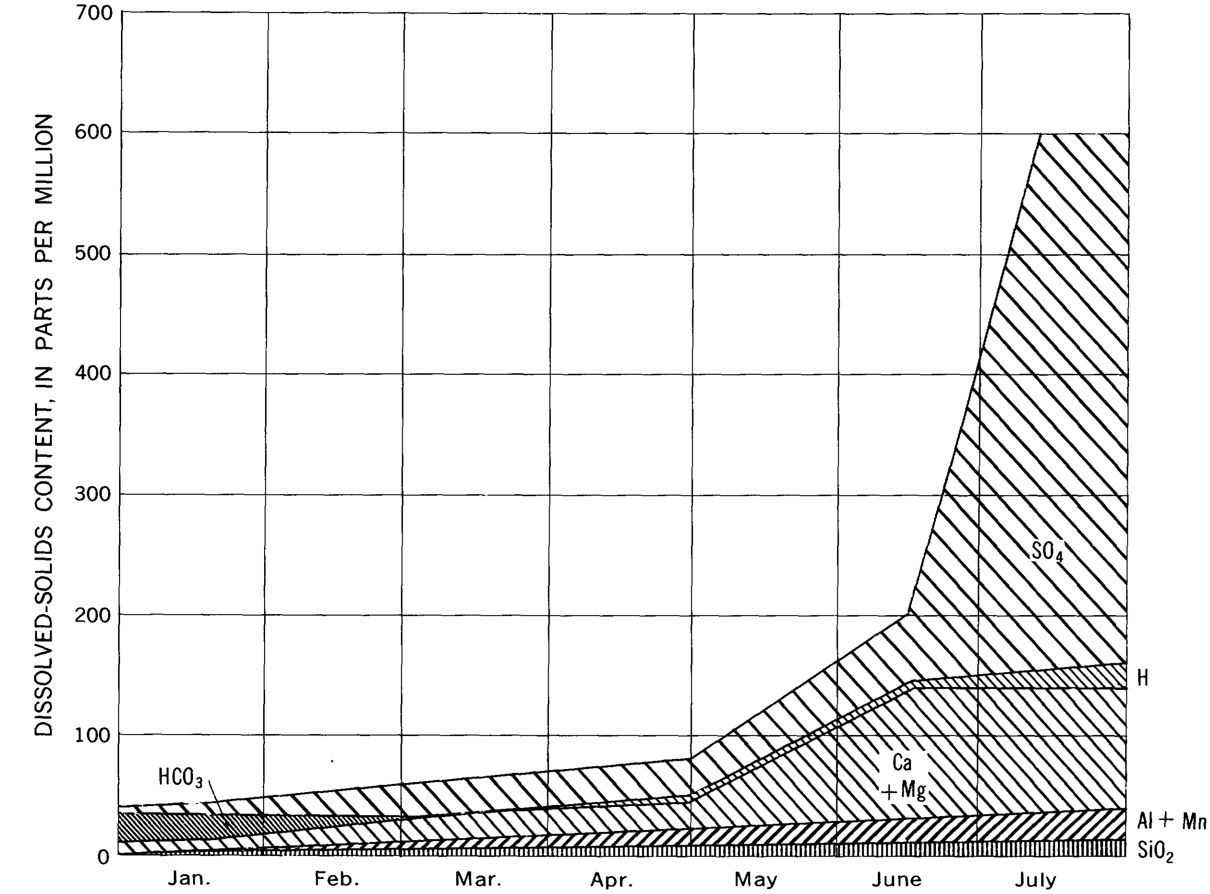

FIGURE 27.—Schematic diagram showing composition of dissolved solids in Cane Branch, January–July 1956.

sodium, and potassium also increased slightly from what they had been in January 1956. The acidity of Cane Branch increased from 0 to 1.0 ppm. The bicarbonate concentration decreased to zero, and the pH decreased from 6.8 to 4.0. The silica concentration doubled but made up an increasingly smaller part of the dissolved solids.

During the levelling of the southwest spoil bank in June 1956, large quantities of fresh material were exposed and the drainage ditches through the bank were cleared to allow overflow from the pools to discharge into Cane Branch. These actions caused further increases in the concentrations of the chemical constituents in Cane Branch. Figure 27 shows the composition of Cane Branch in July 1956 and affords comparisons with the Cane Branch composition in January 1956. The fact that Helton Branch had about the same composition and dissolved-solids content at both times indicates that the changes in the composition of Cane Branch were not due to a natural condition that affected the Beaver Creek area in general.

Seven of the eight chemical analyses given in table 18 show the composition of Cane Branch after June 1956. Four of these analyses are for low water discharges and three are for high water discharges. The concentrations of solutes in Cane Branch are generally greater at low water discharges than at high water discharges (fig. 28) because low discharges are generally composed of ground water effluent from the spoil bank. The ground-water environments provide very large surface areas of solid-liquid contact, and therefore the ground-water effluent has reacted with more of the rock constituents and has a higher dissolved-solids content than the surface runoff, which makes up the greater part of the high water discharges.

Fluctuations in the concentration of solutes in Cane Branch are further complicated because of the variation in the proportion of runoff from the spoil banks and from undisturbed areas. Direct runoff from the spoil banks always has a greater dissolved-solids content than direct runoff from undisturbed areas because fresher material is available on the banks. Between storms the dissolved-solids content of Cane Branch is high. During storms direct runoff from undisturbed areas near the gaging station enters Cane Branch and drastically lowers the solute concentration of Cane Branch. In time, the direct runoff from the spoil banks

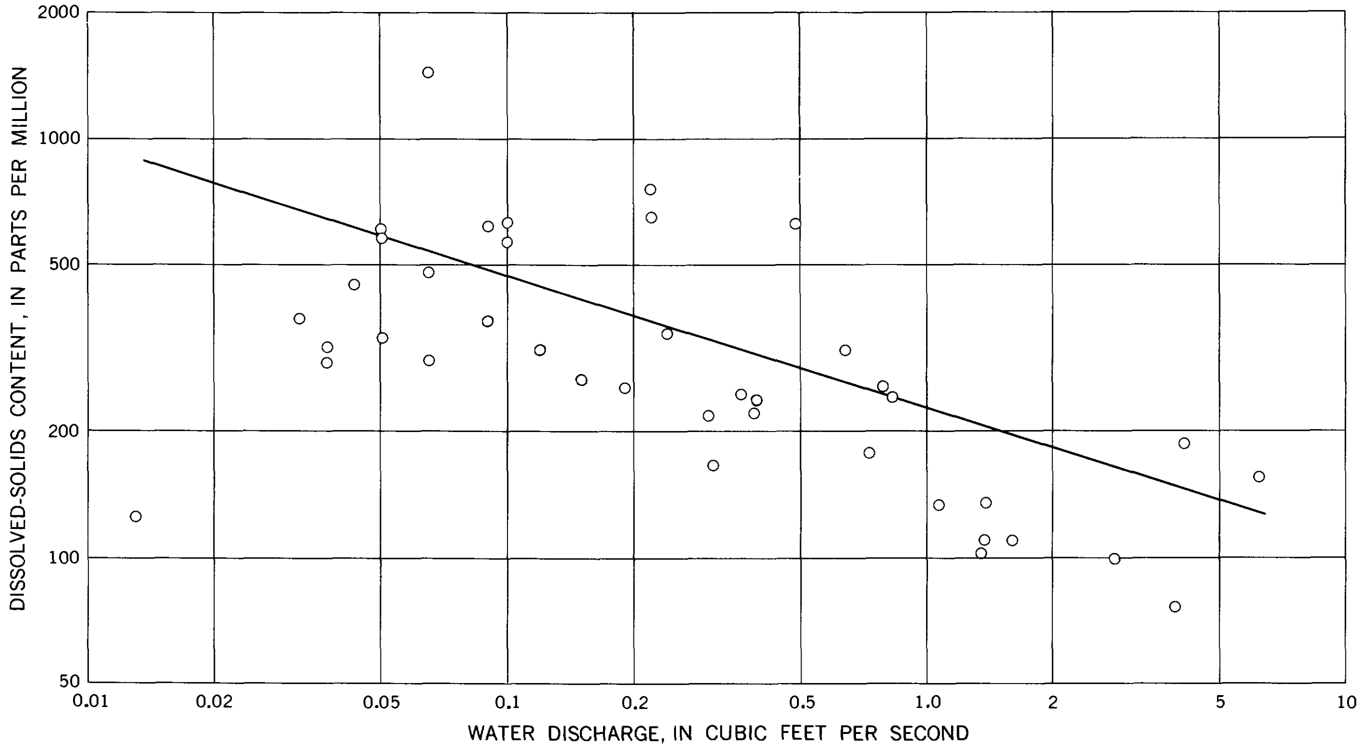

FIGURE 28.—Relation of dissolved-solids content to water discharge in Cane Branch, July 1956 to September 1958.

reaches the gaging station, and the dissolved-solids content of the stream begins to increase. It continues to increase for several days after a storm and then levels off and undergoes slight fluctuations until the next storm.

From June 1956 to December 1959, the dissolved-solids content of Cane Branch ranged from 76 to 1,460 ppm and had a median value of 310 ppm (fig. 22). The principal ionic species in solution were hydrogen, aluminum, iron, manganese, calcium, magnesium, and sulfate. Silica made up about 4 percent of the dissolved-solids content and ranged in concentration from 1 to 19 ppm. From June 1956 to December 1959, the range of silica concentrations generally exceeded the range for January to June 1956. Most of these soluble products of weathering came from the spoil banks.

COMPARISON OF CHEMISTRY OF WATER IN STUDY AREAS

The relative amount of solutes in water in the Beaver Creek study area is related to the precipitation and to the distribution, and in Cane Branch, to the redistribution of the geologic units. The small range in dissolved-solids contents of water from the clastic rocks and residual soils in the Helton Branch area is striking. Hembree and Rainwater (1961, p. 6) stated:

> Precipitation may have what has been called a solution potential for monolithogic terrains, and this potential is depleted rapidly when the water comes in contact with the rocks. Any solution subsequent to the rapid depletion of most of the solution potential is either extremely slow or nonexistent. In more exacting terms, the amount of material that will be dissolved depends on the controlling chemical equilibria between minerals and ionic species in solution.

Although the primary controls on the chemical composition of water are geologic, continuity of transport of solutes is also an important factor. The amount of water in the unmined parts of the Beaver Creek study area is sufficient for the continuous transport of the soluble products of weathering and those brought in by precipitation. Where weathering is proceeding faster than removal of its soluble products, as in the disturbed part of Cane Branch study area, the soluble products accumulate until they are dissolved in fresh water. The dissolved-solids content of water in Cane Branch is related to the accessibility of these soluble materials to the runoff.

pH AND ACIDITY

The pH of Cane Branch from June 1956 to September 1959 ranged from 2.55 to 4.15 and had a median value of 3.2 (fig. 22), as compared to the 6.7 median of Helton Branch and the 6.0 median of West Fork Cane Branch for the same period. The lowest pH in Cane Branch generally occurs during low-water discharge because the constituents causing low pH (aluminum and iron sulfates) have higher concentrations at these times.

The acidity concentration (H^+) of Cane Branch ranged from 0.0 to 17 ppm. The median was 1.7 ppm. Occasionally, Helton Branch and West Fork Cane

Branch have had a maximum acidity concentration of 0.1 ppm. In the Cane Branch study area, the acidity concentration in the auger holes ranged from 0.1 to 12 ppm and in the pools ranged from 0.0 to 44 ppm.

Rain falling to the ground contains small quantities of solids and gases dissolved from the atmosphere. In percolating through the ground or running off over the surface, water reacts with various minerals and carbon dioxide in the soil. Air in soil pores may be several times richer in carbon dioxide than the atmosphere owing to decomposition of accumulations of organic matter and plant respiration, which releases carbon dioxide in the root zone.

The amount of carbon dioxide in most of these soil solutions is much larger than the amount that can be retained in equilibrium with the partial pressure of carbon dioxide in the air. The greater amount of carbon dioxide present increases the number of hydrogen ions in solution controlled by the equilibrium:

$$CO_2+H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^{-1}+H^{+1}.$$

The increase in hydrogen ions lowers the pH of the water in the soil. The pH of the water moving through the soil and rock minerals is important, particularly under conditions of active leaching. If a water of low pH dissolves some solid material through reactions involving hydrogen ions, equilibrium will rapidly be reached at another pH, and the action will stop unless the supply of low-pH water is large enough to offset the effects of the solid-phase material. The oxidation of iron sulfide in the spoil bank, the highwalls, and the pools of the mining areas produces a continuous supply of low-pH water, which maintains the pH level of Cane Branch and some tributary streams well within the acid range of the pH scale. This acid water is effective in releasing elements—particularly aluminum, iron, manganese, calcium, magnesium, and sulfur—from the rock minerals.

ALUMINUM

In the weathering of primary minerals, aluminum is generally left behind in the insoluble residue. In the weathering of feldspar, the clay mineral kaolinite is produced, and some of the silica and cations in the feldspar are carried off in solution. Aluminum is considered highly resistant to removal by solution, and it normally remains behind in the process of rock decomposition.

Aluminum is amphoteric in behavior, and thus can appear in solution either as a cation or as a part of a complex anion. Aluminum cations in solution hydrolyze strongly as follows:

$$Al^{+3}+3OH^{-1} \rightleftharpoons \left\{\begin{matrix} Al(OH)_3 \\ H_3AlO_3 \end{matrix}\right\} AlO_2^{-1}+H^{+1}+H_2O$$

The aluminum hydroxide is only slightly dissociated and is nearly insoluble. Aluminum ions occur only in solutions having a pH of less than 7.0 and become a significant constituent only in solutions whose pH is less than 5.0. In natural water the normal buffer system of carbon dioxide, bicarbonates, and carbonates tends to maintain a pH well above the level required for the occurrence of appreciable amounts of aluminum cations in solution.

In the study areas, the natural surface water is very poorly buffered. (See fig. 23.) The solution of a very small amount of ferrous sulfate is sufficient to produce a marked reduction in the pH. When a pH below 5.0 is maintained, aluminum cations can be present in large amounts.

Surface water unaffected by mining operations has a pH ranging from 5.0 to 7.3. In table 19 the maximum, median, and minimum concentrations of aluminum, iron, and manganese in Cane Branch, West Fork Cane Branch, and Helton Branch are tabulated. In the water of Helton Branch and West Fork Cane Branch, aluminum is present in solution in very small amounts, generally less than 0.1 ppm.

The aluminum concentration in Cane Branch ranged from 0.0 to 85 pm from June 1956 to September 1958. Generally, the highest aluminum concentrations occur when the pH of the water is less than 3. Aluminum concentrations of less than 5 ppm were observed from January to June 1956 before the spoil bank was leveled and when the pH was between 4.0 and 6.8. Since June 1956, the pH has been less than 4.15, and the aluminum concentration has generally been greater than 5 ppm (fig. 29).

TABLE 19.—*Maximum, median, and minimum concentrations, in parts per million, of aluminum, iron, and manganese in surface water in Beaver Creek study area, January 1956 to September 1958*

	Maximum	Median	Minimum
West Fork Cane Branch			
Aluminum (Al)	0.2	0.1	0.0
Iron (Fe)	.42	.11	.00
Manganese (Mn)	.65	.05	.00
Helton Branch			
Aluminum (Al)	0.4	0.1	0.0
Iron (Fe)	2.6	.10	.00
Manganese (Mn)	2.3	.08	.00
Cane Branch			
Aluminum (Al)	85	5.5	0.0
Iron (Fe)	48	2.7	.06
Manganese (Mn)	28	7.0	.05

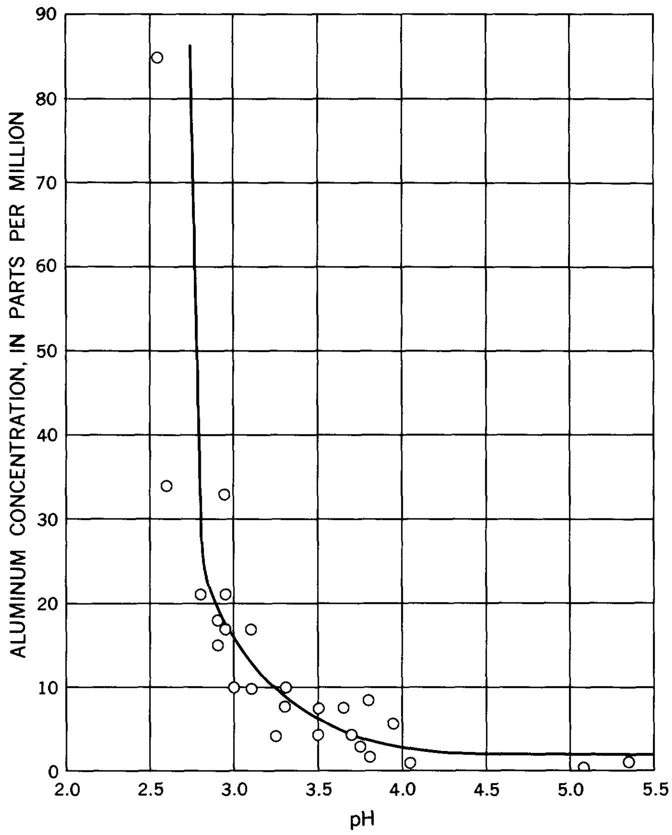

FIGURE 29.—Solubility of aluminum as a function of pH in Cane Branch, 1956–58

The concentration of aluminum in the ground water of the study areas follows a pattern similar to that in the surface water. Water from coal test holes and springs having natural alkalinity and a pH greater than 5 contains less than 0.2 ppm aluminum. Water in coal test holes penetrating iron sulfide-bearing rocks and in the auger holes on the spoil bank has significant aluminum concentrations. As much as 2.3 ppm aluminum has been reported in the water from the coal test holes, and 102 ppm has been found in the water in the auger holes.

The aluminum concentration of water in the pools on the spoil bank ranges from 0.0 to 50 ppm. The higher concentrations correlate with pH values of less than 3.

The main source of the aluminum in Cane Branch is the spoil bank. For a given day, the aluminum concentration of the acid water in the pools and auger holes is generally greater than the aluminum concentration of Cane Branch. The maximum observed aluminum concentration in Cane Branch, however, was greater than the maximum observed aluminum concentrations of the pools and auger holes. This anomaly is due to differences in sampling dates.

IRON

Water that flows from the spoil banks into the channel of Cane Branch contains dissolved iron. Iron has been found in concentrations as high as 48 ppm at the measuring station on Cane Branch, but some of the dissolved iron in Cane Branch has precipitated in the channel above the measuring station through mixing with alkaline water from tributaries. This reaction raises the pH of the water during periods of heavy local runoff.

Iron occurs in water at two levels of oxidation—bivalent ferrous iron and trivalent ferric iron. Although the chemical behavior of the two forms in water is somewhat different, both may be present in the same solution under certain circumstances.

Iron in aqueous solution is subject to hydrolysis. The iron hydroxides formed in these reactions, especially the ferric form, are practically insoluble. The retention of iron in solution is controlled by the pH and Eh of the water (Hem and Cropper, 1959, p. 13–17). In West Fork Cane Branch and Helton Branch study areas, the pH of the water is not low enough to prevent hydroxides from forming, and under oxidizing conditions most of the iron is precipitated as ferric hydroxide:

$$Fe^{+2}+3H_2O \rightleftharpoons Fe(OH)_3+3H^{+1}+e.$$

In the Helton Branch area, the important solid-phase sources of iron are the iron oxide and hydroxide, which are present as a cementing material in the sandstone and as an impurity in the claystone. Iron sulfides are present in the dark claystone beds overlying the cliff-forming sandstone.

Most of the iron minerals in the Cane Branch study area are iron oxides and hydroxides, but iron sulfides are also present in significant amounts. The iron sulfide minerals are exposed to the agents of weathering in the highwalls and spoil banks. The direct oxidation of pyrite to give Fe^{+2} and SO_4^{-2} in solution can be written:

$$FeS_2+8H_2O \rightleftharpoons Fe^{+2}+2SO_4^{-2}+16H^{+1}+14e$$

An oxidizing agent or electron acceptor is needed to complete this reaction. In nature this role is usually played by the oxygen dissolved in aerated water. The dissolved oxygen content of the pools and streams in the study areas is variable, but it generally has a saturation level greater than 60 percent. The ferrous iron released by pyrite oxidation may remain in solution or be oxidized to ferric iron, which will hydrolize and precipitate as ferric hydroxide unless the pH is low. The solubility of ferric iron increases rapidly as the pH decreases below 3. This condition often occurs in Cane Branch.

In West Fork Cane Branch and Helton Branch, the concentration of iron seldom exceeds 0.10 ppm (table 19), although during low-flow periods Helton Branch may contain as much as 2.6 ppm iron. Most of the iron in solution in West Fork Cane Branch and Helton Branch probably is in the ferrous state. Under reducing conditions, at pH 7, the solubility of ferrous hydroxide, $Fe(OH)_2$, in pure water is high, but in the presence of CO_2 the solubility of ferrous iron is controlled by the solubility of ferrous bicarbonate. Ferrous iron is soluble to the extent of 1 to 10 ppm at a pH of 7 and a bicarbonate content of 25 ppm if oxidation does not occur. The concentration of iron in these two streams, however, is controlled by the oxidizing environment of the aerated water, which causes the precipitation of ferrous iron as ferric hydroxide almost as soon as it is brought into the stream by the groundwater discharge.

In the pH range from 6 to 7, a condition that prevails in West Fork Cane Branch and Helton Branch, the amount of ferric iron in solution is limited by the solubility of ferric hydroxide, about 5×10^{-6} mg or less of iron per liter (0.005 ppm), which is below the detection limits of ordinary laboratory methods.

Ferric iron, if present in West Fork Cane Branch and Helton Branch, is in a stable colloidal suspension of ferric hydroxide. The effects of colloidal iron may distort the analytical data for dissolved iron when the amount present is less than 0.10 ppm. The relationship between iron and pH is not well defined at this level for these streams in the study area.

Water in the coal test holes penetrating sulfide-bearing rocks commonly contains an appreciable iron concentration. The iron concentration of this water ranges from 0.05 to 27 ppm, and the median iron concentration is 1.3 ppm. The higher concentrations are generally observed in the water from the holes where the pH is less than 4. The springs contain moderate amounts of iron (table 10), generally about 0.3 ppm.

Water in the auger holes on the spoil banks is high in iron. The iron concentration ranges from 0.04 to 380 ppm, and the median iron concentration is 84 ppm. The highest iron concentrations are found when the water in the holes has a pH of less than 3.00.

Water from the pools on the spoil bank contains from 0.01 to 396 ppm iron in solution (table 16). The highest iron concentrations are associated with water having a pH of less than 3.00.

Ferric hydroxide, as previously noted, is relatively insoluble in water having a pH in the range from 6 to 7, but it is appreciably soluble where the pH is 3 or less. The characteristic red precipitate of ferric hydroxide is noted in the stream channel of Cane Branch from the spoil bank to well below the gaging station, a fact indicating that unfavorable conditions for the complete solution of the ferric iron exist at least part of the time. Storm runoff from unmined areas often has a pH greater than 5.0. As this runoff flows into the Cane Branch channel, a considerable amount of the ferric iron in solution in Cane Branch is precipitated. When the water from the spoil bank reaches the stream channel a few minutes later, some of the iron in the streambed may be picked up and redissolved.

The iron concentration in Cane Branch, as measured at the gaging station, ranges from 0.06 to 48 ppm (table 19). The median iron concentration is 2.7 ppm, 27 times that of the water in the two main streams of the other study areas.

A few measurements of ferric iron were made in the Cane Branch study area. In December 1959, at the measuring point on Cane Branch, the total dissolved iron content was 10 ppm at a pH of 3.4, and the ferric iron content was 5.7 ppm. At supplemental site M, the total dissolved iron content was 104 ppm at a pH of 2.80, and the ferric iron content was 73 ppm. Based on these limited data and theoretical considerations, water in the Cane Branch study area having a pH of 3 or less can be assumed to contain a considerable amount of ferric iron.

MANGANESE

Manganese in the water of the study areas is derived from manganese dioxide minerals weathered from sandstones. Manganese thus tends to accumulate in the soils developed from sandstones, and therefore these soils are an important source of manganese in the study areas.

Manganese is similar to iron in that it occurs in more than one state of oxidation. The oxidation states of manganese in water are the bivalent manganous (Mn^{+2}) ion and the quadrivalent manganic (Mn^{+4}) ion.

In natural water whose pH ranges from 6 to 8, manganese is present as manganous ions. In water containing carbon dioxide, manganous bicarbonate is less subject to oxidation than ferrous bicarbonate. Thus, the manganous ion is frequently found in slightly higher concentrations than iron in these waters.

In general, the amount of manganese present in water from West Fork Cane Branch and Helton Branch is almost identical to that reported for iron, as shown in table 19. No significance is attached to the small variation in the observed maximum, median, and minimum values of manganese in either stream when compared with those observed for iron.

Manganese can exist at low pH values in a bivalent, ionic, freely soluble manganous form, which generally accompanies ferrous iron. When water containing ferrous iron from the spoil bank comes into contact with the manganese oxides in the rocks and soils, the iron may be oxidized:

$$2Fe^{+2}+MnO_2+4H^{+1} \rightleftharpoons Mn^{+2}+2Fe^{+3}+2H_2O$$

The ferric iron will generally be precipitated as ferric hydroxide, $Fe(OH)_3$.

Ground water in the spoil bank contains smaller concentrations of manganese than of iron. The maximum observed concentration of manganese in this water was 179 ppm as compared to 380 ppm of iron, and the median manganese concentration of this water was about 20 ppm.

The range of the manganese content in Cane Branch is given in table 19. The Fe/Mn ratio of the maximum observed concentrations is 1.7. The Fe/Mn ratio of the median concentrations is only 0.38. The median manganese concentration in Cane Branch is higher than the median iron concentration because manganous ions are more stable than ferrous iron. Iron is oxidized to the ferric state in water and is subsequently precipitated as ferric hydroxide. Because manganese is less readily oxidized than iron, manganese remains in solution until the bulk of the iron has been precipitated. Therefore, manganese concentrations would generally be at a higher average level and would persist for a longer period of time than similar concentrations of iron. The manganese ion is not as noticeably affected by slight changes in the pH of the water as is the ferrous ion.

SULFATE

The sulfate ion is a significant constituent in the runoff from the study areas and is the predominant constituent in the waters of the Cane Branch area. The sulfate ion is chemically stable in most of the environments to which natural water is subjected.

Sulfate in the water of the Beaver Creek area comes from two sources. One source is precipitation, which contributes about 3 ppm of dissolved sulfate ions. Sulfate is also made available through the oxidation of iron sulfides present in the dark claystones and siltstones of the study areas. In the upper oxidized layers of soil and rock in the undisturbed parts of the study areas, metallic sulfides have largely been converted to sulfates and leached away by water.

The spoil banks and highwalls of the Cane Branch area contain iron sulfide, which is the principal source of the sulfate in the Cane Branch water. Because large quantities of iron sulfide have been exposed only recently to the atmosphere in the Cane Branch area, oxidation of this mineral is proceeding more rapidly there than in the Helton or West Fork Cane Branch areas.

In Cane Branch, the sulfate ion makes up about 70 percent of the dissolved solids. The sulfate concentration ranges from 46 to 1,220 ppm, and the median sulfate concentration is 220 ppm. In comparison, the maximum sulfate concentration of Helton Branch is 21 ppm and of West Fork Cane Branch is 7 ppm. On an equivalent basis, sulfate makes up about 99.5 percent of the anions present in Cane Branch water (fig. 21).

OTHER SIGNIFICANT CONSTITUENTS

Because of the occurrence of modest quantities of calcium and magnesium in the rocks, soils, and precipitation, small quantities of these elements are detected in the surface and ground waters of the West Fork Cane Branch and Helton Branch study areas.

Calcium and magnesium are constituents of many clay minerals in the study areas. The clay minerals are the only important source of calcium and magnesium, as no natural deposits of limestone or dolomite are found in the study areas.

In the presence of hydrogen ions, calcium and magnesium go into solution as bicarbonates during the weathering process:

$$CaCO_3 + H^{+1} \rightleftharpoons HCO_3^{-1} + Ca^{+2}.$$

The dissociation of carbonic acid is the source of the hydrogen ions in the water of West Fork Cane Branch, Helton Branch, and the zone of aeration in the study areas.

Water in Cane Branch and in the auger holes reacts with the calcium and magnesium through the action of sulfuric acid, produced by the oxidation of iron sulfides, in the following manner:

$$CaCO_3 + H_2SO_4 \rightleftharpoons CaSO_4 + H_2CO_3.$$

The variation in the concentrations of calcium and magnesium in the surface and ground waters of the study area is given in table 20.

TABLE 20.—*Maximum, median, and minimum concentrations, in parts per million, of calcium and magnesium in the water of the Beaver Creek study areas, January 1956 to September 1958*

	Maximum	Median	Minimum
West Fork Cane Branch			
Calcium (Ca)	2.6	0.9	0.3
Magnesium (Mg)	1.0	.6	.6
Helton Branch			
Calcium (Ca)	17	3.5	1.6
Magnesium (Mg)	1.9	.8	.3
Coal-test holes			
Calcium (Ca)	5.2	--------	1.7
Magnesium (Mg)	6.2	--------	2.9
Cane Branch			
Calcium (Ca)	66	20	3.0
Magnesium (Mg)	46	13	1.6
Auger-holes			
Calcium (Ca)	282	--------	8.6
Magnesium (Mg)	182	--------	4.1

The concentrations of calcium and magnesium are greater in the water in Cane Branch and in the auger holes than in the ground water and surface water unaffected by strip mining. On the basis of median values, Cane Branch contains about 20 times as much of these constituents in solution as are found in West Fork Cane Branch and several times the amount present in Helton Branch.

The relatively high concentrations of calcium and magnesium in the water of the Cane Branch area results from exposing unweathered material containing calcium, magnesium, and pyrite to weathering. The hydrogen ions released by pyrite oxidation and, to some extent, by the solution of CO_2 in the water aid in bringing the calcium and magnesium into solution. The ratio of calcium to magnesium in the water in Cane Branch is about 1 to 1.

Sodium and potassium occur in relatively minor amounts in water of the study areas. In Cane Branch, they make up about 2 percent of the cations. The sodium concentration ranges from 0.5 to 3.7 ppm, and the potassium concentration ranges from 0.6 to 6.2 ppm.

Sulfate makes up about 99.5 percent of the anions in Cane Branch on an equivalent basis. The remaining 0.5 percent is composed of chloride, fluoride, and nitrate. There is no detectable bicarbonate in Cane Branch.

A comparison of the dissolved-solids content, which includes all the dissolved constituents, shows the difference between Helton and Cane Branches. The range of dissolved-solids content of the surface water is 14 to 75 ppm in Helton Branch and, after leveling of the spoil bank, is 76 to 1,460 ppm in Cane Branch.

ACCELERATED CHEMICAL EROSION IN CANE BRANCH STUDY AREA

The disturbance of the land surface in the Cane Branch area by strip mining has placed unweathered rocks at or near the surface. Because these unweathered rocks are exposed, the rate of chemical erosion has increased in the mined areas. This has resulted in higher concentrations and loads of chemical constituents in the runoff from the mined areas than from the unmined areas.

To show the quantitative difference between the runoff loads of mined and unmined areas, two examples are outlined herein.

The first example compares mined and unmined subbasins in the southern part of the Cane Branch basin. The Cane Branch drainage passing supplemental site F comes from four geographical sources. These sources are (1) the unmined area east of Cane Branch between supplemental sites C and F, (2) the unmined area above site C, (3) the area above site B which includes a small spoil bank from a 1947 mining venture, and (4) the spoil bank area west of Cane Branch between sites B and F (pl. A).

The dissolved sulfate loads transported from each of these four sources on selected days are listed in table 21. Comparisons of these data show that the greatest loads on a pounds-per-acre basis came from the spoil bank area. In fact, of the total sulfate load passing site F on these days, over 90 percent came from the spoil bank. The remaining 10 percent came from the other three relatively undisturbed sources previously listed.

The sulfate load from these four geographic sources was derived from precipitation and from solute-solid reactions in the soils and bedrock in each source area. Although a part of the sulfate was contributed by the precipitation, the effect of this cyclic sulfate upon the load from each source should be equal because each acre probably received the same amount of precipitation.

TABLE 21.—*Dissolved sulfate load, in pounds per acre, for selected days from four geographical sources in southern part of the Cane Branch area*

	East [1]	Site C	Site B	Spoil bank [2]
1959				
May 23	0.01	(3)	0.01	10.4
Aug. 10	(3)	(3)	(3)	2.1
Nov. 5	1.95	0.01	.05	84.6
1960				
Feb. 15	3.10	(3)	.02	63.7
May 24	.05	(3)	(3)	14.0

[1] Includes the drainage area east of Cane Branch between supplemental sites C and F.
[2] Includes the drainage area of the spoil bank west of Cane Branch between sites B and F.
[3] Less than 0.01 pound per acre.

The second example compares the loads of dissolved constituents being transported by Cane and Helton Branches at their gaging stations. The relation of the monthly water discharge and the monthly gross dissolved yield for Cane and Helton Branches depicted in figure 30 shows that at a given water discharge the Cane Branch load is greater than the Helton Branch load. In both study areas, the greatest loads are transported during winter-type months, when the water discharges are high. Cane Branch has a higher dissolved-solids content and a generally lower water discharge during summer-type months than during winter-type months.

The reason for higher concentrations during summer-type months is that highly mineralized ground water from the mining areas makes up a greater percentage of the Cane Branch base flow. The dissolved-solids content of Helton Branch is about the same during the summer and winter-type months. The difference in the mineral content of the ground and suface waters in the Helton Branch area is small compared with the difference in Cane Branch.

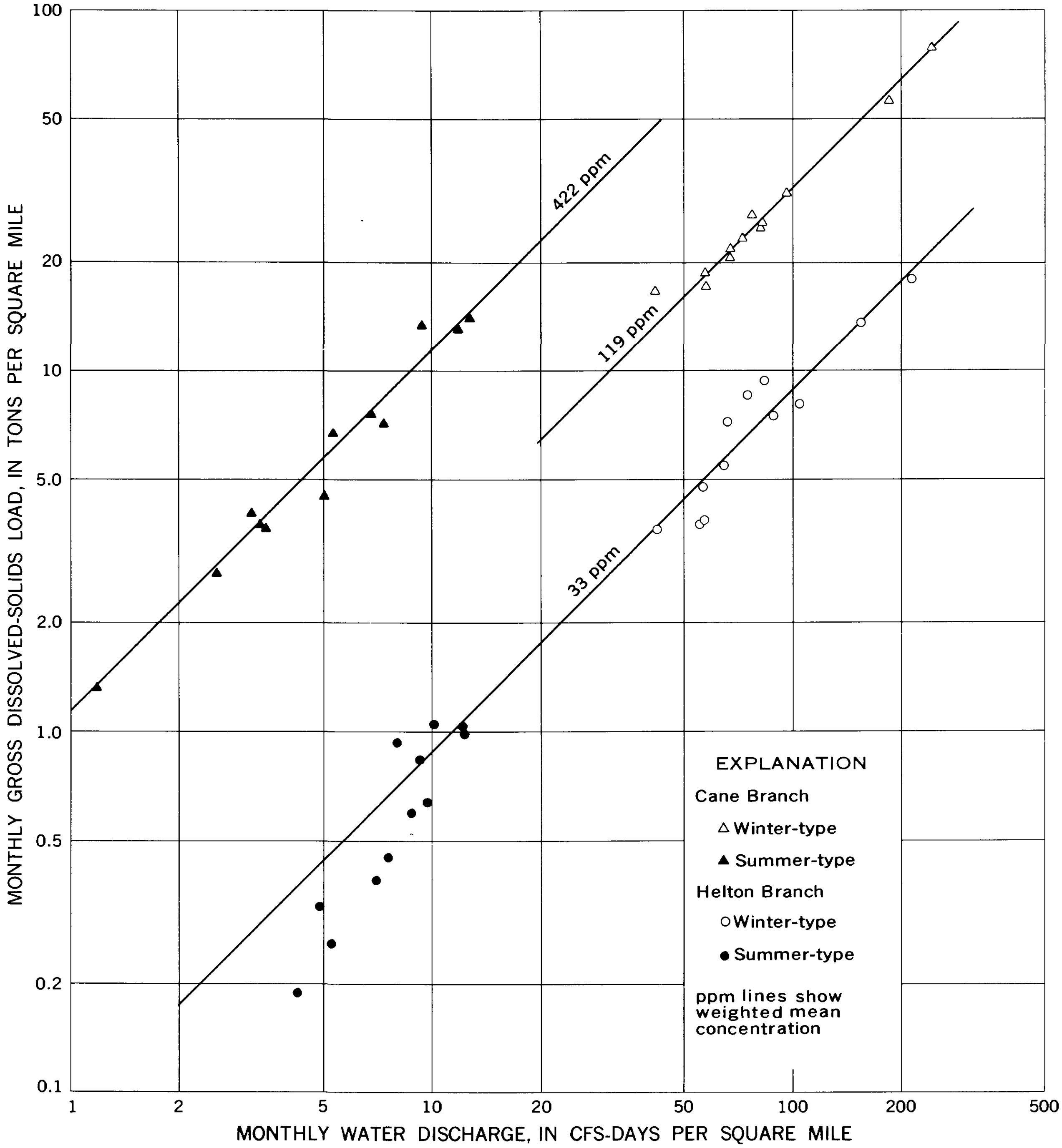

FIGURE 30.—Relation of monthly water discharge to monthly gross dissolved-solids load in Cane and Helton Branches from October 1956 to September 1958.

The annual yields of dissolved solids and sulfate transported by these streams for the 1957 and 1958 water years are listed in table 22 as gross yields. These data show that Cane Branch transported about 4½ times more dissolved solids and about 10 times more sulfate than Helton Branch on a tons-per-spuare-mile basis for the 2-year period.

The gross, or measured, yields in table 22 include the dissolved solids and sulfate contributed to the streams by precipitation and by chemical degradation in the study areas. To determine what part of each gross concentration was due to chemical degradation, the mineral content of the streamflow attributable to precipitation was subtracted from the gross concentrations. A corrected concentration was used for the precipitation in this subtraction because the concentra-

TABLE 22.—*Rates of chemical degradation and runoff in the Beaver Creek study area, for the 1957 and 1958 water years*

Water year	Runoff: Water discharge (cfs-days)	Runoff: Inches	Precipitation: Inches	Precipitation: Concentration (ppm)	Ratio of precipitation to runoff	Gross dissolved solids: Weighted average concentration (ppm)	Gross dissolved solids: Yield (tons per sq mi per yr)	Correction for concentration of precipitation (ppm)	Net dissolved solids: Weighted average (ppm)	Net dissolved solids: Yield (tons per sq mi per yr)
Helton Branch										
1957	471.21	20.61	55.75	8	2.7	31	46	−22	9	13
1958	515.63	22.57	51.92	8	2.3	34	56	−18	16	26
Cane Branch										
1957	388.698	21.57	56.19	8	2.6	145	227	−21	124	194
1958	414.882	23.04	52.00	8	2.3	131	219	−18	113	189
Helton Branch										
						Gross sulfate			Net sulfate	
1957	471.21	20.61	55.75	3	2.7	9	13	−8	1	1.5
1958	515.63	22.57	51.92	3	2.3	9	15	−7	2	3.3
Cane Branch										
1957	388.698	21.57	56.19	3	2.6	94	147	−8	86	135
1958	414.882	23.04	52.00	3	2.3	84	140	−7	77	129

tion of mineral constituents in the precipitation increases as portions of the precipitation leave the area by evaporation.

The part of the gross concentration attributable to chemical degradation is the net concentration, and the net yields of dissolved solids and sulfate for each area were computed from net concentrations.

A comparison of the net yields for the study areas shows that the dissolved solids and sulfate yields for Cane Branch are about 10 and 55 times greater, respectively, than the Helton Branch yields. Sulfate composes about 69 percent of the Cane Branch net yield and only about 12 percent of the Helton Branch net yield. Chemical degradation has definitely accelerated in the Cane Branch area compared to the rate of degradation in the Helton Branch area.

For the 1957 and 1958 water years, the total yield of equivalent sulfuric acid in Cane Branch was about 106 tons per square mile (table 23). This yield was about 28 percent of the net dissolved solids yield of Cane Branch. The amount of acid transported by Helton Branch during this same period was negligible because Helton Branch rarely contains titratable acidity.

TABLE 23.—*Monthly loads of equivalent sulfuric acid transported by Cane Branch from October 1956 to September 1958*

Date	Water discharge (cfs-days per sq mi)	Equivalent sulfuric [1] acid (tons per sq mi)	Date	Water discharge (cfs-days per sq mi)	Equivalent sulfuric [1] acid (tons per sq mi)
1956			*1957*		
Oct	3.37	0.99	Nov	82.8	6.15
Nov	2.51	.74	Dec	76.8	6.20
Dec	72.6	5.40			
			1958		
1957			Jan	41.6	3.84
Jan	242	18.00	Feb	57.4	3.88
Feb	96.1	7.15	Mar	67.0	4.62
Mar	57.7	4.30	Apr	184	12.75
Apr	67.6	5.05	May	81.6	5.65
May	11.9	3.50	June	5.05	1.10
June	12.7	3.74	July	7.38	1.82
July	3.37	.99	Aug	3.18	1.12
Aug	1.19	.35	Sept	5.35	1.91
Sept	9.29	4.60			
Oct	6.82	2.05	Total	1,199.31	105.90

[1] Not determined for Helton Branch because acidity concentration is negligible.

CONCLUSIONS

Before strip mining, the chemical characteristics of the surface water in the three study areas were similar. This chemical similarity is substantiated by the chemical quality of the runoff which now exists in the unmined parts of the study area. The control exerted by chemical equilibria between mineral and ionic species in precipitation is shown by the small variation in the concentration of solutes in these streams.

The large variation in the concentration of solutes in Cane Branch since mining began, and particularly after June 1956, is attributable to the chemical weathering of iron sulfide minerals in the spoil bank and highwalls formed during the strip-mining operations.

Chemical degradation is proceeding at a faster rate in the Cane Branch area than in the Helton Branch area. The net dissolved-solids yield of Helton Branch was 26 tons per square mile for the 1958 water year compared to 189 tons per square mile for Cane Branch.

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U.S. Geol. Survey, issued annually, Quality of surface waters of the United States, parts 1-4, North Atlantic slope basins to St. Lawrence River basin, as follows:

Water year	*Water-Supply Paper*	*Year published*	*Pages*
1956	1450	1960	511-512, 516-517
1957	1520	1960	544-546, 551-554
1958	1571	1962	663-665, 670-673
1959	1641	1963	----------------

SEDIMENTATION

By Charles R. Collier and John J. Musser, U.S. Geological Survey

METHODS OF STUDY

The objective of this investigation required the determination of the sediment yield from natural and strip-mined drainage basins. To meet these requirements, sediment discharge was measured at the three gaging stations operated in the Beaver Creek area.

The daily sediment discharge has been measured at Cane Branch near Parkers Lake from February 1956 to September 1959 and at Helton Branch at Greenwood from February 1956 to September 1958. At West Fork Cane Branch near Parkers Lake, the daily sediment discharge has been measured for short periods and for some storms in the 1958 and 1959 water years. The particle-size distribution of the sediment in transport has been defined for Cane and West Fork Cane Branches.

At the Cane and Helton Branch stations (pls. 1 and 2, respectively), samples of the water-sediment mixture were collected with depth-integrating samplers designated US DH-48 which were fitted with ¼-inch nozzles. The samples were collected from the overfall at the downstream edge of the concrete controls of the gaging stations so that virtually the total load of the clay, silt, and sand was sampled. Some samples were also collected during periods of increasing water discharge by a series of single-stage suspended-sediment samplers installed at the gages. At the West Fork Cane Branch station (pl. 1), suspended-sediment samples were collected with the US DH-48 samplers at the natural control 15 feet downstream from the recorder installation.

Sediment concentrations were determined in the laboratory by decanting, filtering, drying, and weighing each sample. The sediment discharge, in units of weight per day, was computed from a continuous sediment-concentration curve defined by the samples and the water discharge (U.S. Geol. Survey, 1960, p. 4-6, 8).

The particle-size distribution of the sediment was determined from samples selected so that a wide range of concentration, sediment discharge, and water discharge at the time of collection would be represented. The particle-size gradations were determined, in percent by dry weight, by the sieve and bottom-withdrawal methods of analysis. The sand fractions were separated from the sample and subdivided by wet sieving. The silt and clay fractions were then determined by the bottom-withdrawal method which is based on the fall velocity of the particles and which defines the particle sizes as sedimentation diameters. The method is described in detail in the Federal Interagency Report no. 7 (1943, p. 82-90). Most analyses were made in a dispersing settling medium and the resulting distributions approximate that of the primary particle sizes. Some samples were divided and a part analyzed in a settling medium of native stream water. In these analyses, flocculation of the fine particles was allowed, and the distributions thus defined more nearly approach the distribution which may exist when the particles are deposited in the pools of the stream.

An indication of the sources of sediment transported by Cane Branch and West Fork Cane Branch was obtained by investigating 12 small drainage channels during certain storm-runoff events. These channels were selected so that overland flow from various types of land use would be represented. These supplemental sites are located on plate 1. The samples were collected by using the US DH-48 samplers or by catching the water-sediment mixture directly from overfall at rock outcrops; the flows were measured volumetrically or by current meter.

To obtain a direct measure of rate of erosion on the spoil bank, detailed topographic maps of small drainage areas and profiles of guilles were surveyed. These areas and gullies were selected to represent the several topographic features and types of erosion prevalent on the spoil bank, including large and small gullies or rills cut into steep slopes and terraced areas. Detailed maps were also prepared for three reaches of Cane Branch and two reaches of West Fork Cane Branch to measure the deposition of sediment in the channels.

FACTORS AFFECTING SEDIMENTATION

Sedimentation includes the natural processes involved in the destruction of rock; the erosion, transportation, and deposition of the products of destruction together with material derived from any other source, and the diagenesis, cementation, or induration of these products (Twenhofel, 1950, p. 3). The interaction of many interrelated natural processes and agents are involved. The processes of destruction (weathering), erosion, transportation, and deposition, with water as the principal agent, are of primary interest in this study.

Weathering, as a part of sedimentation, is concerned with those chemical and mechanical processes which provide rock fragments for erosion and transport by air, ice, or water. These processes include oxidation, hydration, carbonation, frost wedging, temperature changes, and the action of plants and animals. Oxidation, hydration, and carbonation are generally considered to be chemical processes, whereas the others are mechanical processes.

Chemical-weathering processes tend to increase the solubility of the bedrock and its cementing materials to some degree. When the cementing material from a rock fragment is dissolved, the rock separates into many parts. These chemical processes may also produce volume changes within the rock that cause small fragments to be loosened and made available for transport. A more detailed explanation of the processes of chemical weathering and erosion is given in the section on "Geochemistry of water."

The mechanical processes of weathering disintegrate bedrock for transport by applying forces to the rock that cause it to separate into smaller particles. The most important processes in the study areas are frost wedging, where water freezes along the joints and bedding planes and within the pore spaces of a rock, and atmospheric temperature changes which cause an expansion and contraction of the rock particles.

The chemical and mechanical processes of weathering are both active throughout the study areas, but one process may be dominant in a given location. Chemical weathering dominates in the claystone and siltstone beds and has resulted in the general rounding or smoothing of the hilltops. Chemical processes are particularly important in breaking down the mass of claystone and siltstone which makes up most of the spoil banks. Mechanical weathering processes are dominant among the sandstones and conglomerates and has resulted in the formation of the cliffs in the areas.

The type of weathering which occurs in a given location is influenced by such interrelated factors as the parent rock material, climate, physical environment, time, organisms, and the dynamics of the environment (Trask, 1950, p. 4). The chemical character, porosity, and structure of the sandstone, siltstone, and claystone in the study areas control to a large degree the rate of weathering and the type of soils which are produced. The amount, form, and duration of precipitation and the length of time water is in contact with the rock so that the chemical solution may occur are dependent upon the climate and physical environment of the basins, including their topography, drainage, soils, and vegetal cover. These physical characteristics, along with precipitation, are also important in the removal of weathered particles by erosion.

The dynamics of the environment is the relationship of the rate of weathering to the rate of removal of weathered particles by erosion. Basically, two rates of weathering occur in the Cane Branch and Helton Branch basins: weathering that occurs in the undisturbed areas and weathering that occurs in the areas of strip mining, exploration, and road construction. In the undisturbed areas of the basins, the processes of weathering over a long period of time have produced a soil blanket on most of the land surface, and exposed rocks have undergone some degree of decomposition. The soil supports and is protected by a vegetal cover, and the removal of material by erosion is slow. This rate of weathering is governed by the natural environment and has not been significantly affected by the activities of man. In contrast to these conditions, strip mining in the Cane Branch basin has provided spoil banks and access roads consisting of disturbed or exposed rock and soil. Much of this material is virtually unweathered and without a vegetal cover. This change in environment has greatly accelerated the rate of weathering, and the removal of material from these areas by erosion is rapid.

Erosion by water occurs by the plucking or dislodging of particles from rest by the impact of raindrops, by the force of water flowing over the particles, and by the impact or abrasion of moving particles. Erosion of the spoil banks occurs as sheet erosion, gullying, and stream channel erosion. Sheet erosion, the removal of material by overland runoff from precipitation without the formation of channels, on the spoil banks and natural areas is discussed in the section on "Sheet erosion." Gullying and its associated slumping is prevalent on the steep slopes of the spoil bank. Stream-channel erosion has formed the well-defined channels of the streams in the area. Active erosion of this type is now most noticeable in Cane Branch downstream from the mining area, where the stream is progressively removing and redepositing the sands, silts, and clays carried from the spoil banks. Erosion incident to cultural development, except that which occurs on the farms and roads in the areas, has been of minor importance.

The amount and size gradation of sediment in transport by water at a given time depends upon the interaction of the flow characteristics and the availability of material. The rock and soil particles are transported by water by being held in suspension (suspended load), by bouncing along the stream bed in short leaps (saltation load), or by rolling along and remaining in contact with the streambed (bedload). The method of transportation of a given particle depends upon the following: Its size, density, and shape; the quantity of material in transport; and the velocity, turbulence, temperature, and volume of flow. Large quantities of clay and silt particles are transported by Cane Branch as suspended load by being held in suspension by the upward components of the turbulent currents in the stream which counterbalance the force of gravity. These currents are produced and affected by the shape, roughness, and slope of the streambed and by the temperature and volume of water. The amount of material already in suspension also acts as a control, for a given rate of discharge has a given energy and therefore an upper limit to the amount of material the water is capable of transporting.

The same factors which affect the transportation of sediment by water also influence the deposition of sediment. Fluvial deposition is caused by either (1) a loss of energy necessary to continue the transportation of the sediment load or (2) an increase in the effective particle size of the sediment in suspension by flocculation without an increase in energy.

A reduction in the energy available to transport sediment may be due to a decrease in the volume of flow which produces a lower velocity and a decrease in turbulence. Velocity and turbulence are also decreased by an increase in the cross-sectional area of the stream as it enters the backwater areas of pools in the channel. In these situations the larger particles are the first to be deposited, whereas particles small enough to remain in suspension for a significant length of time are carried farther downstream. The degree of sorting (similarity of particle sizes) in a deposit depends upon the fluctuation of the velocity and accompanying turbulence of the flow. A deposit tends to be well sorted where the fluctuations are small.

An increase in the effective particle size of suspended sediment results from the attraction of the fine particles to each other so that together they assume the settling velocity of a larger-sized particle. This attraction or flocculation occurs with the particles in the silt, clay, and colloid sizes; the sands are not affected. This attraction is due to the difference in the electrical charge of the particles or between the particles and the charge of electrolytes in solution. The degree of flocculation is controlled by the presence and concentrations of ions having opposite electrical charges from those of the particles, by the valency and adsorption of the ions, and by the modifying action of ions carrying the same electrical charge as the fine sediment particles (Twenhofel, 1950, p. 211). Particles of silica and clay minerals, which comprise most of the suspended load of Cane Branch, carry negative charges whereas the colloids of readily oxidizable minerals such as iron and aluminum carry positive charges. Flocculation, particularly of the clay minerals, occurs more readily in acid solutions.

In Cane Branch, flocculation frequently occurs after acid drainage from the spoil banks enters the stream. After flocculation, the stream appears very clear and the streambed is covered by a coating of dark-gray sediment. In the vicinity of the gaging station, some recent deposits have accumulated to a depth of more than 2 feet. These deposits are composed of sediment derived from the spoil banks in the Cane Branch basin. The deposits are more extensive and have a finer size gradation than deposits in Helton Branch or in tributaries draining unmined basins.

WEATHERING AND EROSION IN STUDY AREAS

HELTON AND WEST FORK CANE BRANCH AREAS

The major part of the stratigraphic section in the Helton Branch area is composed of sandstone and conglomerate. Weathering of these rocks by frost wedging and by solution of the cementing material produces sand-to-boulder sized particles for transportation. The remaining part of the stratigraphic section consists of siltstone and claystone beds which weather to form well-developed soils composed of silt and clay particles.

Along the lower reach of Helton Branch, the cliff-forming sandstone forms steep walls that are particularly susceptible to frost wedging in the winter. Many large blocks have wasted from the steep walls to form talus piles at the base of the cliffs. These talus piles then undergo further weathering until the particles are reduced to sizes that can be transported by Helton Branch or its tributaries.

The vegetation and litter, which cover 99 percent of the Helton Branch basin, protect and hold the soil; so, weathering and erosion are slow. Sheet erosion predominates in the vegetated areas and probably contributes the most sediment to the streams.

The unprotected areas of the basin weather and erode faster than the vegetated areas but contribute only a minor amount of sediment to the streams. The cultivated ground and roads along the divides include only 1 percent of the drainage area and are not close to established channels. Much of the sediment eroded from these areas is filtered from the runoff by the litter and vegetation between the unprotected areas and the streams.

The stratigraphic section upstream from the West Fork Cane Branch gaging station consists of the upper few feet of the main cliff-forming sandstone and of sandstone, siltstone, and claystone beds in the strata above the main cliff-forming sandstone. The stratigraphic section is about half sandstone and half siltstone and claystone. Weathering of the sandstone produces the larger fragments that are transported within the area. The siltstone and claystone supply the smaller fragments. Since most of the West Fork Cane Branch study area is above the main cliff-forming sandstone, there are no steep-walled canyons to supply fragments for talus piles.

About 1 percent of the West Fork Cane Branch area is unprotected by vegetation and consists of coal prospecting areas and roads. These unprotected areas contribute nearly all the sediment transported by West Fork Cane Branch. The trenches and small spoil banks in the prospect areas contain various-sized fragments and types of rock, but siltstone and claystone predominate and most of the sediment leaving these areas is silt and clay. A dirt road covered with crushed limestone gravel runs along the divide between the Cane and West Fork Cane study areas. Sections of this road contribute clay- to gravel-sized particles of quartz, clay minerals, and limestone to West Fork Cane Branch.

About 99 percent of the West Fork Cane Branch area is protected by vegetation, and the rate of erosion is slower here than in the unprotected areas. The sandstones, siltstones, and claystones have weathered to form well developed soils, and very few sandstone beds outcrop. Sheet erosion in the protected part of this study area contributes some of the silt- and clay-sized particles to West Fork Cane Branch.

CANE BRANCH AREA

Weathering and erosion in the Cane Branch study area have been influenced by strip mining which occurred intermittently during a 4-year period. The mining activity of 1955–56 disturbed the rock and soil in about 6.4 percent of the study area (see table 26), leaving 93.6 percent of the area unmined. The mining activity of 1958–59 disturbed an additional 4 percent of the area.

The major part of the stratigraphic section in the Cane Branch area, as in the Helton Branch area, is composed of conglomerate and sandstone, and the minor part is composed of siltstone and claystone. The mining activity has occurred in the sandstone, siltstone, and claystone beds overlying the main cliff-forming sandstone.

UNMINED AREAS

The main cliff-forming sandstone is exposed in the valley walls along the lower reaches of Cane Branch. As in Helton Branch, these beds weather principally by frost wedging and by solution of the cementing material. Frost wedging and the action of gravity cause blocks of sandstone of various sizes to separate from the bedrock and fall onto nearby ledges and the valley floor, where they sometimes form talus piles. These piles of sandstone blocks undergo further weathering, and the resulting solutes and particles are then transported by Cane Branch and its tributaries.

The strata above the main cliff-forming sandstone consist predominantly of siltstone and claystone with some interbedded sandstone layers. Chemical weathering processes have been dominant among these beds which are covered by well-developed soils. The meager exposures are usually sandstone.

About 98 percent of the unmined area is protected by vegetation. The rate of erosion is slower in these protected areas than in the unvegetated areas. Since the soils consist mainly of fine-grained particles, these are the principal sizes removed by sheet erosion from the protected areas. The 2 percent of unmined area not protected by vegetation consists of roads and abandoned farmland. The rate of erosion is more rapid in this group, and clay-to-gravel sized particles are removed from these unprotected areas by surface runoff.

STRIP-MINED AREAS

Spoil banks in the Cane Branch study area are composed of a heterogeneous mixture of sandstone, siltstone, claystone, and soil. There is no developed soil zone on the spoil and very sparse vegetation. The rate of weathering, particularly chemical weathering, is faster in this freshly exposed material than in the unmined parts of the Cane Branch area.

The spoil bank on the southwestern side of the Cane Branch area resulted from the mining activity of 1955–56, and the effects of weathering and erosion have been studied in more detail on this bank than on those formed during the mining activities of 1958–59. The observations and studies outlined in the following paragraphs refer specifically to the southwest spoil bank.

Weathering and erosion began on the southwest spoil bank as soon as the mining operation provided the unconsolidated and unprotected material. The spoil bank had a rugged and irregular surface until June 1956 when the bank was leveled and the two drainage ditches were cleared. The general topography of the bank has remained the same since leveling. The inner edge of the bank slopes steeply into the strip pit and has up to 20 feet of relief. The outer edge slopes steeply toward Cane Branch, but in some places there are terraces along the slope.

The level areas on the top of the bank erode more slowly than the steep slopes, but definite drainage networks and some gullies have been formed. The steep slopes erode by sheet erosion and by gullying and associated slumping. The most noticeable changes can be observed in the large gullies which have been cut into the steep slopes. Figure 31 shows the changes that have occurred in a small channel at the top of a steep slope. The 1960 photograph shows that the channel is deeper, and that slumping has occurred along the banks of the channel. The spoil masses that slump into the channels are transported downslope to Cane Branch during storm events.

Erosion along a terraced part of the spoil bank is shown in figure 32. A comparison of the two photographs shows that from 1958 to 1960 the spoil-bank material weathered, the channel on the right widened, and slumping occurred along this channel.

Access roads built by the mining operators for hauling coal erode at a faster rate than the areas covered by vegetation. These low standard dirt roads are a source of clay- to gravel-sized particles which are transported by surface runoff. The sediment concentration of the road drainage was measured at 12,000 ppm and is comparable to the concentration of sediment in the surface runoff from the spoil banks. The rate of erosion from a road is being measured in area 13 (pl. 1).

FIGURE 31.—Comparative photographs of a channel on the southwest spoil bank in area *11*, Cane Branch study area, showing gullying and slumping of spoil-bank debris. Upper photograph, December 10, 1958; lower, March 22, 1960.

SEDIMENT TRANSPORT

SEDIMENT TRANSPORT AT SUPPLEMENTAL SITES

Measurements were obtained at 10 supplemental sites in the Cane Branch study area to determine the relative amounts of sediment being removed from subbasins with varying land uses and to define more exactly the sources of the sediment being transported at the Cane Branch gaging station. Data were also obtained at two sites within the West Fork Cane Branch study area. The location of these sites is shown on plate A and in figure 33.

The following list gives the sites where observations on sediment transport were made and the types of land use in the drainage area above each site at the time of measurement:

Site	*Land uses*
A	Coal haul road.
B	Forest, abandoned farmland, and small strip mine.
C	Forest and abandoned farmland.
E	Forest.
G	Strip mine and logging road.
H	Forest.
J	Forest and gravel road.
K	Forest, gravel road, and prospect pit.
L	Forest.
M	Strip mine.
N	Strip mine and forest.
P	Strip mine.

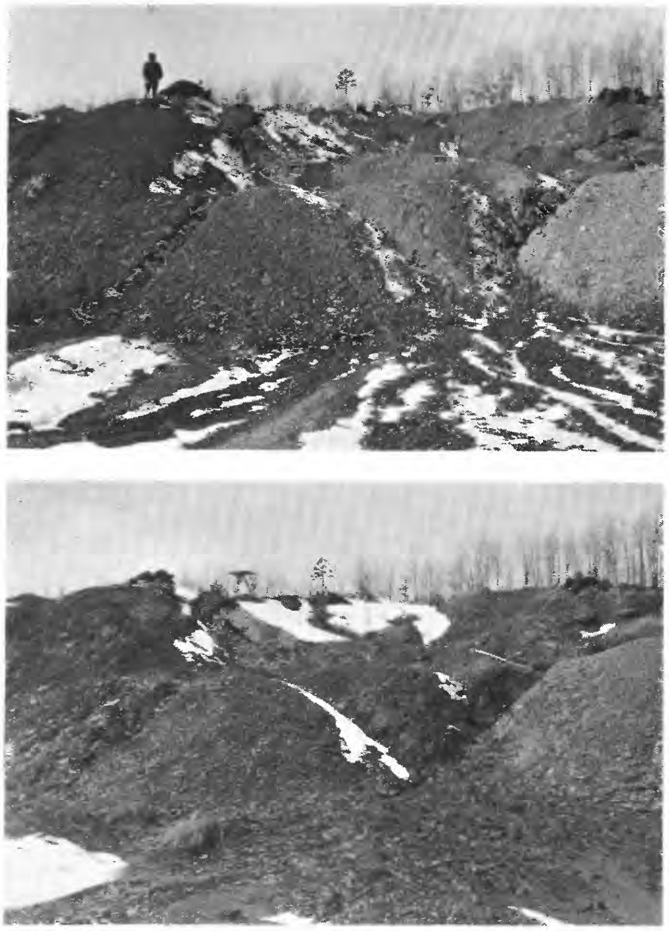

FIGURE 32.—Comparative photographs showing erosion on a terraced part of the southwest spoil bank, area *12* in the Cane Branch study area. Upper photograph, December 16, 1958; lower, March 22, 1960.

The maximum observed sediment concentration from April 1958 to September 1959 at each of these sites is shown in figure 33. Drainage from site A (coal haul road) had the highest observed concentration of 12,000 ppm. Except for sites P and H, drainage areas which include large parts of a spoil bank had streamflow containing concentrations of more than 400 ppm. The concentration at site P is based on only one observation, and the concentrations at site H were observed before mining began in that subbasin. Drainage areas with a rather complete vegetal cover had concentrations of less than 50 ppm. Drainage from the unvegetated sections of the study areas transports the highest concentrations of sediment.

Sediment concentrations and water discharges at some of the supplemental sites during two storms on February 10, 1960, are shown on the hydrographs in figure 34. The higher sediment concentrations and surface runoff occurred during the afternoon storm owing to the more intense rainfall and higher water discharges. Surface runoff from unvegetated areas has much higher sediment concentrations than the surface runoff from areas protected by vegetation.

SEDIMENT TRANSPORT AT GAGING STATIONS

Before strip mining, the hydrologic environment of the study areas was similar, and the sediment yields were probably of the same magnitude. The spoil bank resulting from strip mining in the Cane Branch basin provided a large volume of disturbed and unconsolidated material for erosion and transportation by surface runoff. These banks are without vegetal cover; so, the processes of chemical and physical weathering and the removal of sediment by erosion have accelerated.

Comparison of the annual sediment discharges and yields (table 24) show that much more sediment was transported by Cane Branch than by Helton Branch. During the 1958 water year the sediment discharge of Cane Branch was 1,290 tons, a yield of 1,930 tons per square mile. This yield was 69 times the yield of 27.9 tons per square mile for Helton Branch.

This increase in yield has resulted from the strip mining of 6.4 percent (27.4 acres) of the Cane Branch study area. The sediment yield from the undisturbed parts of the Cane Branch area should be about the same as that of Helton Branch; then the sediment yield from the strip-mined part of the Cane Branch area would equal about 30,000 tons per square mile for the 1958 water year.

TABLE 24.—*Summary of sediment discharge by water years, Cane Branch and Helton Branch*

Period	Cane Branch				Helton Branch			
	Water discharge (cfs-days)	Sediment concentration [1] (ppm)	Sediment discharge (tons)	Sediment yield (tons per sq mi)	Water discharge (cfs-days)	Sediment concentration [1] (ppm)	Sediment discharge (tons)	Sediment yield (tons per sq mi)
Feb.–Sept. 1956	333. 032	437	393. 64	588	405. 43	15	16. 2	19. 0
Water year:								
1957	388. 698	537	562. 74	840	471. 21	14	18. 1	21. 3
1958	414. 882	1, 160	1, 294. 65	1, 930	515. 63	17	23. 7	27. 9
1959	187. 711	1, 640	830. 84	1, 240	248. 24	---	---	---

[1] Weighted with water discharge.

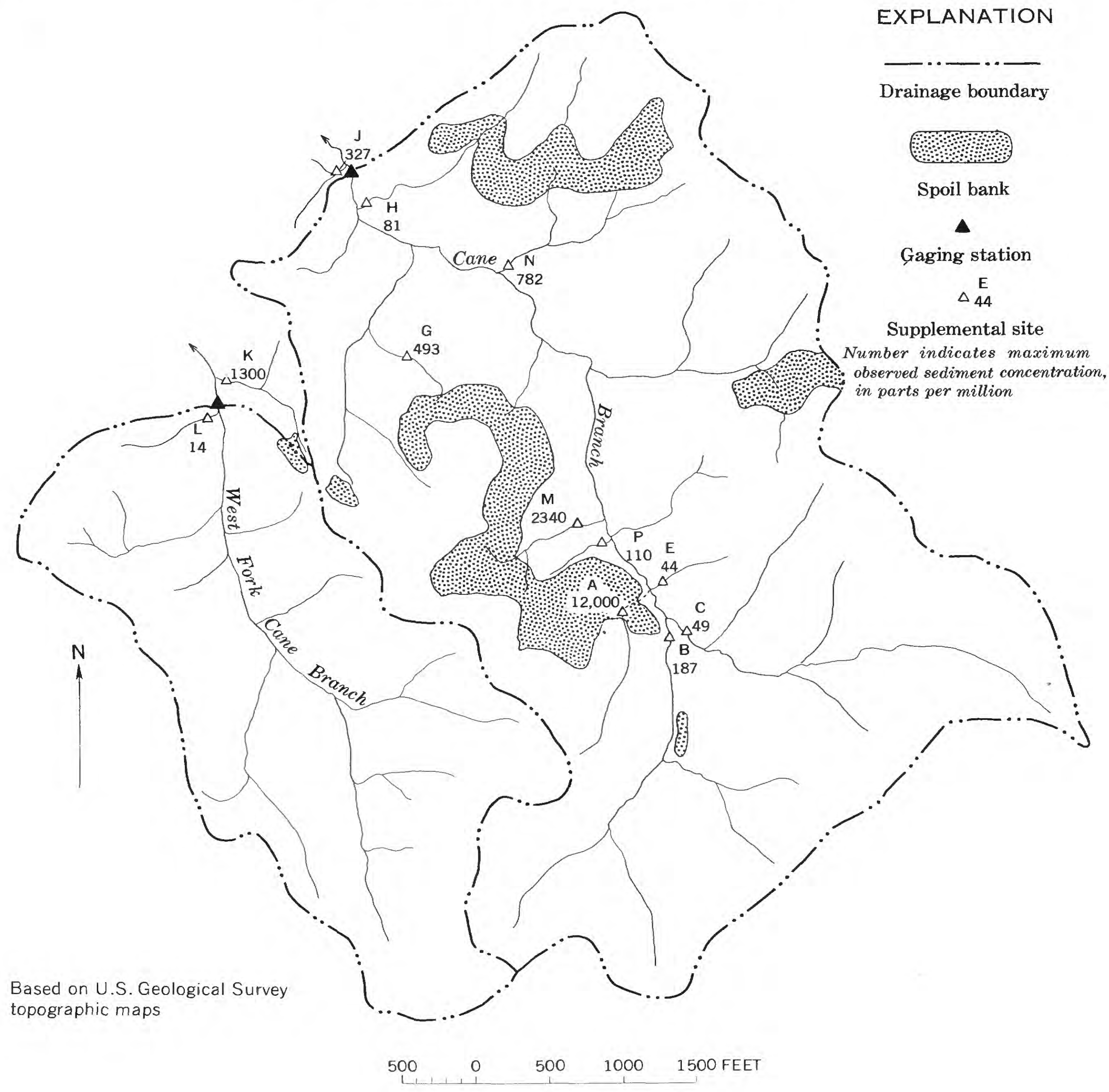

FIGURE 33.—Map of Cane Branch and West Fork Cane Branch study areas, showing maximum observed sediment concentration in selected subbasins, 1958 and 1959 water years.

The downstream migration of sediment by repeated movement and deposition in the stream channel has resulted in an increased proportion of sediment to water discharge at the Cane Branch gaging station. This increase is shown by the annual weighted mean concentrations of Cane Branch (table 24). The weighted mean concentration was highest for the 1959 water year, although less runoff that year resulted in a lower sediment discharge and less yield than in 1958.

A summary of the sediment discharges by months is given in table 25. The daily sediment discharges, daily mean concentrations, and available particle-size analyses are published annually (U.S. Geol. Survey, 1956–59).

The differences in the sediment discharge of Cane and Helton Branches may be seen by comparing the duration curves of daily sediment discharge shown in figure 35. The curves were compiled from the data for only the 1957 and 1958 water years so that each curve would be representative of the same time period and so that each season of the year would be equally represented.

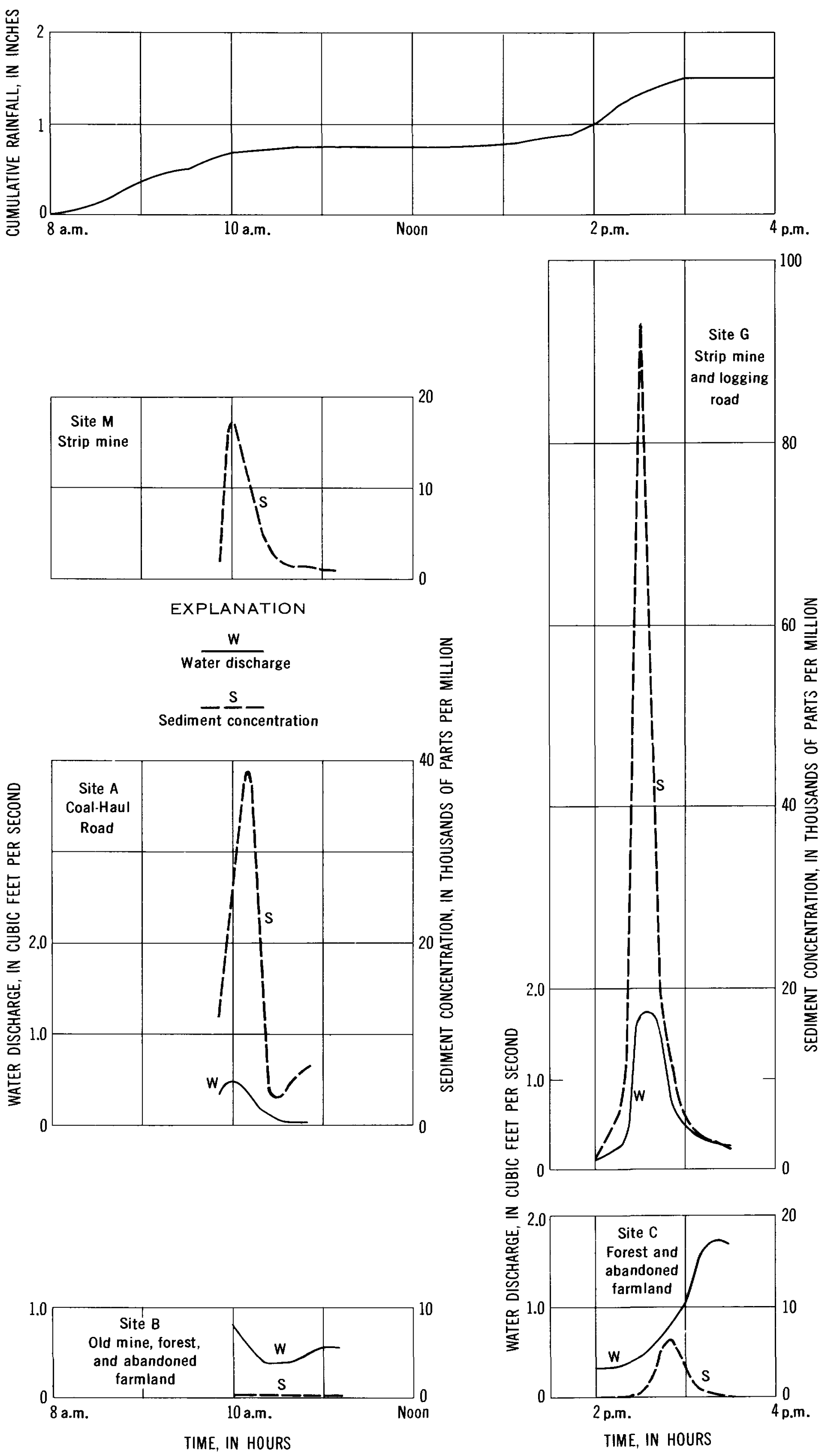

FIGURE 34.—Hydrographs of storm runoff at supplemental sites in Cane Branch study area for February 10, 1960.

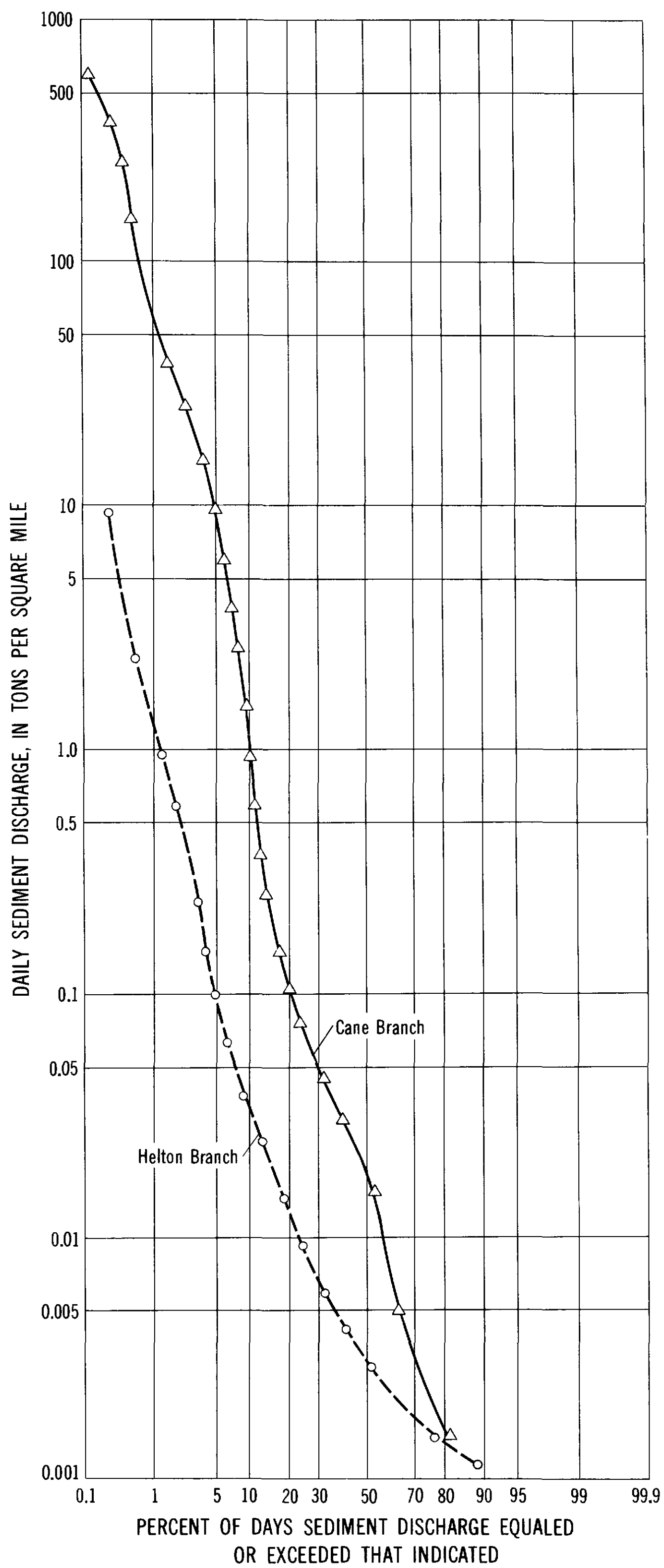

FIGURE 35.—Duration curves of daily sediment discharge for Cane and Helton Branches, October 1956 to September 1958.

The duration curves illustrate that Cane and Helton Branches had sediment discharges of less than 0.0015

TABLE 25.—*Summary of sediment discharge by months, Cane Branch and Helton Branch*

Month and year	Cane Branch			Helton Branch		
	Water discharge (cfs-days)	Sediment concentration [1] (ppm)	Sediment discharge (tons)	Water discharge (cfs-days)	Sediment concentration [1] (ppm)	Sediment discharge (tons)
1956						
Feb	151.05	343	140.04	196.09	20	10.5
Mar	90.91	364	89.32	104.60	12	3.30
Apr	65.83	363	64.60	69.24	11	2.10
May	7.318	10	.20	11.83	2	.058
June	3.948	2,620	27.88	4.97	2	.033
July	8.139	2,330	51.12	9.68	5	.132
Aug	4.429	1,710	20.46	5.99	4	.074
Sept	1.408	5	.02	3.03	3	.024
Oct	2.257	46	.28	3.59	2	.025
Nov	1.679	24	.11	4.44	2	.025
Dec	48.662	648	85.23	56.21	7	1.10
1957						
Jan	162.03	637	279.05	182.26	29	14.4
Feb	64.36	163	28.35	88.29	2	.550
Mar	38.67	21	2.26	47.45	3	.350
Apr	45.28	267	32.68	48.55	8	1.00
May	7.962	2,610	56.12	10.43	2	.055
June	8.517	956	21.98	10.41	4	.112
July	2.255	504	3.06	6.85	5	.095
Aug	.800	14	.03	4.16	3	.030
Sept	6.226	3,190	53.59	8.57	15	.338
Oct	4.569	1,070	13.18	7.89	4	.082
Nov	55.467	3,130	468.07	63.57	58	10.0
Dec	51.47	258	35.92	70.80	15	2.82
1958						
Jan	27.84	56	4.18	35.78	5	.480
Feb	38.47	130	13.51	48.07	10	1.33
Mar	44.90	63	7.66	54.63	3	.418
Apr	123.42	1,850	617.43	131.54	20	7.05
May	54.70	358	52.89	75.26	6	1.19
June	3.386	396	3.63	8.25	6	.126
July	4.944	4,520	60.17	7.47	4	.078
Aug	2.131	527	3.03	5.95	2	.039
Sept	3.585	1,550	14.98	6.42	3	.055
Oct	3.114	6,520	54.81	6.23	----------	----------
Nov	7.831	1,210	25.55	9.21	----------	----------
Dec	6.21	16	.26	8.04	----------	----------
1959						
Jan	26.80	389	28.24	32.33	----------	----------
Feb	37.48	489	49.54	42.19	----------	----------
Mar	27.54	400	29.68	30.46	----------	----------
Apr	44.91	270	32.81	49.40	----------	----------
May	7.77	678	14.22	13.54	----------	----------
June	5.560	2,120	31.82	37.45	----------	----------
July	9.710	11,900	312.31	6.23	----------	----------
Aug	6.033	6,190	100.91	5.84	----------	----------
Sept	4.753	11,700	150.69	7.32	----------	----------

[1] Weighted with water discharge.

ton per square mile for about the same number of days. During these days the streams were at low or base flow. Acid water in Cane Branch caused the fine sediment particles to flocculate and settle to the bottom, thereby keeping the water clear and the sediment discharge low. During periods of storm runoff this deposited material is resuspended and is again transported along with newly added material, and the sediment discharge is high. The water in Helton Branch is nearly neutral and only a limited amount of fine material is available for transport in the basin.

High sediment discharges occurred at Cane Branch much more frequently than at Helton Branch. For 16 percent of the days (one standard deviation from the median) the sediment discharge of Cane Branch equaled or exceeded 0.16 ton per square mile compared to 0.016 or more ton per square mile discharged by Helton Branch. For 1 percent of the days the difference was even greater: more than 62 tons per square mile was discharged by Cane Branch, and more than 1.3 tons per square mile was discharged by Helton Branch.

Most of the sediment is discharged during the relatively few days having storm runoff. For Cane Branch, the daily sediment discharge exceeded 25 tons (37.3 tons per square mile) on 11 days in the 2-year period included in the duration curve and on 18 days in the 3⅝ years of record. The maximum daily sediment discharge of Cane Branch was 520 tons on April 24, 1958, which was 40 percent of the load for that year. Helton Branch, in the 1957 and 1958 water years, had daily sediment discharges of over 2 tons (2.35 tons per square mile) on only 4 days. The maximum daily load was 11.4 tons on January 29, 1957.

SEDIMENT CONCENTRATIONS

A comparison of the sediment concentrations in the streams shows that much more sediment is being transported from the Cane Branch area than from the other two study areas. The maximum observed sediment concentration in Cane Branch was 112,000 ppm on October 28, 1958. This concentration was due to the draining of pool 1 (pl. 1) by a mining operator rather than to storm runoff. The water from this pool transported large quantities of spoil downstream past the Cane Branch gaging station. The maximum observed concentration due to storm runoff was 75,000 ppm on July 1, 1959. The observed concentration exceeded 30,000 ppm during many storms.

In contrast to these conditions, the maximum observed concentration in West Fork Cane Branch was 2,780 ppm on July 1, 1959, and in Helton Branch it was 553 ppm on February 18, 1956. The observed concentration in West Cane Branch frequently exceeded 1,000 ppm, and in Helton Branch it exceeded 300 ppm on several occasions during storm runoff.

The maximum daily mean concentrations in Cane and Helton Branches were 4,890 ppm (Sept. 10, 1959) and 90 ppm (Nov. 18, 1957), respectively.

The seasonal variation in the sediment load and concentration of Cane and Helton Branches is shown in table 25. The months of high sediment discharge generally occur in the winter and early spring and coincide with the months of high water discharge. The high weighted mean concentrations, however, occur generally in late spring, summer, and fall, particularly for Cane Branch. In these warm months, intense thunderstorms result in greater rates of overland flow, causing a high erosion rate on the spoil banks. The winter storms have a longer duration and provide more precipitation than the summer storms, but they are less intense and cause a lower rate of erosion on the spoil banks. Also, the spoil is often frozen in the winter and is therefore more resistant to erosion.

Examples of the difference in rainfall intensity, water discharge, and sediment concentration of Cane Branch during summer- and winter-type storms are shown in figures 36 and 37, respectively. Rainfall was more intense in the summer storm, 1.62 inches in 1½ hours compared to 1.02 inches in 9 hours, and resulted in a more rapid increase in water discharge and a higher peak flow. The average flow for the day, however, was 1.9 cfs on July 1, 1959, compared to 5.9 cfs on April 10, 1958. The sediment concentration during the summer storm increased from 5 to 75,000 ppm in three-fourths of an hour, whereas the concentration during the winter storm increased from 20 to 5,950 ppm in 4¼ hours. The daily mean concentration was 3,200 ppm, and the daily sediment discharge was 106 tons for July 1, 1959, and 468 ppm and 14.2 tons for April 10, 1958.

The peak sediment concentration in Cane Branch occurred before the peak water discharge during all storms (figs. 36 and 37). Material which was recently weathered to easily transportable size is available for erosion by the early overland flow. In addition, sedi-

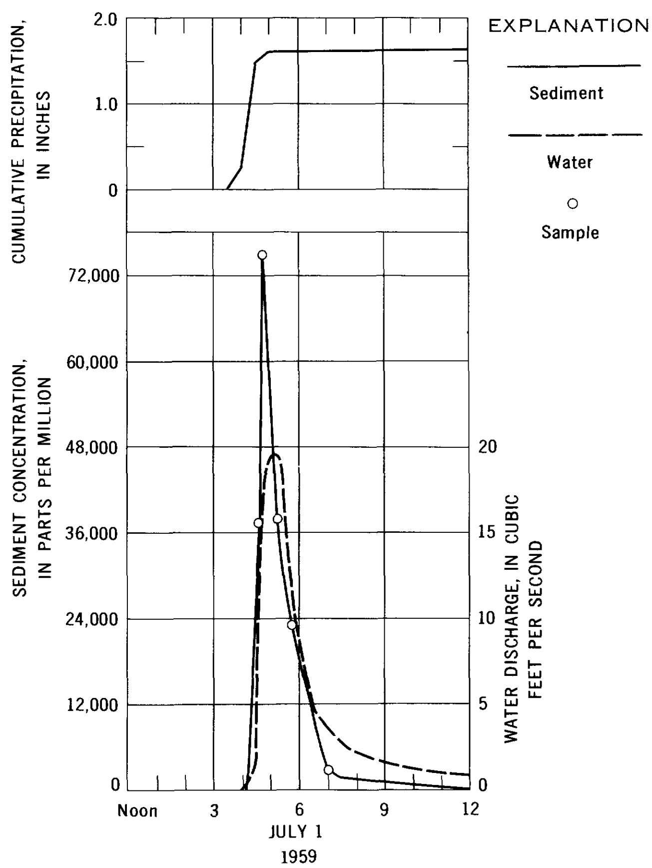

FIGURE 36.—Graph of sediment concentration, water discharge, and cumulative precipitation, Cane Branch near Parkers Lake, Ky., July 1, 1959.

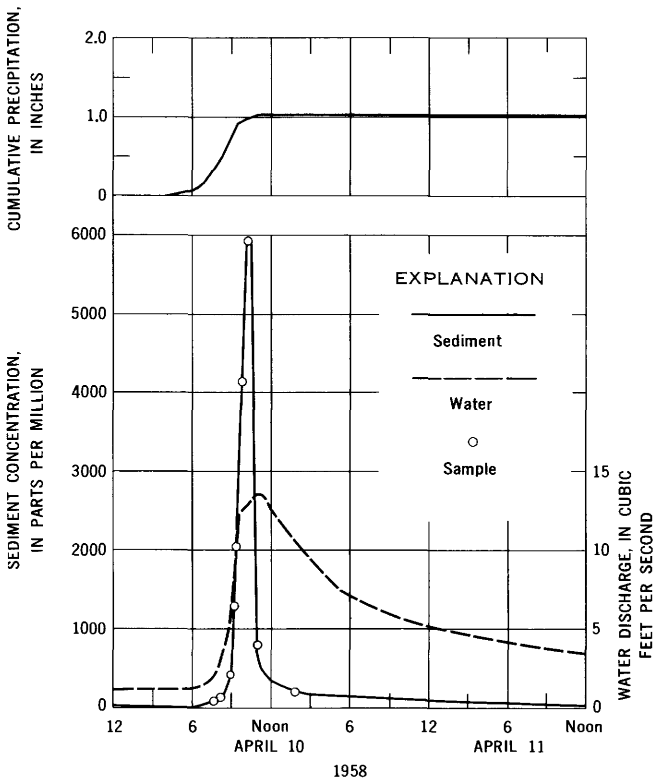

FIGURE 37.—Graph of sediment concentration, water discharge, and cumulative precipitation, Cane Branch near Parkers Lake, Ky., April 10–11, 1958.

ment deposited in the channel is resuspended by the increased turbulence and velocity of the stream during increasing water discharge.

The hydrograph for the April 10, 1958, winter-type storm in Helton Branch is shown in figure 38 and can be compared with the hydrograph for the storm in Cane Branch. The precipitation curves for both study areas are very similar, but the water discharge and sediment concentration curves are different. The sediment concentration of Helton Branch reached only 23 ppm compared to 5,950 ppm in Cane Branch.

STORMS

A further analysis of the sediment yield of Cane and Helton Branches was made by considering only the water and sediment discharged as direct runoff from storms. The part of the water discharge considered to be base flow was subtracted from the total flow for each storm. The sediment discharge for the base flow was estimated and subtracted from the total sediment discharge of each storm. The analysis included 70 storms that occurred in the Cane Branch basin from February 1956 to September 1959, and 39 storms in the Helton Branch basin from February 1956 to September 1958.

The correlation of sediment discharge to water discharge of Cane and Helton Branches is shown in figure 39. For both streams the sediment discharge increases as the water discharge increases. Notice, however, that the plots for both summer-and winter-type storms for Helton Branch and for winter-type storms for Cane Branch tend to have a slope of approximately 45°. This is due to less variation in the sediment concentration and is an indication of a deficiency in the availability of material which the stream can transport. There appears to be no seasonal affect on the relation between the water and sediment discharge of Helton Branch, except that there is more variability in the sediment discharge for a given flow in the winter-type storms.

The sediment discharges for a given runoff are much higher and more variable for Cane Branch than for Helton Branch. Accelerated weathering and erosion on the unprotected strip-mined areas cause Cane Branch to be more sensitive to factors such as the form, intensity, and duration of precipitation and to antecedent moisture conditions. This results in the wide scatter and no well defined slope in the plot of Cane Branch, particularly for the summer-type storms (fig. 39). Although there is some intermingling of the points which represent summer- and winter-type storms, the sediment discharge is generally greater during the summer for a given direct runoff. The hydrographs shown in figures 36 and 37 also illustrate the seasonal variation in the sediment load of Cane Branch during storms. This seasonal effect was considered in determining the trend of the sediment yield of Cane Branch.

A time-trend study of the sediment yield of Cane and Helton Branches was made with the storm data. The seasonal variation in the sediment yield of Cane Branch required separate cumulative curves for the

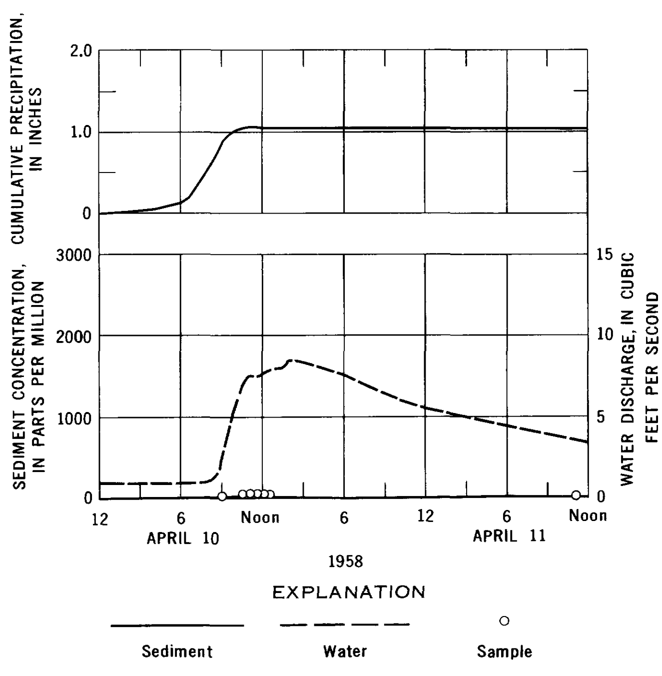

FIGURE 38.—Graph of sediment concentration, water discharge, and cumulative precipitation, Helton Branch at Greenwood, Ky., April 10–11, 1958.

41 summer-type and the 29 winter-type storms. For Helton Branch only the 26 storms yielding a water discharge of more than 1.0 cfs per sq mi were used to compute the cumulative curve. These storms represent the winter-type storm (fig. 39). The other 13 storms for Helton Branch, all summer type, had a total sediment yield of only 0.341 ton per square mile and were not included in the curves. The storms included 92 percent of the sediment discharge and 39 percent of the water discharge of Cane Branch, and 87 percent of the sediment and 32 percent of the water for Helton Branch. The points shown in figure 40 are for the cumulative totals at the end of each month, and several storms may therefore be included between adjacent points.

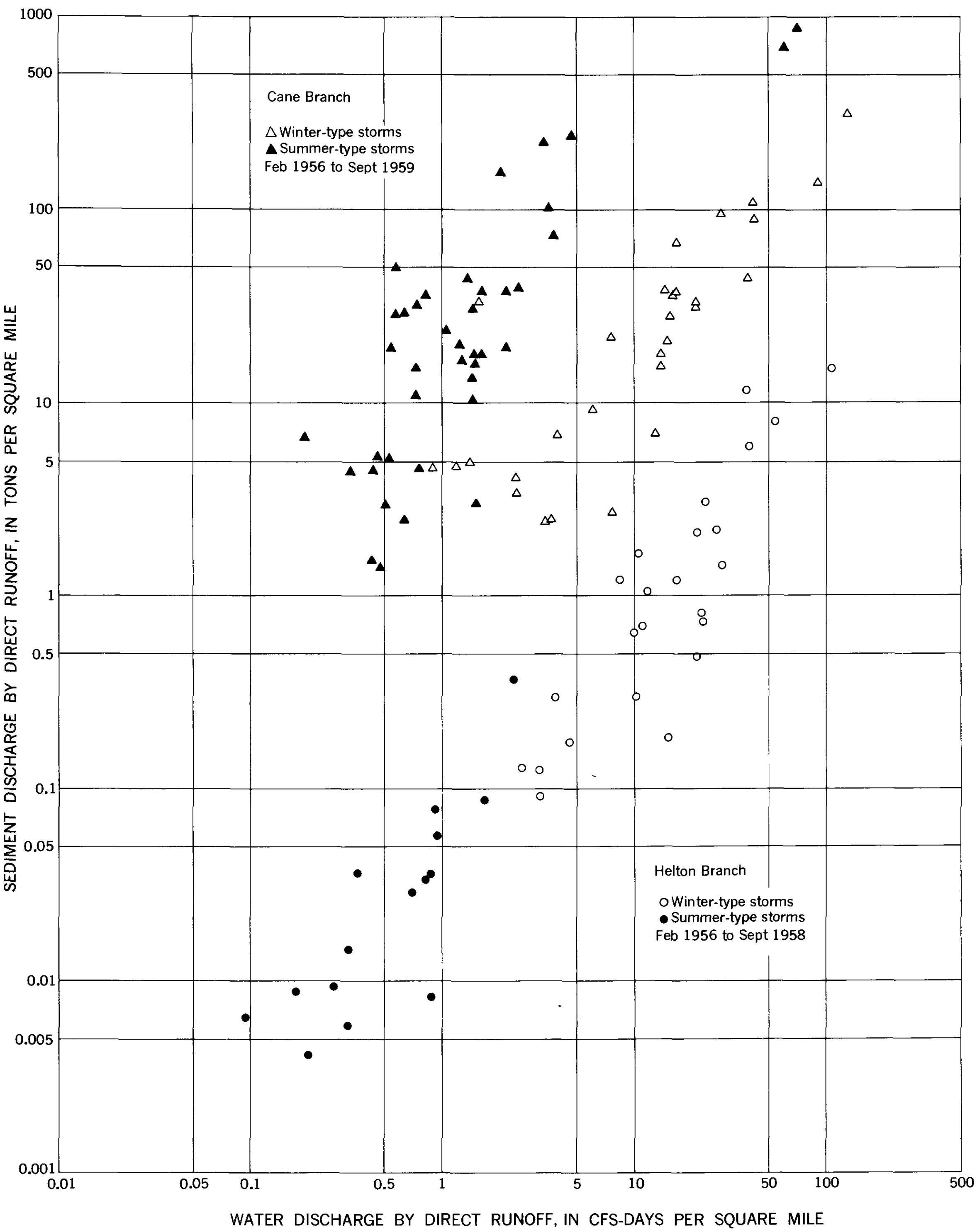

FIGURE 39.—Relation of sediment discharge to water discharge by storms for Cane and Helton Branches.

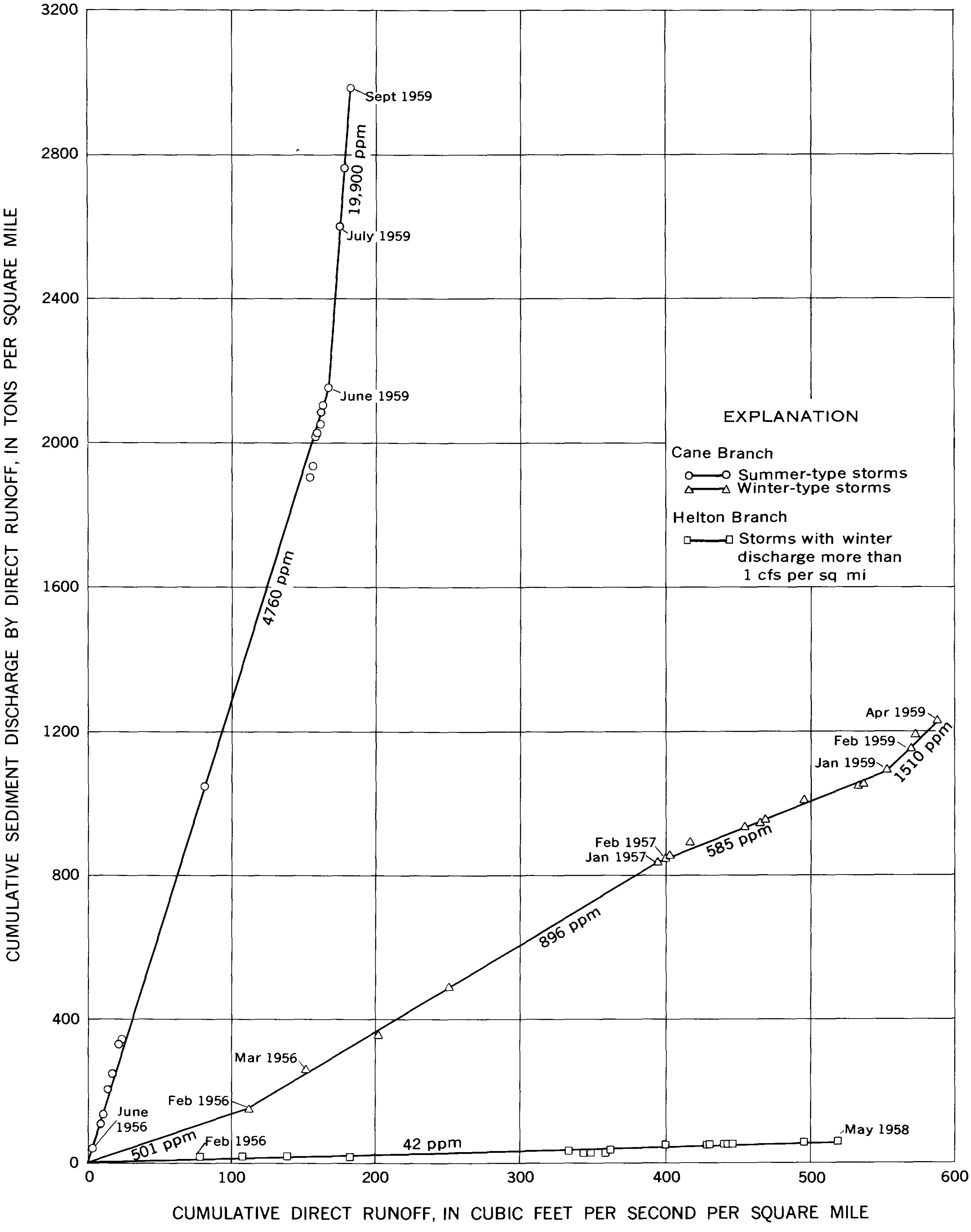

FIGURE 40.—Cumulative sediment discharge in relation to cumulative direct runoff by storms for Cane and Helton Branches.

The significant breaks in the curves for Cane Branch indicate a change in the water discharge-sediment discharge relationship and coincide with changes in strip mining. Unfortunately, no measurements of the sediment yield of Cane Branch were made previous to mining, but because of the hydrologic similarity of the basins it is assumed that the yield was similar to that of Helton Branch. This assumption is supported by the similarity of the sediment concentrations in tributaries draining forested subareas in the Cane Branch basin and the concentrations in Helton Branch. If Cane Branch had been calibrated before mining, a change in the slope of the curve would have occurred when the increased sediment yield due to strip mining first reached the Cane Branch gage. The break in the winter curve after February 1956 (110 cfs per sq mi) is significant at the 5-percent level and indicates the time at which the full effect of the strip mining on the southwest side of the basin began to be measured at the gaging station. The weighted mean sediment concentration was 501 ppm for three storms in February 1956 and then increased to 896 ppm until January 1957. The second break in the winter curve, beginning in February 1957, was not significant at the 5-percent level. The lower weighted mean concentration (585 ppm) after this break may have been caused by the lack of intense storms or by a gradual healing of the southwest spoil bank, New mining on the northeast side of the Cane Branch study area began in late 1958 and resulted in an increased sediment yield shown by the break in the winter curve from 585 ppm to 1,510 ppm beginning in January 1959. This change in slope is significant at the 1-percent level.

The effect of the new mining is also shown in the summer curve for Cane Branch by the increase from 4,760 ppm to 19,900 ppm in June 1959. This change in slope is also significant at the 1-percent level. The weighted mean sediment concentration thus increased more than four times as a result of the 63-percent increase in the area disturbed by strip mining.

The great difference between the sediment yields of Cane and Helton Branches is also illustrated by figure 40. The weighted mean sediment concentration of the direct runoff of Helton Branch in the winter-type storms was 42 ppm whereas that of Cane Branch was 501 to 1,510 ppm.

PARTICLE-SIZE DISTRIBUTION OF FLUVIAL SEDIMENT

The sediment discharged by Cane, West Fork Cane, and Helton Branches is predominately clay with some silt and a small percentage of sand. The average particle-size distributions of the sediment are shown in figure 41.

West Fork Cane Branch has the finest suspended sediment, averaging 82 percent clay, 16 percent silt,

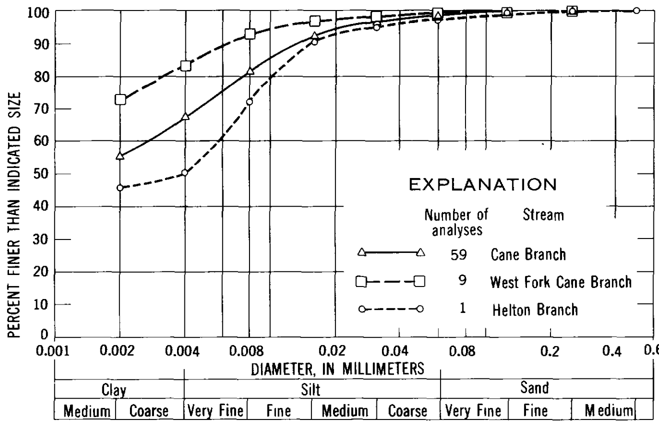

FIGURE 41.—Particle-size distribution of suspended sediment in Cane, West Fork Cane, and HeltonBranches.

and 2 percent sand. The West Cane gage is only a short distance downstream from the prospect areas (see pl. 1), where large quantities of fine material are available for erosion and transport.

In West Fork Cane Branch the particle-size distribution of the suspended sediment becomes coarser as the concentration increases. The major changes occur in the clay and silt sizes. As the percentage of clay decreases, the percentage of silt increases. The quality of the water in West Fork Cane Branch does not significantly affect flocculation of the sediment, as differences in the size distributions defined in a dispersing medium or in native stream water are negligible.

Of the three streams, the coarsest mean size of sediment in transport is tentatively concluded to occur in Helton Branch. Although the data on which the Helton Branch curve in figure 41 is based are scanty, this is a reasonable conclusion because the source areas of the Helton Branch sediment have fewer claystones and siltstones and more sandstones exposed to erosion than the West Fork Cane Branch and Cane Branch areas.

The particle-size distribution of the suspended sediment in Cane Branch is coarser than that of West Fork Cane Branch and is finer than that of Helton Branch (fig. 41). Figure 42 shows that the particle-size distribution of Cane Branch varies with the suspended-sediment concentration in storm runoff. The low concentrations are composed of fine sizes; as the stream velocity and turbulence increase, the sediment concentration and the percentage of coarser particles that are being picked up and transported by the stream also increase.

The difference in the particle-size distribution of suspended sediment in Cane Branch, was when analyzed in native stream water and in distilled water with a dispersing agent, is shown in figure 43. Under dispersed conditions, the particle-size distribution was 81 percent clay, 17 percent silt, and 2 percent sand, whereas

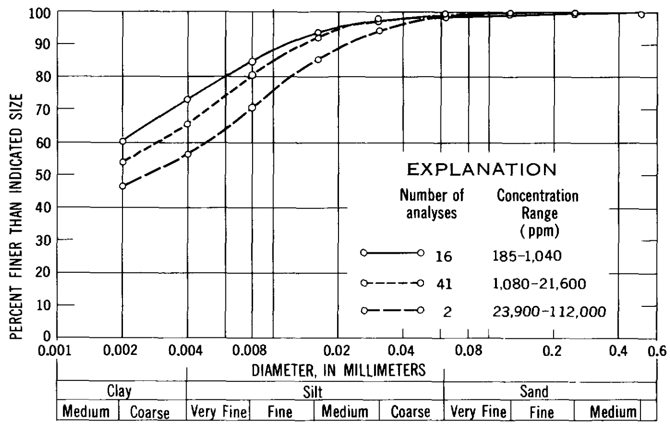

FIGURE 42.—Particle-size distribution of suspended sediment by range of concentration, Cane Branch, 1956–59.

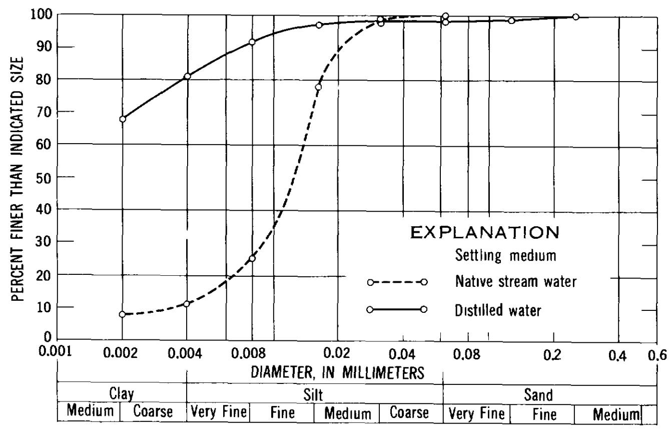

FIGURE 43.—Particle-size distribution of Cane Branch suspended sediment analyzed in settling media of native stream water and distilled water with a chemical dispersing agent.

in the native water the distribution was 12 percent clay and 88 percent silt. This large increase in the amount of silt-sized particles and the accompanying decrease in the amount of clay-sized particles was due to the flocculation of the clay particles in the acid stream water. A similar flocculation occurs in Cane Branch when the volume of storm runoff is decreasing. The clay particles flocculate in the acid stream water and settle to the bottom of the channel, and so there is a rapid decrease in the concentration of suspended sediment. (See figs. 36 and 37.)

The data on particle size indicate that there have been changes in the particle-size distribution of sediment transported by Cane Branch that coincide with some of the strip mining in the study area. When the southwest spoil bank was leveled in June 1956, the suspended-sediment in Cane Branch became finer owing to the increased amount of fresh clay exposed to erosion on the spoil bank. Between December 1956 and January 1959, the sediment transported by Cane Branch gradually became coarser. When fresh debris from the new mining, which began in December 1958, reached Cane Branch in January 1959, the size of the suspended sediment became finer again.

Particles of clay, silt, and sand are not the only sizes that are transported in the study areas. Comparative photographs taken of deposits along several reaches of the Cane Branch channel at various times indicate that all particle sizes, including small boulders, are transported by Cane Branch. In April 1958, yellow paint was added to some sandstone gravel and cobbles in a bar in the Cane Branch channel. One month later, these particles were gone. One of the cobbles, which was about 5 x 5½ x ½ inches, was found about 70 feet downstream from the bar. A detailed search of the nearby channel failed to recover any of the other painted particles.

Gravel and cobbles have been deposited behind the concrete weir at the Cane Branch gaging station. Occasionally, some of them may be carried over the weir during periods of high water discharge.

SEDIMENT DEPOSITION IN STREAMS

Channels at the upper elevations of the Helton Branch study area contain extensive deposits of sediment between outcrops of sandstone which form small waterfalls or riffles. The deposits are usually only a few inches thick and consist of clay, silt, and sand.

The channel of Helton Branch, particularly the lower reaches below the cliffs, is mainly bedrock and has only small deposits of sand and gravel. These deposits are coarser than those in the upper reaches. They are confined to deep pools that occur between some riffles. Most of the clay and silt particles that reach Helton Branch during storm runoff are apparently held in suspension and are transported beyond the gaging station. Below the cliffs the channel contains flat sandstone slabs of cobble and boulder size, and also some sandstone blocks weighing several tons each. The narrow flood plains along the lower reach of Helton Branch are composed primarily of sand mixed with some gravel.

Channels in the upper reaches of the West Fork Cane Branch study area are covered with thin deposits of clay- to boulder-sized particles. There are bars of sand and gravel and some flat boulders scattered along the channels. A few riffles occur at outcrops of the sandstone bedrock.

Along the reach of West Fork Cane Branch between the prospect trenches and the gaging station (pl. 1), the channel bottom is covered with material ranging in size from clay to boulders except where sandstone beds outcrop and form riffles. The deposits along this reach are thicker than those in the channel upstream from the prospect trenches owing to the substantial amount of clay and silt that is contributed to the stream by the erosion of the trenches and small spoil banks. The channel has numerous bars composed of silt, sand, and gravel. This reach also contains a few quartz sandstone slabs of cobble and boulder size. Small flood plains near the gaging station are composed of clay, silt, and sand.

In the upper reaches of Cane Branch, the bed material in the channels not affected by mining is very similar to that found in the upper Helton Branch and West Fork Cane Branch areas. The channels contain thin deposits of clay, silt, and sand, except at riffle sections caused by sandstone bedrock.

The bed material is different in the tributaries which are affected by mining. These channels are clogged with deposits as much as 2 feet thick. The bed material is mostly clay and silt containing some larger particles of siltstone and claystone. Most of this material was derived from the spoil banks; it is dark gray because it has not been "bleached" or weathered as much as the material in the channels not affected by mining.

The channel of Cane Branch from the southwest spoil bank to beyond the gaging station (pl. 1) is also clogged with sediment derived from the mine spoil. The deposits are made up primarily of clay, silt, and sand. They are dark gray and are similar to the deposits in the Cane Branch tributaries affected by mining. In some places sandstone ledges outcrop to form waterfalls and riffles. The riffles are free of clay and silt, and the bed material consists of sand, gravel, and boulders.

Deposition of this debris has caused some reaches of the stream to become braided, with shifting bars and shifting channels. Special studies are being conducted along selected areas of the channel to define these changes. These areas are shown by italic numerals *1*, *2*, and *4* on plate 1.

Sediment deposits in the channel of Cane Branch in area *4* are shown in figure 44. The spoil on the stream bank has come from the southwest spoil pile, which lies to the right of the area shown on these photographs, and during storm runoff sheet erosion washes this debris directly into Cane Branch. In the 1959 photograph, Cane Branch has two shallow channels separated by a bar consisting of about half sand and half silt and clay. In the 1960 photograph, there is only one channel, the bar has disappeared, and the flat area to the left of the channel has been extended by additional deposits of sand and gravel. This condition of constantly shifting sediment is common along Cane Branch.

The type of deposit that is common in the lower reaches of Cane Branch is shown in figure 45, a view of area *1*. The channel along this reach is clogged with recent deposits of dark gray sediment. Deposits consisting of layers, ¼- to ½-inch thick, that were laid down during periods of storm runoff have accumulated to a maximum thickness of 2.5 feet. The particle-size distribution of this deposit is 20 percent clay, 39 percent silt, and 41 percent sand.

FIGURE 44.—Comparative photographs of the Cane Branch channel in area *4*, showing the effects of mining. Upper photograph, April 26, 1959; lower March 23, 1960.

Along the reach of channel near the southwest spoil bank, the cobbles and boulders are composed of claystone, siltstone, and sandstone. Downstream near the gaging station the larger-sized blocks are sandstone. Either the blocks of claystone and siltstone have not been transported very far as yet, or they are breaking up into smaller particles before reaching the gaging station.

The flood plains that are 3 feet or more above the Cane Branch channel have not been inundated by flood water since strip mining began in this area; so, they do not contain the gray deposits. The deposits on these flood plains are composed of sand and gravel mixed with organic debris, and they represent the

FIGURE 45.—Sediment deposits along Cane Branch in area 1, April 20, 1958.

type of material that occurred on both the high and low flood plains along Cane Branch before mining.

Sediment deposits that are similar in character to those in Cane Branch extend downstream into Hughes Fork. In November 1959, deposits of dark-gray clay and silt were traced 4,000 feet downstream from the mouth of Cane Branch. As more sediment from the spoil banks is carried by Cane Branch into Hughes Fork, these deposits will probably extend even farther downstream.

CONCLUSIONS

The sedimentation characteristics of the three study areas were probably similar before strip mining began owing to the similarity of the hydrologic environment. This conclusion is substantiated by the similarity in characteristics which now exist at the supplemental sites in those parts of the Cane Branch and West Fork Cane Branch study areas not affected by mining and in the Helton Branch study area.

Since strip mining and exploration began in the Cane Branch and West Fork Cane Branch study areas, the sediment characteristics of these streams have changed greatly. The sediment yield of Helton Branch was 27.9 tons per square mile for the 1958 water year compared to (1) 1,930 tons per square mile for Cane Branch and (2) an estimated 30,000 tons per square mile from only the strip-mined part of the Cane Branch area. The increased sediment discharge of Cane and West Fork Cane Branches has a much greater percentage of fine particles (67 and 82 percent clay, respectively) than the sediment discharge from the undisturbed, wooded areas. Channels receiving drainage from strip-mined or exploration-pit areas have become clogged with recently deposited sediment. Noticeable deposits of this fine material have been observed in Hughes Fork below the confluence with Cane Branch.

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U.S. Geol. Survey, issued annually, Quality of surface waters of the United States, parts 1–4, North Atlantic slope basins to St. Lawrence River basin, as follows:

Water year	*Water-Supply Paper*	*Year published*	*Pages*
1956	1450	1960	4-6, 8, 513–515
1957	1520	1960	4-6 8, 548–550
1958	1571	1962	5–6, 8–9, 667–669 675–676
1959	1641	1963	

SHEET EROSION

By JOHN W. ROEHL and A. S. JOHNSON, U.S. Soil Conservation Service

One objective of the study in the Beaver Creek basin is the determination of the sources of sediment produced in three gaged watersheds. Sediment is the product of erosion; thus the isolation of the various sources of sediment in terms of erosion is a means of accomplishing this objective. This part of the study is on sheet erosion and compares and evaluates, in terms of land use, the various components of the total sheet erosion as sources of sediment. As changes in the components of the total sheet erosion takes place in the future, changes in their relative importance as sources of the measured sediment can be estimated.

It must be realized that some of the material made available by erosion may be deposited before reaching the gaging stations, and therefore is not included in the loads given in the section on "Sedimentation." It also must be realized that quantitative values placed on sheet erosion should be increased by the amounts of erosion from other sources such as gullies, eroding roadbanks, and eroding streambanks to arrive at the total erosion. However, an analysis of the sheet erosion occurring in each watershed will provide a sound basis for identifying the important sources of sediment.

In order to arrive at the relative importance of the several land uses as they affect the total sheet erosion, estimates of the annual rate of sheet erosion were calculated for the first year of the study. In subsequent years, surveys of changes in cover conditions and extent of the several land uses allowed adjustments to be made in the erosion estimates. Modifications in the relative importance of the land uses as sediment sources were then evaluated.

Soil loss, or rate of soil movement, due to sheet erosion can be estimated by use of the "soil decline" equation developed by G. W. Musgrave (1947) and his associates. This equation—expressed in terms of the inherent erodibility of the soil, land cover and management, length and degree of slope, and the intensity, duration, and frequency of rainfall—provides a means of placing quantitative values on soil loss. Estimates of erosion rates thus derived indicate the amount of soil movement caused by sheet erosion. These estimated rates, however, do not indicate the distance the soil will move. These calculated values, when used with other data, will provide estimates of sediment yield and of the relative importance of the various sediment sources.

The information necessary to calculate the rate of sheet erosion is tabulated in table 26 and was obtained from the soil surveys of the study areas. The average degree and length of slope by each land use within each study area are given in this tabulation. The physical data in the tabulation are for the years 1957, 1958, and 1959. Basically, the only physical changes that may occur in subsequent years are the size of an area given to a particular land use and the cover conditions. The average degree and length of slope for any given land use will change only if a part of the land given to a particular use is converted to another use, thus changing the base acreage upon which the averages were calculated or if conservation measures (terraces) are installed. The required rainfall information was obtained from "Rainfall Intensity-Frequency Data," a publication of the U.S. Department of Agriculture (1935).

The information in table 26 was analyzed in terms of the "soil decline" relationship, and the rate of soil movement was calculated. In the analysis, various values were placed on the cover condition of each major land-use class in terms of an estimated percentage of soil surface exposed to sheet erosion. As the basic soil surveys were made in 1957, subsequent surveys of cover conditions were made in 1958 and 1959, and erosion estimates were calculated for each of these years and are shown in table 27.

TABLE 27.—*Estimates of sheet erosion, in tons per acre per year*

Study areas	1957	1958	1959
Helton Branch	0.95	0.60	0.61
Cane Branch	4.89	4.86	7.82
West Fork Cane Branch	(1)	.71	.71

[1] No soil survey in 1957.

The estimates of the rates of sheet erosion in the several study areas are of about the same order of magnitude as are the amounts of measured suspended sediment leaving the study areas. Low rates of sheet erosion in Helton Branch are compatible with the small amounts of measured sediment, and high rates of sheet erosion are consistent with the large amounts of sediment measured at the sampling station on Cane Branch.

Table 26 indicates that the average degree and length of slope for Helton Branch are greater than those for Cane Branch, yet the estimated rate of sheet erosion is markedly less. The steeper and longer slopes indicate that a higher rate of erosion would occur in Helton Branch than in the other watersheds. If each watershed has comparable woodland conditions, the annual

TABLE 26.—*Land use and average slopes within study areas*

Land use	Cane Branch						West Fork Cane Branch				Helton Branch			
	Area				Average slope		Area [1]		Average slope		Area [1]		Average slope	
	1958		1959 [1]		Degree (percent)	Length (feet)	Acre	Percent	Degree (percent)	Length (feet)	Acre	Percent	Degree (percent)	Length (feet)
	Acre	Percent	Acre	Percent										
Cultivated	0.7	0.2	0.7	0.2	9	100					0.5	0.1	5	70
Woodland	394.3	92.0	377.1	88.0	25	205	163.7	99.0	23	165	491.8	90.9	40	225
Idle	6.2	1.4	6.2	1.4	8	80	.3	.2	4	100	2.7	.5	9	65
Pasture [2]											46.0	8.5	14	100
Other [3]	27.4	6.4	44.6	10.4	[4] 20	[4] 75	1.3	.8	[4] 20	[4] 75				
Total or average [5]	428.6	100.0	428.6	100.0	25	195	165.3	100.0	23	165	541.0	100.0	38	215

[1] To Dec. 31, 1959.
[2] Includes homestead areas.
[3] Strip-mined and prospect areas.
[4] Estimated.
[5] Averages are weighted by area.

rates of sheet erosion would be 0.27, 0.14, and 0.12 ton per acre for Helton Branch, Cane Branch, and West Fork Cane Branch study areas, respectively. Thus, the differences in the annual rates of sheet erosion between the areas apparently result from the differences in land use.

The distribution of major land uses in the three study areas is shown in table 26. The land uses have not changed in Helton Branch and West Fork Cane Branch basins during the period of study (through Dec. 31, 1959), although some variation in the cover conditions was noted in Helton Branch. There have been measurable and significant changes of land use in the Cane Branch basin, however. During 1959, new areas of strip mining were opened, replacing 17.2 acres of woodland. No changes occurred in any of the watersheds with respect to the average degree and length of slope.

The relative importance of the various land uses as causative factors of sheet erosion is shown in table 28. It is significant that in the watersheds the greatest degree of sheet erosion occurs in strip-mined areas. The strip-mined part in the Cane Branch study area constituted only 6.4 percent of that area in 1958, yet it accounts for more than 96 percent of the sheet erosion. In the West Fork Cane Branch study area, the prospect pits make up only 0.8 percent of the area, yet they contribute nearly 83 percent of the sheet erosion.

In the Helton Branch and West Fork Cane Branch study areas, there is little difference in the relative importance of the various land uses as causes of sheet erosion between the years 1958 and 1959. Helton Branch does show a considerable difference between the years of 1957 and 1958 which can be accounted for by the improvement in the pasture cover. The rate and amount of sheet erosion in Helton Branch, however, are both rather small, and small changes will be reflected by large percentage differences.

TABLE 28.—*Sources of sheet erosion in terms of land use*

[Results are given in percent]

	Cane Branch			West Fork Cane Branch			Helton Branch		
	1957	1958	1959	1957 [1]	1958	1959	1957	1958	1959
Cultivated	0.8	0.1	0.1	------	------	------	0.9	0.2	1.4
Woodland	2.5	2.6	1.5	------	17.0	17.0	25.8	40.9	40.4
Idle	.5	.5	.3	------	.2	.2	1.0	1.6	1.6
Pasture	------	------	------	------	------	------	72.3	57.3	56.6
Other [2]	96.2	96.8	98.1	------	82.8	82.8	------	------	------
Total	100.0	100.0	100.0	------	100.0	100.0	100.0	100.0	100.0

[1] Not estimated in 1957.
[2] Strip-mined and prospect areas.

In the Cane Branch study area 96.2 percent of the sheet erosion occurred in the strip-mined area in 1957, and this percentage increased from 96.8 to 98.1 percent between the years 1958 and 1959. This increase in relation to the total sheet erosion does not appear significant when considered alone. Notably, however, the strip-mined area increased by about 63 percent, which amounted to only 4.0 percent of the study area, while the annual rate of sheet erosion occurring in the watershed increased on the average by about 61 percent. Thus it is apparent that most of the sediment resulting from sheet erosion was derived from the strip-mined areas.

As cover conditions improve or worsen, or as new strip-mining or prospecting areas are opened in the watersheds, the relative importance of changes in land uses as causative factors of sheet erosion will become more significant.

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FOREST AND FOREST DEVELOPMENT

By ROBERT S. SIGAFOOS, U.S. Geological Survey

Strip mining in the Beaver Creek drainage basin has affected the forests in two ways: (1) the operation destroyed the trees and formed new topography at the mine area, where vegetation started to grow as soon as the mining ended, and (2) runoff from the mine area flows through the forest in the drainage basin below the mine. This runoff is different in quality than that in undisturbed drainage basins because it contains high concentrations of dissolved constituents and large quantities of sediment. The source of this water has not been differentiated; it comes from overflow of pools formed in the pit, from surface flow off the spoil banks, from seepage beneath the banks, and from an abondoned drift mine. The objective of this study, then is twofold: (1) to determine the growth rates of trees on ridges and slopes and along stream channels where runoff from the mine flows through the forest that was not destroyed by the mining operation, and (2) to determine the kind of trees and the rate of their establishment on the newly formed land. This paper contains the preliminary results of the study from 1958 through 1960.

The growth rates of selected trees are compared for comparable periods before and after mining. Some of the trees downslope from the mine are irrigated by acid mine drainage. Others upslope from the mine or on isolated ridges downslope from the mine are irrigated by natural water. These comparisons are presented in the next subsection of this paper. Because insufficient time has elapsed, no firm conclusions can be drawn about the rate of establishment of trees on the mined area; therefore only a brief discussion of this phase of the study is presented, in the third subsection of this paper.

The background and scope of the entire project, of which the botanical study reported herein is a part, are described by Musser (1963). Included in this description are a physical description of the Beaver Creek area and a discussion of the history of mining in selected areas.

In order to understand the botanical aspects of this study, a knowledge of the strip-mining events and of the geology of Cane Branch is necessary; however, only a minimum outline, taken from Musser (1963), is presented here. The strip-mining operation first exposed the coal seam by removing the overburden and depositing it outside the pit on the downslope side, thereby forming the first spoil-bank ridge. After this coal was loaded, subsequent cuts were made and the overburden was cast into the mined pit. This operation effectively cut and dammed small ephemeral streams that are tributary to the main stem of Cane Branch. Water accumulated in parts of the pit after mining ended, and so some pools remain.

In the southern part of the Cane Branch area, 1 acre was stripped in 1947. The strip mining with which the present project is concerned, however, was started on May 28, 1955, on the west side of Cane Branch. Strip mining ended on April 7, 1956, and the tailings were leveled in June 1956. Mining was started in a small drift entry into the base of the highwall on the southwest side of the strip mine in October 1957 and was stopped in January 1959. A cut, made through the tailings on the north end of the mine on October 28, 1958, drained a pool and formed a channel from this end of the mine into the forests downslope. Strip mining was begun on the northeast side of Cane Branch in September 1958 and ended August 3, 1959; subsequently, the tailings were leveled on August 6. Botanical studies have not been made in this area, thus all results reported herein pertain to the west side of the basin.

The parent material of the mine spoil is derived from the rock overlying the coal and from a parting of carbonaceous shale within the coal seam. The lower units of the overlying rock, as well as the coal and the shale parting, contain varying quantities of iron pyrite and sulfur compounds. The total sulfur content ranges from 7,300 ppm to 18,400 ppm. (See section on "Geochemistry of water.") The chemical quality of the runoff downslope from the mine is due, in a large part, to the high concentrations of sulfate resulting from the oxidation of pyrite.

Results of the study through the growing season of 1960 show that trees downslope from the mine area have grown more rapidly since 1955 than before and more rapidly than trees upslope, and tree seedlings are becoming established on and below the spoil banks and above the mine.

ACKNOWLEDGMENTS

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EFFECTS OF STRIP MINING UPON SURROUNDING FORESTS

Because the contour method of strip mining was used in Cane Branch (Musser, 1963), the premining drainage system was disrupted. Water now flows from the mine area in channels eroded in the spoil bank or in ditches cut during subsequent mining operations. Much runoff flows down the outer slope of the spoil banks and across the forest floor before it reaches the premining stream channels. This water is acidic and contains high concentrations of dissolved constituents. (See section on "Geochemistry of water.") Deposits of fine-grained sediment, which contain larger fragments of shale and coal, occur on the forest floor in a discontinuous band around the downslope side of the spoil banks, in minor channels below the cliff, and on Cane Branch flood plain for a distance of at least a half mile below the gage. Growth rates of trees in these areas of deposition are being studied to determine the effects of acid runoff from the mine upon tree growth.

METHODS OF STUDY

Trees in 20 areas in the vicinity of the mine were sampled (fig. 46). Of these, 12 are downstream from the mine and sediment from it is present on the ground around the trees. The remaining eight areas were selected in order to determine the growth rates of trees in areas not affected by mining. Of these seven areas are in topographic positions that are more or less com-

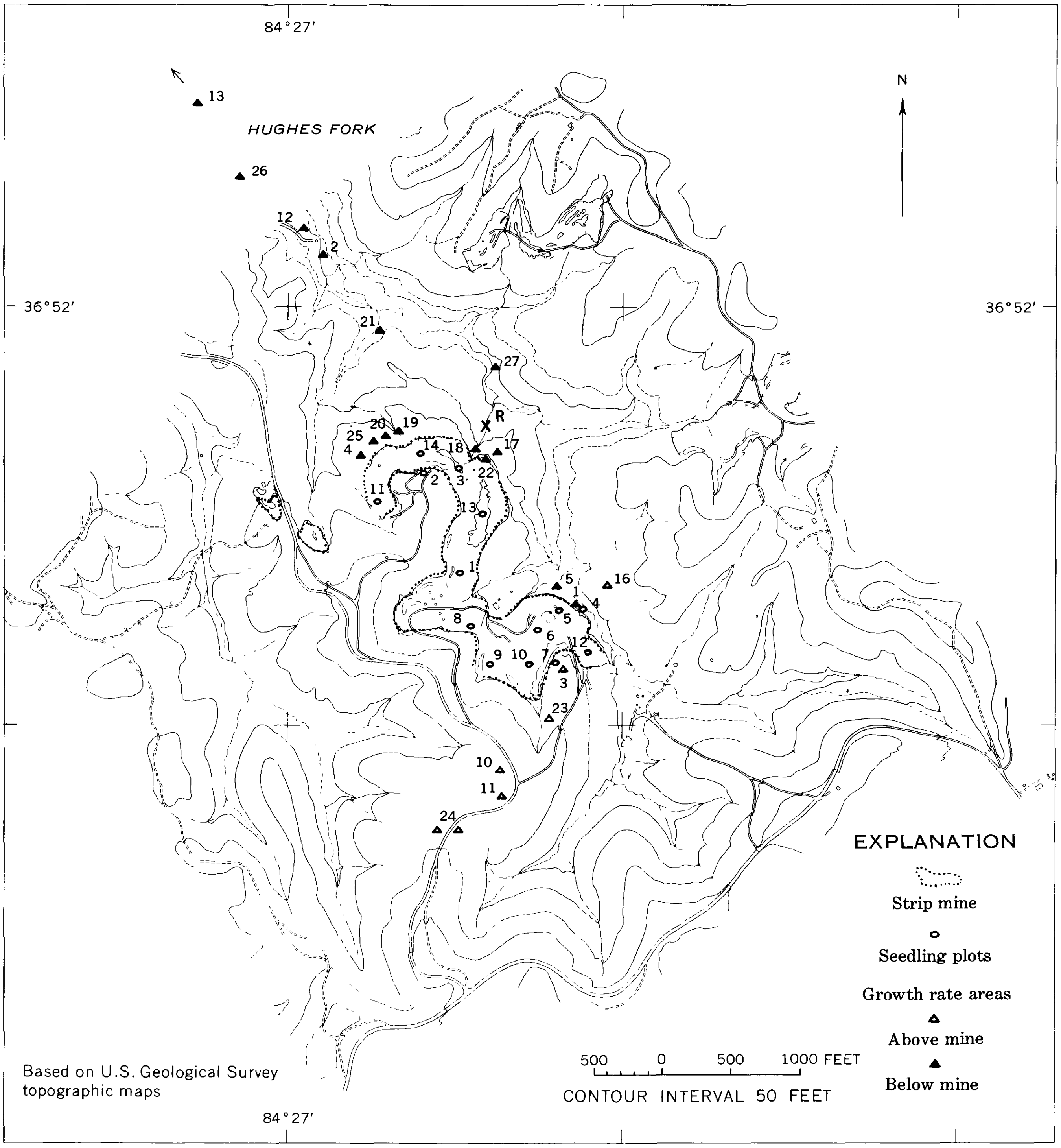

FIGURE 46.—Cane Branch area showing location of botanical study areas.

parable to those selected below the mine, and one area is downslope from the mine but is outside the mine drainage. Trees in the vicinity of the gage on Helton Branch were also sampled, and analysis of data from them is included.

Because all readers may not be familiar with the mechanism of tree growth, a brief review will aid in understanding the data that are the basis for this part of the study. These data are on the widths of annual growth increments of wood in the trunk or stem. Trees grow in height, and branches and trunks increase in girth each growing season as a result of the formation of a layer of wood that encircles the trunk and each branch from the base to the tips of the twigs. Each layer is unique and may be visualized as a complete envelope. The layers can be distinguished one from the other when viewed in cross section because the wood formed early in the growing season is different from that formed later in the growing season. In order to examine these growth layers, a core is taken horizontally from a trunk. A core consists of a cylindrical sample of wood composed of short arcs of the annual rings along part or all the radius. The widths of these rings are segments of the radius and thus represent only a part of the annual growth of a tree. Detailed discussions on the growth of trees are presented by Brown, Panshin, and Forsaith (1949), Eames and MacDaniels (1947), and Esau (1953, 1960).

SELECTION OF AREAS AND TREES

The location of the areas downslope from the mine was determined primarily by the presence of sediment from the mine on the forest floor. Brief study of these areas showed, however, that the amount of water available to some ridge and slope sites is greater than it was before mining. Furthermore, two areas were partly cut over just prior to mining. Thus increased water supply and higher light intensity, in addition to increased concentrations of dissolved constituents in the water flowing from the mine, have affected the growth of trees downslope from the mine.

The locations of areas upslope from the mine and outside the drainage from it were selected in order to sample trees in comparable sites to determine growth rate of trees in areas not affected by mining. Trees of comparable size of the same species and composing the same forest type were purposely selected. An attempt was made to select areas in which only one of the three variables, quality of water, quantity of water, or light intensity had changed in the immediate past, or in which none had changed.

Various individual trees were selected in each area so that all species and a wide range of trunk diameters would be sampled. Cores were taken from the trees by use of an increment borer at heights between 2 and 3 feet above the ground; therefore all samples were taken above the basal swell of the trunks and from a part of the trunk that showed no visible scars or deformities.

The use of widths of one or several annual rings to estimate the change in tree volume is subject to error partly because of different radial growth rates at different levels in the trunk (Spurr, 1952, p. 230–236). This study, however, is concerned solely with the growth rates of trees as they are related to the effects of strip mining; therefore, the comparison of the radial growth rate of trees before and after mining is the only relevant parameter.

Trees have been cored over a period of 3 years. The first trees were cored in May 1958 and provide data on growth from 1955 to 1957. The annual growth rate during this period is compared with that of the 3 years prior to mining, 1952 to 1954. Trees in additional areas were cored in May 1959 and provided data for the years 1951 to 1958. Two areas were sampled in September 1960, and growth during the years 1949 to 1960 was analyzed. In addition, three areas first sampled in 1958 were resampled in 1960 to determine if the relative growth rate from 1958 to 1960 was comparable to that calculated for the preceding 3-year period. Finally, large diameter cores and leaves were taken from one white oak [1] downslope from the mine and from another upslope from the mine to determine the iron content in the wood, bark, and leaves. These data are discussed in the final part of this paper.

RADIAL GROWTH RATES OF TREES

To determine the effect of runoff from the strip mine upon the growth rate of the trees, a base or normal growth rate must be defined. This so-called normal growth rate is the rate at which trees would grow if they had not been affected by mining. The rate of growth for the years prior to 1955 must be considered as the normal rate. These growth rates cover a broad range of values, which should be expected in an area as diverse in its geologic, hydrologic, and botanical characteristics as Cane Branch (Musser, 1963). For the white oak, for example, the most commonly occurring species sampled in this study, the maximum rate prior to mining found in any one individual is 4.5 mm per year, which is 15 times greater than the minimum rate of 0.30 mm per year for the same period. For any single area the rate for individual white oak trees ranges from 0.56 to 2.78 mm per year during the period prior to mining.

RESULTS

Data from 21 species of trees were analyzed and, of these, 11 species grow both upslope and downslope from the mine. To determine the average growth rates of all trees for the period prior to mining and then to assign it as the normal rate would be meaningless because of the great diversity of size, environmental requirements, and heredity of the different species. It is also meaningless to average the growth rates of different species growing in the same area. Some meaning could be derived from averaging the growth rates of individuals of the same species in each area; however, in many areas only one individual of a species was sampled. Thus the growth rates for the period since 1955 are compared with the growth rate for a like number of years prior to 1955 for trees growing upslope and downslope from the mine. The growth rates during the two periods are plotted against each other and shown in figures 47*A* and 47*B*. In figure 47*A* the points appear to be clustered

[1] Common names are those used by Little (1953).

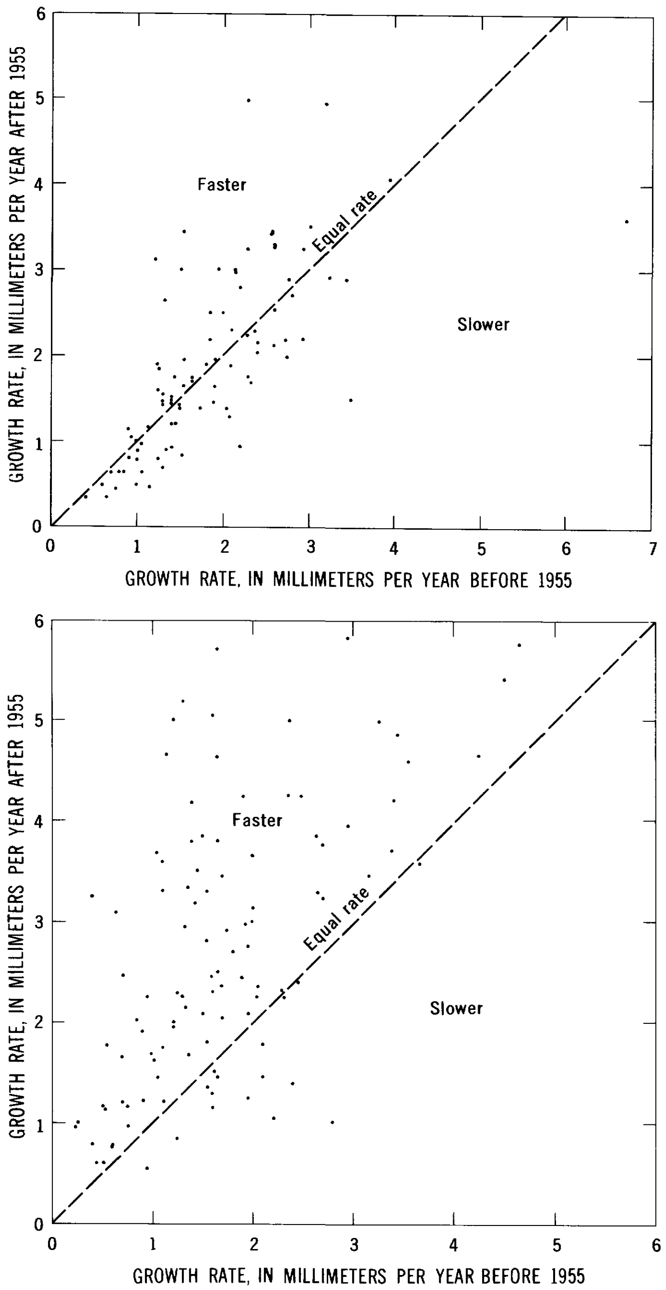

FIGURE 47.—Growth rates before mining plotted against growth rates since mining for trees sampled above (*A*, upper) and below (*B*, lower) the mine.

about a line that represents equal growth for the two periods. This scatter shows that the trees above the mine have, on the average, grown at about the same rate before and since mining; that is, since mining began, about half of the trees have grown slower and the other half faster than before. Figure 47*B* shows that most trees sampled below the mine have grown faster since mining began than before.

In the analyses which follow, the rate of growth for the period since mining is calculated as a percentage of the rate for that tree for the period prior to mining and is called the relative growth rate. The species sampled, their location relative to the mine drainage, the range in relative growth rate since 1955, and the number of individuals which have a higher growth rate since 1955 are listed in table 29.

TABLE 29.—*Relative growth rates since 1955 of all trees sampled*

Species	Location in relation to mine drainage	Number of trees sampled	Individuals having a greater growth rate since 1955		Growth rate (percent)	
			Number	Percent	Range in relative growth since 1955	Average
Hemlock	Above	11	6	55	76–207	117
	Below	22	19	86	58–505	198
Virginia pine	Above	7	6	86	54–219	121
	Below	8	7	87	98–400	171
Pitch pine [1]	Above	10	7	70	60–142	107
Shagbark hickory	do	1	1	100	103	103
Mockernut hickory	Below	5	4	80	51–256	150
Pignut hickory	Above	6	4	67	73–148	106
	Below	2	1	50	48–209	129
Bitternut hickory	do	1	1	100	148	148
Sweet birch	do	6	3	50	57–218	109
Yellow birch	do	5	0	-------	44–85	66
American beech	do	1	1	100	134	134
White oak	Above	22	12	55	62–214	111
	Below	36	34	94	36–401	203
Post oak	do	3	2	67	98–225	151
Chestnut oak	Above	11	3	33	64–263	104
	Below	5	3	60	57–350	153
Northern red oak	Above	1	1	100	171	171
Pin oak	do	2	0	-------	86–89	88
Scarlet oak	Above	2	0	-------	80–90	85
	Below	5	5	100	153–225	175
Black oak	Above	5	0	-------	42–87	70
	Below	2	1	50	64–121	93
Big leaf magnolia	Above	1	0	-------	67	67
	Below	1	0	-------	85	85
Yellow poplar	Above	5	0	-------	50–68	58
	Below	6	4	67	57–181	115
Sweetgum	Above	14	7	50	68–143	93
	Below	5	5	-------	109–141	148
Red maple	Above	4	3	75	43–203	124
	Below	13	11	85	69–825	226 (177)

[1] May include shortleaf pine.

The summary of all species sampled is as follows:

Location	Number of trees sampled	Individuals having a greater growth rate since 1955		Average growth rate (percent)
		Number	Percent	
Above	101	49	48.5	101
Below	127	102	80.3	144

The summary of those species that grow both above and below the mine is as follows:

Location	Number of trees sampled	Individuals having a greater growth rate since 1955		Average growth rate (percent)
		Number	Percent	
Above	89	42	47.2	96
Below	104	89	85.6	154

A total of 228 trees of 21 species was cored, of which 101 grow above the mine and 127 grow below it. The trees upslope from the mine have not been affected by the mining operation nor by coincident hydrologic events; during the postmining period 48.5 percent of the trees grew faster and the rest grew slower. Thus, for these trees no significant difference exists between growth rates for the two periods. The maximum relative growth rate is 263 percent. The average relative growth rate for all species sampled upslope from the mine is 101 percent.

Of those that grow downslope from the mine, 80.3 percent grew faster during the postmining period. The maximum relative growth rate is 825 percent, which is that of one red maple; the next largest is 505 percent. The average relative growth rate for all trees sampled downslope from the mine is 144 percent.

If one considers only those species that grow both upslope and downslope from the mine, the differences are somewhat more striking. A total of 193 trees of 11 species were sampled. Of those sampled upslope from the mine, 47.2 percent grew faster since mining and the rest have grown slower, whereas of those sampled downslope from the mine, 85.6 percent grew faster during the postmining period. The average relative growth rate for the trees upslope from the mine is 96 percent; that for the trees downslope from the mine is 154 percent. The percentage of trees sampled that have grown faster since 1955 is shown in figure 48.

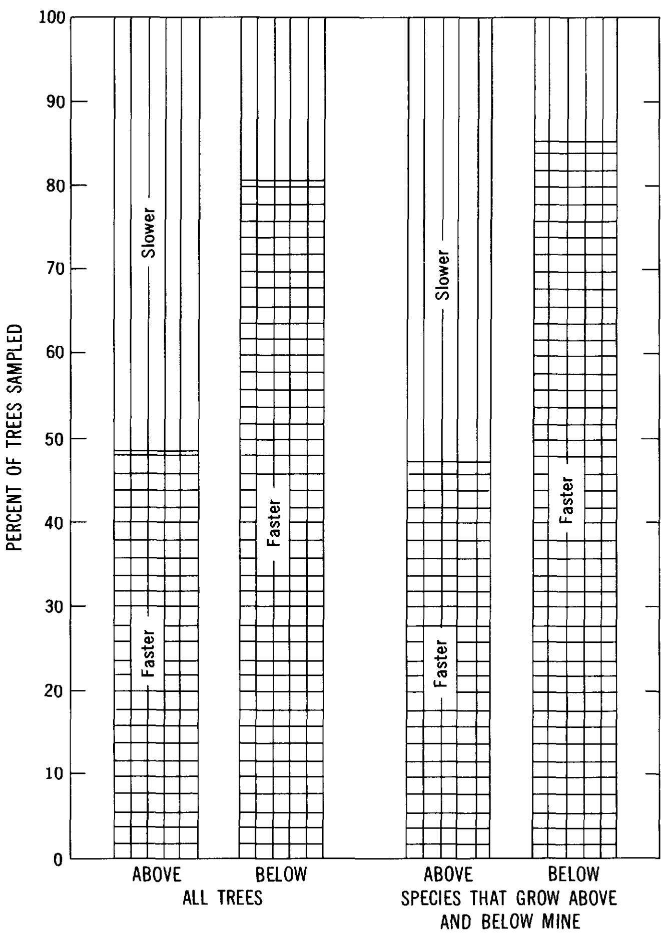

FIGURE 48.—Summary comparison of growth rate before and after 1955, expressed in percent of trees sampled.

With the exception of one species, yellow birch, the growth rate of trees downslope from the mine since mining is either higher than it was prior to mining or the relative growth rate is higher than it is for individuals of the same species upslope from the mine. Yellow birch was sampled only along a tributary stream downslope from the mine. Black oak and big leaf magnolia have grown more slowly since mining than before, however the relative growth rate for the period since mining is higher for those individuals downslope from the mine than for those upslope.

In general, about half of the trees beyond the influence of the mine have grown faster since mining than before, whereas 80 to 85 percent of those downslope from the mine have grown faster since mining. Furthermore, the magnitude of the increase in growth is greater in those trees downslope from the mine than it is for the trees upslope from the mine that are growing faster.

These data are summarized by plots in table 30.

TABLE 30.—*Summary of growth rate of trees by plots*

Plot	Location in relation to mine	Topographic site	Number of trees sampled	Individuals having a greater growth rate since 1955		Growth rate (percent)	
				Number	Percent	Range in relative growth since 1955	Average
1	Below	Channel	14	11	79	88–257	138
2	do	do	13	11	85	68–825	134
3	Above	Ridge	7	3	43	----	105
4	Below	do	17	15	88	95–401	179
5	do	Channel	10	10	100	109–400	156
10	Above	Slope	17	9	53	43–263	97
11	do	Swamp	15	8	53	80–203	100
12	Below	Slope	4	4	100	112–207	145
13[1]	do	Channel	12	3	25	50–143	94
15	Outside	Helton Branch.	4	3	75	88–128	110
16	Above	Slope	12	5	42	43–139	95
17	do	Ridge	7	6	86	54–214	113
18	Below	Channel	6	6	100	120–256	162
19	do	do	8	7	88	64–344	135
20	do	Slope	7	5	71	36–350	167
21	do	Channel	10	1	10	57–218	85
22	do	Slope	10	6	60	48–236	121
23	Above	do	12	4	33	55–118	92
24	do	do	9	4	44	42–148	98
25	Below	Ridge	11	11	100	153–395	227
26	do	Channel	10	4	40	44–161	95
27	do	do	13	11	85	85–505	171

[1] Below confluence with Hughes Fork.

The increased growth rate may be the result of increased light intensity within the canopy due to cutting, of larger quantities of water available to the trees, of an increased concentration of dissolved constituents in the mine runoff, or of some combination of these factors. An attempt can be made to determine the relative importance of each of these factors by examining the growth rates of trees in areas where only one factor has varied in the past and by comparing them with growth rates of trees in areas where two or more factors have varied.

Trees in areas 4 and 25 (fig. 46) are receiving runoff from the mine, as evidenced by the presence of sediment deposits from the spoil banks in minor depressions. According to a local miner, timber was cut here about 1953–54, and sprouts from cut stumps had started to grow in those 2 years. Cutting the forest stand often results in a sharp increase in growth of trees, which is believed to be due to increased light intensity within the canopy and to more available water (Baker, 1950, p. 339–341). Area 24 is upslope from the mine along the road and powerline, where trees were cleared during the winter of 1955–56 for construction of the line to the gaging station on Cane Branch. Some trees along the road to the gage were cut at about the same time. Trees were sampled here primarily to determine the effect of increased light on their growth and to compare their growth rates with those of trees in areas 4 and 25.

In areas 4 and 25, downslope from the mine, 28 trees of 5 species were sampled. Of these, 26 trees or 92 percent have grown more rapidly since 1955. The relative growth rate for these 26 trees ranges from 109 to 395 percent. In area 24 along the powerline, nine trees of five species were sampled. Of these, three trees or 33 percent have grown more rapidly since 1956, which is the first growing season since the powerline was constructed. The relative growth rate for these three trees ranges from 103 to 148 percent. These data suggest that factors other than an increase in light intensity as a result of cutting are responsible for the increase in growth rate of trees in areas 4 and 25 downslope from the mine

Comparison of the data from these areas, numbers 4 and 25, with data from areas 2 and 27 will permit the evaluation of the effect of additional quantities of water upon tree growth since mining. Areas 2 and 27 are along the flood plain of Cane Branch, and the trees are growing in places where sediment from the mine has deposited on the surface. The areas are in the mixed hardwood type of forest which grows on the more moist sites (Musser, 1963). Furthermore, because Cane Branch is a perennial stream, the trees along it probably had an adequate supply of water most of the time. Thus if there has been any increase in streamflow since mining, the increase has been added to an already sufficient supply and would have no affect upon the growth of trees. In addition, no evidence of recent cutting was found in these two areas, so a variation in light has not been a factor in affecting the growth.

A total of 23 trees of 7 species were sampled in the two flood-plain areas. Of these, 21 trees, or 91 percent, have grown faster since mining, and the relative growth rate ranges from 107 to 825 percent. The largest increase, 825 percent, was found in only one tree and is several times greater than the average. The next highest relative growth rate is 418 percent. Thus the range of relative growth rates in areas 2 and 27 is comparable to growth rates of trees in areas 4 and 25; namely, 109 to 395 percent, and 92 percent with increased growth. Trees in areas 2 and 27 show as large an increase in growth rate since mining, and the only environmental factor that has changed has been the quantity of dissolved constituents in the water.

In summary, trees growing downslope from the mine in an area that has received more light, more water, and a higher concentration of dissolved constituents in the water have grown at higher rates than trees that have received only more light during a comparable period. This fact infers that water or higher concentrations of at least some dissolved constituents are the cause of the increase in growth. Comparison of the growth rates of these trees with those in an area which has received only higher concentrations of dissolved constituents suggests that the high concentration of dissolved constituents is responsible for increased growth.

CHEMICAL ANALYSES OF PLANT PARTS

Wood, bark, and leaves from one white oak tree downslope from the mine and another upslope from the mine were analyzed for iron content. The results are reported here as one case study conducted to determine if trees downslope from the mine have absorbed greater quantities of minerals. Because of the physical and chemical problems involved in sampling and analyzing soils in which trees are growing, many investigators have concluded that the analysis of plant tissues is the most reliable method of determining mineral absorption of trees (Reuther and others, 1958, p. 175). Iron is essential for the synthesis of chlorophyll in green plants, and a deficiency in iron in the plant results in light green or white leaves (Meyer and others, 1960, p. 316). The availability of iron to plants increases with an increase in soil acidity (Black, 1957, p. 149–150; Wilde, 1958, p. 227, 231). Iron was chosen as the element for analysis partly because the concentration of dissolved iron in runoff from the mine is high (see section on "Geochemistry of water") and partly because iron remains fixed in plant parts when first used and is not retranslocated (Meyer and others, 1960, p. 316). Thus quantities of iron found in plant parts that grew in a given year would, unlike other elements, indicate the amount absorbed that year.

The tree downslope from the mine grows in area four, where the postmining growth rate of 10 white oak trees sampled in 1958 was 226 percent of the rate prior to mining. The growth rate of four trees resampled in September 1960 showed that the average relative growth rate is 312 percent. The tree sampled for chemical analysis is 11.2 inches in diameter and has a relative growth rate of 192 percent. The tree upslope from the mine grows between areas 23 and 10, where six white oaks have an average relative growth rate of 98 percent. The tree sampled for chemical analysis is 14.3 inches in diameter and has a relative growth rate of 109 percent.

Two cores, 10 mm in diameter, were taken from one side of each tree between 2 and 3 feet above the ground. Leaves were collected from the north side of the trees about 30 feet from the ground in the lower part of the canopy. Results of analyses of the leaves, the bark remaining on the cores, and the wood are summarized as follows:

Iron content[1]

Plant part	Above mine		Below mine	
	Mg per g of dry matter	Percent in ash	Mg per g of dry matter	Percent in ash
Leaves	0.07	0.11	0.29	0.47
Bark	.13	.13	.32	.35
Wood before 1955	.05	1.72	.04	1.40
Wood after 1955	.07	1.25	.10	1.79

[1] Analyses made of additional parts of different trees since this report was prepared indicate that the quantity of iron found in plant parts may not reflect the amount absorbed in a given year. Results of the new analyses are directly opposed to these reported here. Additional studies are in progress to try to determine the cause of this anomaly.

These analyses show that more iron was absorbed by the tree growing downslope from the mine than by the tree growing upslope. Furthermore, more iron has been absorbed by the tree downslope from the mine since 1955 than it absorbed before. The leaves of the tree downslope contain more than four times as much iron per gram of dry material as leaves of the tree upslope. This content, of course, represents the iron absorbed only during the growing season of 1960. The iron content of the bark of the tree downslope from the mine is three times that of the bark of the tree upslope. Bark, however, includes layers that grew prior to 1955; so, the iron content is an average of the iron absorbed over an unknown number of years. The amount of iron that has accumulated in the bark since 1955 in the tree downslope may well be higher than that listed in the table. The amount of iron in the two samples of wood reflect the amount of iron accumulated in the wood during the periods before and after mining. In the tree downslope from the mine, 2½ times as much iron accumulated in wood that grew since 1955 than accumulated prior to 1955. About 1½ times as much iron accumulated in the tree downslope from the mine than in the tree upslope since 1955. The fact that both trees had equal concentrations of iron in the wood prior to 1955 indicates that the differences since mining are a true reflection of altered soil chemistry coincident with altered runoff from the mine.

DISCUSSION OF THE EFFECTS OF DISSOLVED CONSTITUENTS IN MINE DRAINAGE UPON GROWTH OF TREES

Available experimental data on the mineral requirements of trees and on the quantities of dissolved constituents available to the trees in areas downslope from the strip mine are inadequate to permit an explanation of the roles that the high concentrations of dissolved constituents in the mine drainage play in increasing the growth of the trees. Studies of the mineral requirements of trees, as well as most other plants, have been concerned primarily with the effects of mineral deficiencies (Kramer and Kozlowski, 1960, p. 227–239), and most studies of the mineral nutrition of trees have been for orchard crops (Reuther and others, 1958). Most of these experiments, and those designed to determine the effect of excess quantities of minerals upon the growth of plants, have been limited largely to nitrogen, phosphorus, and potassium—the elements found in most commercial fertilizer.

Aluminum and manganese concentrations as low as 1 to 4 ppm are toxic to plants grown in culture solutions (Black, 1957, p. 142–143), yet the concentrations of these elements in the runoff from the strip mine have frequently been higher. At the Cane Branch gage, the median concentration of aluminum from January 1956 through September 1958 was 5.5 ppm and the maximum was 85 ppm. The median concentration of manganese was 7.0 ppm and the maximum was 28 ppm. (See table 19, in "Geochemistry of water.") Samples of water in a gully downslope from the mine were collected at area 18 on September 11, 1960, during a rainstorm and analyzed chemically. The analyses of this sample and of three other samples collected at the same site during periods of dry weather are listed in table 31.

TABLE 31.—*Chemical analyses, in parts per million, of water samples at area 18, supplemental site R*

	Storm sample	Nonstorm samples		
Sample	A	B	C	D
Date of collection	9/11/60	5/23/59	8/10/59	2/15/60
Silica (SiO_2)	4.2			
Iron (Fe)	.23	0	0.07	
Aluminum (Al)	3.9	0	.2	
Manganese (Mn)	2.2	0.22	.82	
Copper (Cu)	.10			
Zinc (Zn)	.9			
Calcium (Ca)	5.6			
Magnesium (Mg)	4.9			
Sodium (Na)	2.4			
Potassium (K)	3.6			
Total acidity (H^+)	.5			
Bicarbonate (HCO_3)	0	5	3	
Carbonate (CO_3)	0	0	0	
Sulfate (SO_4)	57	12	19	45
Chloride (Cl)	3.1			
Fluoride (F)	.2			
Nitrate (NO_3)	.4			
Phosphorous (as PO_4)	.13			
Dissolved solids (residue on evaporation at 180°C)	89			
Hardness as $CaCO_3$	34	.13	18	41
Noncarbonate hardness as $CaCO_3$	34	9		
Alkalinity as $CaCO_3$	0			
Specific conductance (micromhos at 25°C)	172	62	62	155
pH	4.12	6.1	5.80	4.7
Color	15			

Comparison of the analyses of these samples collected in an area where the trees have grown more rapidly since mining suggests an explanation for the effects of mine drainage upon tree growth. The growth rates of the six trees sampled in area 18 after mining have exceeded the rates prior to mining. The relative growth rates of three sampled white oak trees, the only species sampled here, that were sampled upslope from the mine (table 29) range from 120 to 198 percent; the maximum relative growth rate of any of the sampled trees is 256 percent, which is the growth rate of a 10.7-inch diameter mockernut hickory.

Sample A was collected at 11:00 a.m. about 2 hours after the second heavy rainfall stopped during the general storm of September 10 and 11, 1960. During the first period of rainfall from 4:30 p.m. to 11:00 p.m. September 10, 0.64 inch of rain fell. During the second period, from about 5:00 a.m. to 9:00 a.m. September 11, 1960, about 0.35 inch of rain fell (F. F. Schrader, written communication, Dec. 2, 1960).

If the assumption is correct that the chemical quality of sample A is representative of the quality of mine drainage that is received by the trees, then at least some of the dissolved constituents are probably causing the trees to grow more rapidly. The higher content of several constituents may be responsible for the increased growth, as all elements listed in table 31, except possibly aluminum, have been found to be essential for plant growth. The effect of different concentrations absorbed by the plants is not known, but it is known, for example, that iron and magnesium are essential in the formation of chlorophyll and are part of the enzymes that affect certain metabolic processes in plants (Meyer and others, 1960, p. 314–316).

Comparison of the analyses of sample A with B, C, and D (table 31) suggests that many dissolved constituents in the mine drainage are removed when the water percolates through the forest soil and underlying bedrock. The location of the collection points in relation to the mine and area 18 and the flow of water at the time of collection are shown in figure 49. Samples B, C, and D represent drainage from the base of the soil mantle and flowing across a bedrock lip located about 100 feet downstream from the collection site of sample A. No water was draining across the surface directly from the mine when the samples B, C, and D were collected; so, the flow may represent subsurface flow from the spoil bank and pools after it had percolated through the soil. The higher pH and lower concentrations of minerals in samples B, C, and D compared to A suggest that some minerals are quickly removed from solution as the water moves through the soil. The concentration of aluminum and manganese in soil drops sharply as the pH increases from 4 to 5 (Black, 1957, p. 142–144).

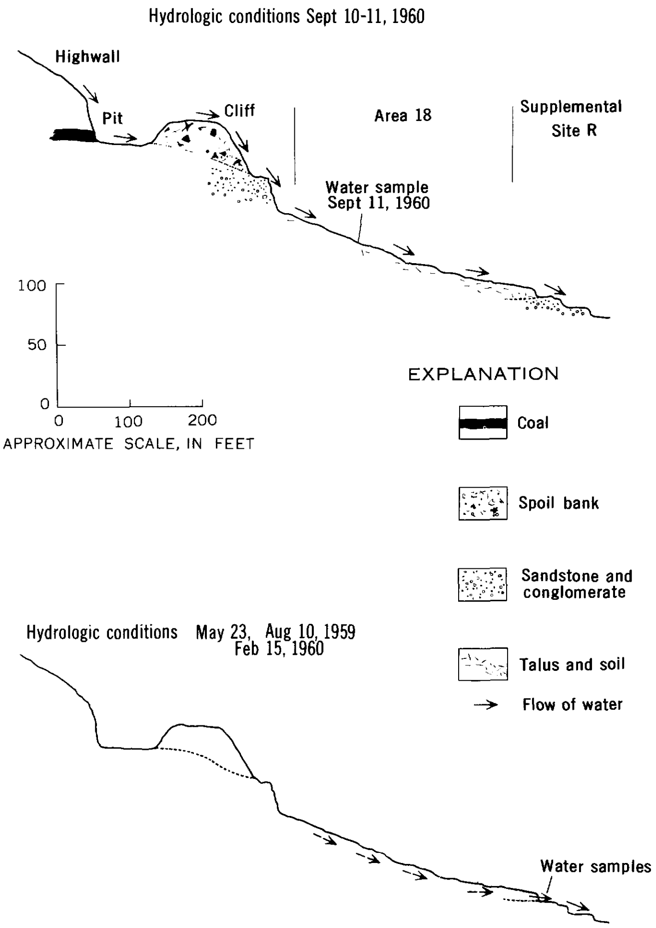

FIGURE 49.—Sketch showing location of collection points for water samples listed in table 31. *A*, Solid arrows represent flow of water as observed on September 9, 1960. *B*, Dashed-line arrows represent probable path of flow when samples were collected during dry weather.

How the other elements react to a slight rise in pH has not been learned, nor is it known that this reaction exists in the soils downslope from the strip mine. It seems likely, however, that the pH of the mine drainage would increase rapidly as it percolates through the soil, and many of the dissolved constituents would be precipitated.

A rise in pH and the precipitation of aluminum and manganese would result in lowering the concentration of these elements to below their toxic level. Iron, on the other hand, probably would remain in solution as the water percolated through the soil because its solubility is affected by tannic acid which is present in forest leaf litter. Hem (1960, p. 87–88) found experimentally that appreciable quantities of iron remained in solution in the presence of tannic acid and that even with an increase in pH from 4 to 6 some iron remained in solution for as long as 30 days.

The data, consisting of analyses of parts of a tree downslope from the mine and of a tree upslope from the mine and of analyses of a sample of surface drainage from the mine and of samples of subsurface flow, are the basis for two hypotheses: (1) some of the dissolved constituents in the mine drainage cause an increase in tree growth, and (2) percolation of mine drainage through the forest soil results in the removal of a large quantity of many of the elements.

This discussion of the effects of the dissolved constituents upon the growth of the trees and the effect of the forest soil upon the chemical quality of the water is presented primarily to indicate the usefulness of two lines of study. These are the study of absorption and utilization of minerals by trees, and the effect of forest soils upon the chemical quality of water. However, more data are required in both areas of study.

NATURAL ESTABLISHMENT OF TREES ON NEW LAND

Forestation of strip-mine spoil banks in the Midwestern States has been the subject of intensive research by personnel of the U.S. Forest Service for more than 20 years, and the results have been summarized recently by Limstrom (1960). He points out (p. 39–41) that planting of tree seedlings on strip-mined lands is necessary because adequate stands do not generally develop from natural seeding.

Natural seeding of strip-mined lands, according to Limstrom (1960, p. 39), is by wind-blown light-weight seed, and the kinds of species that become established are limited to those that grow in the surrounding forest. Of the four tree species in the surrounding forest that produce lightweight seed, only pine grow in the forest close to the mine. Hemlock, birch, and sycamore trees are limited to the narrow valley, about 100 to 200 feet deep, below the mine (Musser, 1963). Seeds from this area are probably not blown to the mine.

Studies of natural forestation of land have shown that about 5,000 seedlings per acre, 100 per 1,000 square feet, are probably necessary to insure reproduction of trees (Baker, 1950, p. 183). An adequate stand of trees may become established on strip-mined lands that are close to a seed source. Merz and Plass (1952) calculated that more than 8,000 tree seedlings per acre were growing on 2-year-old strip-mined lands that were within 120 feet of a seed source. Natural stands on older strip-mined areas, however, are composed of poorly formed trees of uneven age (Deitschman and Lane, 1952). The volume of wood in a natural stand of sycomore on strip-mined lands in Ohio was reported by Limstrom (1960, p. 39–41) to be considerably smaller than the volume of wood in plantations of the same age. Some of these trees, too, were found to be poorly formed. Furthermore, plantations require only 700 to 1,200 trees per acre to provide optimum forest establishment on strip-mined lands (Limstrom, 1960, p. 51–52). Study of the vegetation on the spoil banks on the west side of Cane Branch shows that the trees are of uneven age and that differences exist in the number of seedlings per unit area.

METHODS OF STUDY

A total of 14 plots of different size and shape have been located in the strip-mine area (fig. 46) during the 3 years of study. Of the total, 11 plots are located on the mine spoil, 2 are located on the cleared area above the highwall, and 1 is located downslope from the spoil bank. Plots were located arbitrarily and more or less evenly spaced in order to sample the mined area.

Three plots are located in areas away from the spoil banks in order to provide data from contrasting kinds of sites. Two are located above the highwall, where soil and some loose rock mantle was removed during the mining operation forming a cleared strip of variable width. One plot was established on sediment that is being deposited downslope from the spoil banks by surface runoff.

The sizes of the plots were dictated partly by the local topography. An attempt was made to select plots of a size and shape within which the topography, surface materials, and erosion appeared to be uniform. Some are long and narrow, others are square. Most are on relatively smooth higher surfaces, and only one contains both a steep slope and a flat surface.

The location of all tree seedlings is recorded on a sketch map of each plot, and identifications of the seedlings are made with repect to genus or species. Most of the pines are 1- and 2-year-old seedlings, and identification of species has not been made. However, some pines that are now about 4 years old have been identified as Virginia pine; others appear to be shortleaf or pitch pine. All species of pine are lumped together in this report because most cannot be identified with certainty. These plots are revisited each year, and similar yearly records are made.

RESULTS

The number of seedlings in each plot has differed from year to year because of transient factors of unknown magnitude. For example, the stakes marking one plot were destroyed between May 1958 and May 1959, apparently by a heavy tractor. Erosion has modified some plots and sediment deposition has occurred on a few, resulting apparently in a loss of some seedlings. Furthermore, a number of additonal variables known to inhibit the establishment and growth of seedlings are operative in the strip-mined area but are of unknown magnitude. These include distance from the seed source (Baker, 1950, p. 183, 211–212), compaction of the surface materials (Limstrom, 1952, p. 13–17), and toxicity of the soil (Limstrom, 1960, p. 10). Therefore, only the number of seedlings per 1,000 square feet of plot area are reported as follows:

Plot number	Seedlings per 1,000 sq ft	Plot number	Seedlings per 1,000 sq ft
1	8	8	4
2	0	9	8
3	0	10	2.5
4	0	11	6.5
5	0	12	9
6	1	13	1
7	33	14	4

The number of seedlings in the plots per 1,000 square feet is many times below the minimum number necessary to insure natural forestation of land, and no seedlings were found in four plots. The most per 1,000 square feet in any plot is 33, and the number in the remaining 9 plots ranges from 1 to 9. Even though seedlings are becoming established on the spoil banks, they are far too few to insure an adequate stand of trees.

Since the spoil banks were leveled, insufficient time has elapsed for any firm conlusions to be drawn about the rate of establishment of trees on the mined area. Reforestation will probably continue for a long period, yet the data are too inadequate to determine how much time will be required for the area to support a forest as dense as the surrounding forests on the upland.

CONCLUSIONS

Unlike the adverse effects of mine drainage upon bottom fauna and fish in Cane Branch (see section on "Stream bottom fauna" and section on "Fish population"), data presented here show that trees in the drainage basin below the mine have not been injured. In fact, these trees are growing more rapidly than before mining. This evidence suggests that runoff from the mine creates favorable growth conditions if excess sedimentation has not created water-logged sites. The soils of the Cane Branch drainage basin may have been partly depleted of essential minerals because, as Wilde (1958, p. 219) has suggested, repeated logging and fire remove them more rapidly than they are replaced by weathering. The history of exploitation of the forests in the Beaver Creek area has not been learned. However, numerous stump sprouts of several ages, the absence of any large, old trees in accessible areas, and fire scars on trunks indicate fires and a long and continued history of cutting. The effect of mining upon the forest soils seems to be equivalent to suddenly replacing large quantities of minerals in a manner that results in their being immediately available to the trees. Thus the present growth rate of trees not affected by mining may be the growth rate of the several species growing in a depleted soil. The maximum growth rate for the species growing in undisturbed sites may be somewhat between their present rate and the accelerated rate of the trees which are receiving mine drainage.

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STREAM-BOTTOM FAUNA

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The abundance of bottom fauna in streams is important to the vital processes of higher aquatic life inhabiting the streams. The purpose of this study is to describe and evaluate the aquatic animal life being supported in and upon the bottom materials of Cane Branch and Hughes Fork of Beaver Creek, streams receiving acid mine water and sediment, and Helton Branch and Little Hurricane Fork, streams located in an adjacent watershed and unpolluted from coal mine operations.

METHODS

Bottom samples were collected in May, June, and September 1956, in June and September 1957, and in June 1958. Samples were taken throughout the entire lengths of each stream during each collection period and sampling sites were duplicated whenever possible. However, because of the difference in waterflows during the various collection periods, duplication was not always possible. An effort was made to sample the most productive areas of the stream bottom; therefore, the sampling was not random but deliberately biased for the greatest productivity.

All collections were made with a square-foot bottom sampler. The organisms were separated from debris and other bottom materials when collected and preserved in alcohol for later study.

In compiling and presenting the data for stream-bottom productivity, all samples taken of each of the streams on a given date were combined and adjusted to a standard base of 20 square feet of stream bottom. Therefore, data presented in the tables in the following subsection can be directly compared on an equal stream-bottom basis.

RESULTS

This study was started in May 1956; therefore, the production of bottom fauna in Cane Branch and Hughes Fork before mining began is unknown. There is strong indication that acid mine water was affecting the production of stream-bottom fauna in Cane Branch when the collections were made in May 1956 (table 32). In Helton Branch 280 organisms per 20 square feet of stream bottom were present; in an equal stream-bottom area in Cane Branch, only 30 organisms were present.

Table 32.—*Stream-bottom fauna from Helton Branch and Cane Branch, May 16, 1956*

Class and order	Number of each organism per 20 sq ft of stream bottom		Percent of total organisms found in each stream		Percent of samples containing organism	
	Helton	Cane	Helton	Cane	Helton	Cane
Oligochaeta	-------	10	-------	33	-------	50
Crustacea: Decapoda	20	-------	7	-------	100	-------
Insecta:						
Plecoptera	40	10	14	33	100	50
Ephemeroptera	160	-------	58	-------	100	-------
Coleoptera	20	-------	7	-------	100	-------
Diptera	-------	10	-------	34	-------	50
Amphibia: Caudata	40	-------	14	-------	100	-------
Total	280	30	100	100	-------	-------

Analyses of collections made in May 1956 from Hughes Fork (the stream into which Cane Branch flows) and Little Hurricane Fork (the stream into which Helton Branch flows) show that samples from these streams are similar with respect to types of organisms present and total number of organisms. However, there is evidence that adverse environmental factors were operative in 1956 in Hughes Fork. The relative abundance of mayflies, Ephemeroptera, an insect group very important in the diet of most stream-inhabiting fishes, was used as an indicator of clean, unpolluted waters in this study after it became apparent that this group of insects was either absent or present in relatively low numbers in the streams receiving acid mine water and sediment. The data presented in table 33 clearly show the difference in the mayfly abundance of the two streams. Little Hurricane Fork was supporting 129 mayflies per 20 square feet of stream bottom, whereas Hughes Fork below the mouth of Cane Branch was supporting only 15 mayflies per 20 square feet of stream bottom.

Table 33.—*Stream-bottom fauna from Little Hurricane Fork and from Hughes Fork below mouth of Cane Branch, May 1956*

Class and order	Number of each organism per 20 sq ft of stream bottom		Percent of total organisms found in each stream		Percent of samples containing organism	
	Hurricane	Hughes	Hurricane	Hughes	Hurricane	Hughes
Oligochaeta	1	4	1	2	5	20
Crustacea: Decapoda	20	9	7	4	40	20
Insecta:						
Plecoptera	20	26	7	12	40	55
Ephemeroptera	129	15	51	7	75	35
Odonata	1	11	1	5	5	45
Hemiptera	4	-------	2	-------	15	-------
Megaloptera	8	9	3	4	20	45
Trichoptera	28	4	11	2	50	20
Lepidoptera	1	-------	1	-------	5	-------
Coleoptera	20	11	7	5	35	45
Diptera	21	24	8	11	40	75
Unidentified	1	-------	1	-------	5	-------
Amphibia: Caudata	-------	103	-------	48	-------	20
Total	254	216	100	100	-------	-------

The hypothesis that acid water and (or) sediment does adversely affect the mayfly population is further supported by an analysis of collections made in September 1956 from Hughes Fork above the mouth of Cane Branch, Hughes Fork below the mouth of Cane Branch, and West Fork Cane Branch (table 34). West Fork Cane Branch, although not comparable in

TABLE 34.—*Stream-bottom fauna from Hughes Fork above mouth of Cane Branch, Hughes Fork below mouth of Cane Branch, and West Fork Cane Branch, September 1956*

Class and order	Number of each organism per 20 sq ft of stream bottom			Percent of total organisms found in each stream			Percent of samples containing organism		
	Hughes Fork above Cane Branch	Hughes Fork below Cane Branch	West Fork Cane Branch	Hughes Fork above Cane Branch	Hughes Fork below Cane Branch	West Fork Cane Branch	Hughes Fork above Cane Branch	Hughes Fork below Cane Branch	West Fork Cane Branch
Insecta:									
Ephemeroptera	300	--------	20	37	--------	6	100	--------	100
Odonata	40	--------	--------	5	--------	--------	100	--------	--------
Hemiptera	20	--------	--------	2	--------	--------	100	--------	--------
Megaloptera	--------	40	--------	--------	100	--------	--------	100	--------
Trichoptera	40	--------	240	5	--------	75	100	--------	100
Lepidoptera	20	--------	--------	2	--------	--------	100	--------	--------
Coleoptera	360	--------	--------	44	--------	--------	100	--------	--------
Diptera	40	--------	40	5	--------	13	100	--------	100
Amphibia: Caudata	--------	--------	20	--------	--------	6	--------	--------	100
Total	820	40	320	100	100	100	--------	--------	--------

size to Hughes Fork, is not receiving mine drainage and the analysis of the samples collected from this stream is included in the table as additional support of the hypothesis that mayflies are drastically affected by mine pollution and can be used as indicator organisms in this study.

In Hughes Fork above the source of pollution, 300 mayflies were collected; downstream in Hughes Fork below the source of pollution, there were no mayflies in the collection; in West Fork Cane Branch, 20 mayfly larvae were collected.

During this same collecting period, September 15 and 16, 1956, samples were collected from Helton Branch and Cane Branch (table 35). Helton Branch was supporting a rich variety of organisms, whereas only one order of insects, Diptera, was found in Cane Branch. Although not identified as to species, these four-gilled fly larvae are known to be exceptionally hardy organisms and are able to withstand very adverse environmental conditions. At the time of sampling, a layer of sediment covered much of the stream bottom of Cane Branch. These fly larvae were collected from this sediment deposit.

TABLE 35.—*Stream-bottom fauna from Helton Branch and Cane Branch, September 1956*

Class and order	Number of each organism per 20 sq ft of stream bottom		Percent of total organisms found in each stream		Percent of samples containing organism	
	Helton	Cane	Helton	Cane	Helton	Cane
Oligochaeta	5	--------	2	--------	25	--------
Crustacea: Decapoda	40	--------	14	--------	50	--------
Insecta:						
Plecoptera	30	--------	10	--------	25	--------
Ephemeroptera	60	--------	20	--------	75	--------
Odonata	15	--------	5	--------	75	--------
Hemiptera	5	--------	2	--------	25	--------
Megaloptera	10	--------	3	--------	25	--------
Trichoptera	20	--------	7	--------	50	--------
Coleoptera	5	--------	2	--------	25	--------
Diptera	95	1,776	32	100	75	100
Amphibia: Caudata	10	--------	3	--------	25	--------
Total	295	1,776	100	100	--------	--------

In June 1956, 1957, and 1958, a series of bottom samples were collected from Helton Branch and Cane Branch and the results of these collections are reported in table 36. It is apparent from a comparison of the data included in this table that Helton Branch was consistently supporting a faunal complex composed of various insect orders, in addition to crayfish and salamanders, whereas the fauna of Cane Branch was

TABLE 36.—*Stream-bottom fauna from Cane Branch and Helton Branch, June 1956, 1957, and 1958*

Class and order	Number of each organism per 20 sq ft of stream bottom						Percent of total organisms found in each stream						Percent of samples containing organism					
	1956		1957		1958		1956		1957		1958		1956		1957		1958	
	Cane	Helton	Cane	Helton	Cane	Helton	Cane	Helton	Cane	Helton	Cane	Helton	Cane	Helton	Cane	Helton	Cane	Helton
Crustacea: Decapoda	------	12	------	12	------	10	------	2	------	5	------	5	------	60	------	60	------	10
Insecta:																		
Plecoptera	------	12	------	32	------	------	------	2	------	12	------	------	------	40	------	40	------	------
Ephemeroptera	------	88	------	120	------	74	------	17	------	47	------	36	------	20	------	100	------	100
Odonata	7	4	------	4	------	------	26	1	------	2	------	------	33	20	------	20	------	------
Hemiptera	20	20	------	------	------	------	74	4	------	------	------	------	67	40	------	------	------	------
Megaloptera	------	52	------	------	5	5	------	10	------	------	1	2	------	60	------	------	25	10
Trichoptera	------	92	------	56	------	40	------	18	------	22	------	20	------	60	------	60	------	50
Coleoptera	------	12	------	8	------	5	------	2	------	3	------	2	------	20	------	20	------	10
Diptera	------	160	200	24	420	70	------	30	100	9	99	35	------	100	100	80	100	75
Amphibia: Caudata	------	76	------	------	------	------	------	14	------	------	------	------	------	40	------	------	------	------
Total	27	528	200	256	425	204	100	100	100	100	100	100	------	------	------	------	------	------

represented by four orders of insects only, of which no more than two were collected during any one collection period.

In September 1957, bottom samples were collected from Helton Branch and Cane Branch and the results of these field collections are tabulated in table 37. Approximately the same faunal complex was existant at this time in Helton Branch as was present in this stream during previous collections. There was, however, some difference in the number of specimens representing specific orders of insects. In June 1957 only fly larva, Diptera, were present in the samples from Cane Branch; in September 1957 only Dobson fly larvae, Megaloptera, were present in the samples taken from this stream. The reasons for the presence of Megaloptera and the absence of Diptera in the September collection are unknown. However, both orders were present in the June 1958 collection.

TABLE 37.—*Stream-bottom fauna from Cane Branch and Helton Branch, September 1957*

Class and order	Number of each organism per 20 sq ft of stream bottom		Percent of total organisms found in each stream		Percent of samples containing organism	
	Cane	Helton	Cane	Helton	Cane	Helton
Crustacea: Decapoda	--------	10	--------	4	--------	50
Insecta:						
Plecoptera	--------	20	--------	9	--------	50
Ephemeroptera	--------	50	--------	22	--------	100
Odonata	--------	30	--------	13	--------	100
Hemiptera	--------	10	--------	4	--------	50
Megaloptera	80	--------	100	--------	100	--------
Trichoptera	--------	--------	--------	--------	--------	--------
Coleoptera	--------	10	--------	4	--------	50
Diptera	--------	90	--------	40	--------	100
Amphibia: Caudata	--------	10	--------	4	--------	50
Total	80	230	100	100	--------	--------

A total of 230 organisms, of which 50 were mayflies, were present in the September 1957 collection from Helton Branch, and 80 organisms, which included no mayflies, were present in the samples from Cane Branch at this time.

The effects of strip-mine drainage upon basic fish-food production or stream-bottom animal life is further demonstrated in tables 38 and 39. These data were collected in September 1957 and in June 1957 and 1958 from Hughes Fork above the mouth of Cane Branch, Hughes Fork below the mouth of Cane Branch, and from Little Hurricane Fork. At these times no mayflies were collected in Hughes Fork below the mouth of Cane Branch. Mayflies were very abundant in Hughes Fork above the mouth of Cane Branch and in Little Hurricane Fork. In addition, stream-bottom life was consistently more abundant in the streams receiving no mine drainage than it was in the streams which were receiving mine drainage.

CONCLUSIONS

From the data presented it can be concluded that natural drainage including sediment and acid water from strip-mined areas adversely affects stream-bottom invertebrate life. Concurrently, there was no indication during the period of study that the stream-bottom invertebrate life of the polluted streams was increasing, either qualitatively or quantitatively, with the passing of time.

TABLE 38.—*Stream-bottom fauna from Hughes Fork below and above the mouth of Cane Branch and from Little Hurricane Fork, September 1957*

Class and order	Number of each organism per 20 sq ft of stream bottom			Percent of total organisms found in each stream			Percent of samples containing organism		
	Hughes Fork below Cane Branch	Hughes Fork above Cane Branch	Hurricane	Hughes Fork below Cane Branch	Hughes Fork above Cane Branch	Hurricane	Hughes Fork below Cane Branch	Hughes Fork above Cane Branch	Hurricane
Crustacea: Decapoda	40	--------	22	30	--------	11	88	--------	43
Insecta:									
Plecoptera	10	--------	36	8	--------	18	25	--------	100
Ephemeroptera	--------	40	45	--------	11	22	--------	100	86
Odonata	3	80	34	2	22	17	13	100	71
Hemiptera	8	60	25	6	16	12	38	100	43
Megaloptera	15	20	6	11	6	3	63	100	29
Trichoptera	12	40	3	9	11	1	25	100	14
Coleoptera	5	100	8	4	28	4	25	100	29
Diptera	40	20	22	30	6	11	63	100	71
Amphibia: Caudata	--------	--------	3	--------	--------	1	--------	--------	14
Total	133	360	204	100	100	100	--------	--------	--------

TABLE 39.—*Stream-bottom fauna from Hughes Fork below and above the mouth of Cane Branch and from Little Hurricane Fork, June 1957 and 1958*

Class and order	Number of each organism per 20 sq ft of stream bottom						Percent of total organisms found in each stream						Percent of samples containing organism					
	1957			1958			1957			1958			1957			1958		
	Hughes Fork below Cane Branch	Hughes Fork above Cane Branch	Hurricane	Hughes Fork below Cane Branch	Hughes Fork above Cane Branch	Hurricane	Hughes Fork below Cane Branch	Hughes Fork above Cane Branch	Hurricane	Hughes Fork below Cane Branch	Hughes Fork above Cane Branch	Hurricane	Hughes Fork below Cane Branch	Hughes Fork above Cane Branch	Hurricane	Hughes Fork below Cane Branch	Hughes Fork above Cane Branch	Hurricane
Oligochaeta	8	60	-	-	-	-	29	18	-	-	-	-	40	100	-	-	-	-
Crustacea: Decapoda	-	-	8	6	-	44	-	-	5	6	-	13	-	-	30	30	-	20
Insecta:																		
Plecoptera	-	40	28	66	20	48	-	13	17	67	8	13	-	100	70	60	80	60
Ephemeroptera	-	40	42	-	80	150	-	13	26	-	30	42	-	100	70	-	80	100
Odonata	4	-	16	2	40	16	13	-	10	2	15	5	20	-	50	10	100	40
Hemiptera	-	-	12	-	-	-	-	-	7	-	-	-	-	-	50	-	-	-
Megaloptera	8	20	-	18	8	2	29	6	-	19	3	1	40	100	-	70	40	10
Trichoptera	-	20	6	4	-	8	-	6	4	4	-	2	-	100	30	10	-	30
Coleoptera	-	40	20	-	80	40	-	13	12	-	30	11	-	100	40	-	80	70
Diptera	8	100	30	2	36	48	29	31	19	2	14	13	40	100	60	10	60	90
Total	28	320	162	98	264	356	100	100	100	100	100	100	-	-	-	-	-	-

FISH POPULATION

By MARVIN A. SMITH, U.S. Bureau of Sport Fisheries and Wildlife

There is a striking difference between the fish populations of streams that receive strip-mine effluent and those that do not. The purpose of this paper is to describe the fish life in the streams of the Beaver Creek area and the changes which occurred during and after strip mining in the Cane Branch watershed.

METHODS OF CONDUCTING FISH POPULATION STUDIES

Sampling of the fish populations in the strip-mined and nearby watersheds was accomplished biannually by the cresol method as described by Wilkins (1955). After a sample station had been selected, the streamflow was estimated and emulsifiable cresol (phenol coefficient 30) was added directly to the water at the upper end of the station. Cresol was added at a volume of 1 quart for each cubic foot per second of flow. The fish showed distress within several minutes after the release of the cresol and were captured with dipnets. After identification, counting, and weighing, the fish were released into the stream. Mortality was slight. Collection of fish by this method of sampling was virtually complete, with two exceptions. These exceptions took place on Hughes Fork on June 5, 1957, at which time adverse stream conditions permitted a recovery of about 50 percent of the fish within the sample areas. Water temperatures, pH, estimated streamflows, and the surface area of the station were recorded each time a sample was collected.

No sampling was conducted prior to strip mining. It is reasonable to assume, however, that the streams in the study areas were originally populated with comparable numbers of fish of species indigenous to the Beaver Creek area.

RESULTS OF SAMPLING FISH POPULATIONS

The results of the fish sampling in the Beaver Creek basin from 1956 to 1958 are summarized in table 40. May 16, 1956, was the last recorded date on which fish were observed in Cane Branch; recently hatched fry were observed on only one occasion (June 3, 1958) in lower Hughes Fork. Normal fish populations were collected in Helton Branch, West Fork Cane Branch, and upper Hughes Fork during the 3-year period of study.

The disappearance of the fish populations from Cane Branch appears to be directly correlated with strip mining which began in 1955 and ended in the spring of 1956. Greatly reduced fish populations were observed in the streams containing strip-mine effluent until June 1956, after which time fish life disappeared. This reduction and disappearance of fish life is directly associated with the change of pH of these streams. At the Cane Branch gaging station, the pH ranged from 6.8 to 3.9 between January 18 and May 16, 1956.

Although these pH levels were not sufficient to eliminate the fish population, they did apparently reduce it to a sparse population of creek chubs (*Semotilus atromaculatus*), which appear to be more tolerant of the acid water than other indigenous species.

In June 1956, the spoil bank in the strip-mine area was leveled by a bulldozer and drainage ditches were cleared. These drainage ditches carried acid strip-mine effluent directly into Cane Branch, causing the pH of

TABLE 40.—*Fish production in streams affected and not affected by strip-mine pollution*

Affected streams				Nonaffected streams			
Sample area (sq ft)	Fish per acre (lbs)	pH	Date	Sample area (sq ft)	Fish per acre (lbs)	pH	Date
Cane Branch above West Fork Cane Branch				**Helton Branch**			
	(1)		5/16/56	610	17.0	6.6	6/27/56
350	0	3.2	6/27/56	610	10.0	6.7	9/12/56
350	0	3.0	9/12/56	610	9.3	7.1	6/5/57
350	0	2.7	6/5/57	610	19.3	7.2	10/10/57
350	0	5.1	10/10/57	610	10.7	7.1	6/3/58
350	0	3.9	6/3/58	610	21.4	7.2	10/22/58
350	0	3.2	10/22/58				
Cane Branch below West Fork Cane Branch				**West Fork Cane Branch**			
	(2)		5/16/56	28	228		9/13/56
240	0	3.5	6/27/56	28	218	6.8	6/5/57
240	0	5.1	9/12/56	21	207	7.2	10/10/57
240	0	5.2	6/5/57	27	370	6.8	6/3/58
240	0	3.5	10/10/57	28	233	6.8	10/22/58
240	0	4.0	6/3/58				
240	0	3.4	10/22/58				
Lower Hughes Fork				**Upper Hughes Fork**			
80	0	6.8	9/13/56		(2)		5/16/56
2,050	4.0	6.0	6/5/57	320	84.4	6.8	9/13/56
320	0	5.0	10/10/57	270	4.8	6.8	6/5/57
180	0	5.0	10/10/57	420	69.5	7.3	10/10/57
164	0	5.0	10/10/57	290	111.0	7.0	6/3/58
790	0	4.8	6/3/58	340	128.0	6.7	10/22/58
310	0	4.2	10/22/58				
240	(3)	4.8	6/3/58				
164	0	4.2	10/22/58				

[1] One Creek Chub was observed.
[2] Several unidentified fish were observed.
[3] Fry observed.

Cane Branch to be drastically reduced to about 2.7. At the same time fish life disappeared completely from Cane Branch. Ellis (1939) reports that acid water having a pH of 4.0 or less is toxic to fish, regardless of the acid-salt combination producing the acidity.

The effect of the strip-mine pollution on the fish life in the streams of the Beaver Creek basin is shown in figure 50. Hughes Fork below the confluence of Cane Branch has a seasonal capacity to support fish life. No fish were found in this stretch of stream in the fall of 1956 or 1957. In June 1958, lower Hughes Fork yielded a few fingerling creek chubs and some recently hatched fry of this species. In October 1958, fish life again disappeared from lower Hughes Fork. The reason for this seasonal appearance of fish life is that in the spring and early summer, when streamflows are high, the Cane Branch discharge is diluted by the flow of upper Hughes Fork. This increased flow reduces the acidity of lower Hughes Fork to a point where fish life can tolerate the stream conditions. As the summer progresses and this flow declines, the effect of the strip-mine effluent becomes greater, and gradually a point of acidity is reached in lower Hughes Fork which the fish cannot tolerate.

The various species of fish and their relative abundance in the Beaver Creek basin are given in the following tabulation. The creek chub is the dominant species in these small tributary streams.

	Number of fish	*Percent*
Creek chub (*Semotilus atromaculatus*)	687	93.3
Southern redbelly dace (*Chrosomus erythrogaster*)	24	3.3
Gilt darters (*Percina evides*)	17	2.3
Northern hog sucker (*Hypentelium nigricans*)	5	.7
American brook lamprey (*Lampetra lamottei*)	2	.3
White sucker (*Catostomus commersonii*)	1	.1
Total	736	100

FISH MORTALITY STUDIES

In July 1958, fish-mortality studies were conducted in Cane Branch above West Fork Cane Branch to determine if fish could survive in water of low pH. Helton Branch was used as the control stream. Three species of fish were used in the experiments:

1. Goldfish (*Carassius auratus*) purchased from a commercial source.
2. Bluegill sunfish (*Lepomis macrochirus*) seined from a farm pond.

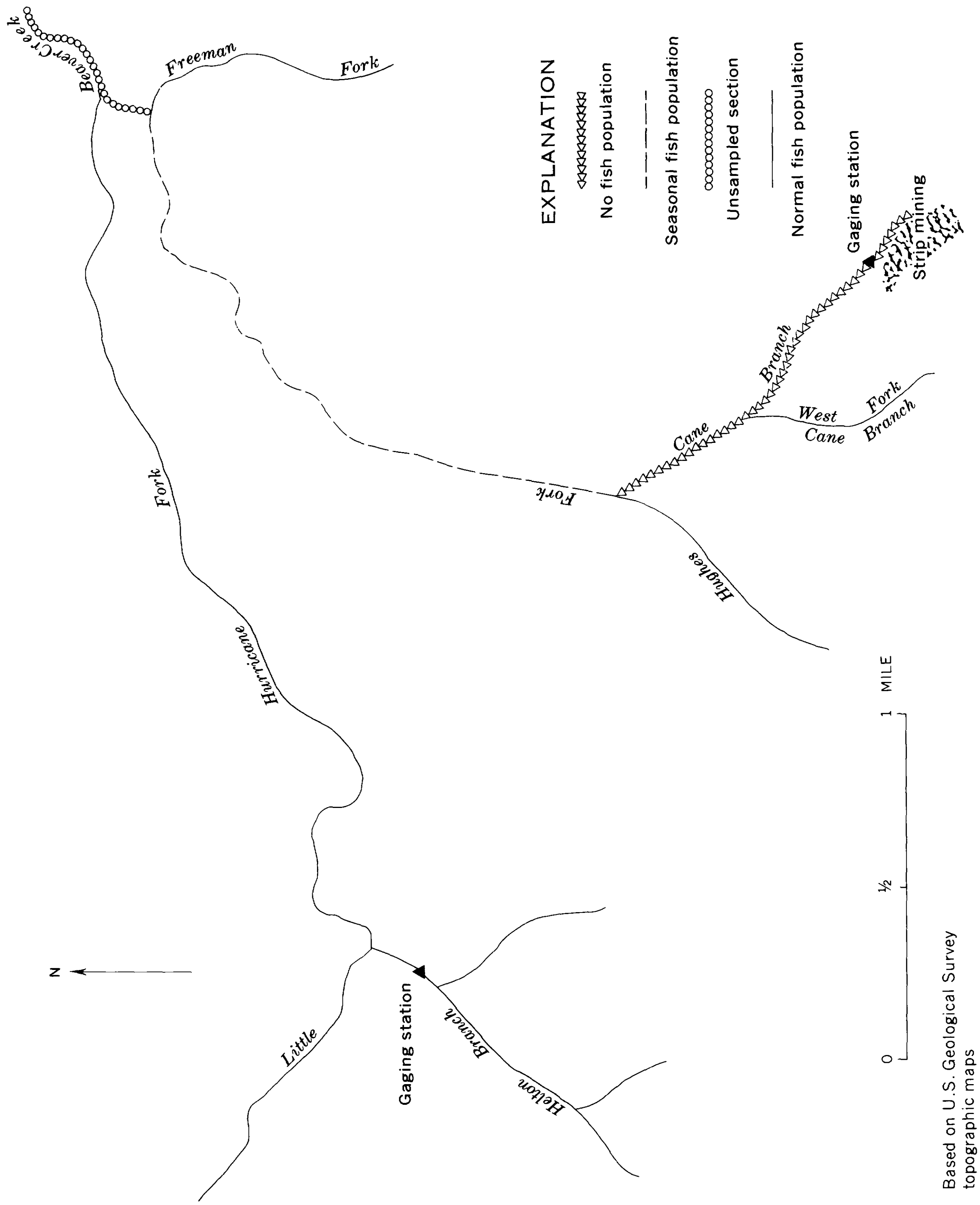

FIGURE 50.—Effect of strip mining on fish populations, Beaver Creek basin, McCreary County, Ky.

3. Creek chub (*Semotilus atromaculatus*) seined from West Fork Cane Branch.

The first mortality experiment was conducted in the vicinity of the gaging stations by comparing the effects of Cane and Helton Branches on six bluegills and six goldfish which had been placed in submerged wire live boxes. Attendance at the test sites was not continuous, but the fish placed in Cane Branch were dead within 4 hours after exposure to the acid water, while the fish placed in Helton Branch were alive when checked the following morning. The experiment was repeated in these two streams under continuous observation. With one exception, the procedure used was identical with the initial experiment. The exception was the addition of six creek chubs to the live boxes containing the bluegills and goldfish.

The following results were recorded:

Time, in minutes, to distress and death of fish exposed to acid strip-mine polluted water (pH 2.9) of Cane Branch

Species	Distress	First fish dead	All fish dead
Creek chub	15	20	30
Goldfish	45	75	90
Bluegill	120	150	190

Distress of fish subjected to acid mine water was very different from that exhibited by fish subjected to lack of oxygen. Instead of gasping on the surface or exhibiting frantic movements, the fish became inactive and underwent a color change to a lighter hue. Exact time of death was difficult to determine.

The fish placed in Helton Branch at pH 6.6 remained alive and were in apparent good health after 24 hours of confinement. The tests were terminated at this point.

CONCLUSIONS

Three years of study have demonstrated the deleterious effect of acid mine effluent on the fish life of the streams. Disappearance of fish life is shown to be directly associated with the toxic effects of the effluent from the strip mine.

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