SUMMARY OF THE U.S. GEOLOGICAL SURVEY AND U.S. BUREAU OF LAND MANAGEMENT NATIONAL COAL-HYDROLOGY PROGRAM, 1974–84

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1464

Prepared in cooperation with the
U.S. Bureau of Land Management

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Edited by L.J. BRITTON, C.L. ANDERSON, D.A. GOOLSBY, *and* B.P. VAN HAVEREN

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CONVERSION FACTORS

The inch-pound units in this report may be converted to SI (International System) units by using the following conversion factors.

Multiply inch-pound units	By	To obtain SI units
acre	4,047	square meter
acre-foot	1,233	cubic meter
acre-foot per square mile	476	cubic meter per square kilometer
cubic foot per second	0.028317	cubic meter per second
cubic foot per second per square mile	0.01093	cubic meter per second per square kilometer
cubic yard	0.7646	cubic meter
foot	0.3048	meter
gallon per day	3.785	liter per day
gallon per minute	3.785	liter per minute
inch	25.40	millimeter
mile	1.609	kilometer
pound per cubic foot	16.02	kilogram per cubic meter
square mile	2.590	square kilometer
ton	0.9072	megagram
ton per square mile	0.3503	megagram per square kilometer

Temperature in degree Celsius (°C) may be converted to degree Fahrenheit (°F) by using the following equation:

$$°F = 9/5\ °C + 32.$$

Temperature in degree Fahrenheit (°F) may be converted to degree Celsius (°C) by using the following equation:

$$°C = 5/9(°F - 32).$$

SUMMARY OF THE U.S. GEOLOGICAL SURVEY AND U.S. BUREAU OF LAND MANAGEMENT NATIONAL COAL-HYDROLOGY PROGRAM, 1974-84

Edited by L.J. BRITTON, C.L. ANDERSON, D.A. GOOLSBY, and B.P. VAN HAVEREN

ABSTRACT

During the decade 1974-84, the U.S. Geological Survey and the U.S. Bureau of Land Management cooperated on investigations to collect information and to study hydrologic processes related to development and mining of federally owned coal. In addition, the U.S. Geological Survey conducted similar investigations related to nonfederally owned coal. As a result of these nationwide investigations, a large quantity of hydrologic information and data has been collected and compiled in more than 500 reports. This report summarizes the major findings and accomplishments that have resulted from data-collection activities, hydrologic studies, and research concerned with the effects of coal mining on water resources.

This summary report includes: (1) A description of the Nation's coal- and water-resource issues related to coal development, including history, objectives, and design of the coal-hydrology program; (2) a summary of the hydrologic information collected in the major coal provinces and published in more than 500 reports and journal articles; and (3) a summary and application of results obtained from topical studies undertaken throughout the program, including discussions on watershed modeling, salinity modeling, ground-water flow systems, geochemistry of mine spoils, mine drainage, sedimentation, and aquatic biology. A detailed coal-hydrology reference list concludes the report.

INTRODUCTION

During 1974, the U.S. Geological Survey and the U.S. Bureau of Land Management began cooperative coal-hydrology investigations to collect information and to study hydrologic processes related to development of some federally owned coal resources. With passage of the Surface Mining Control and Reclamation Act in 1977, Congress directed the U.S. Geological Survey to expand the coal-hydrology studies to other coal provinces nationwide and to include nonfederally owned coal. Results from these investigations were to be used in making coal-leasing decisions to help minimize effects of coal mining on water resources. As a result of these investigations, a large quantity of hydrologic information and data has been collected and published, and major accomplishments related to the understanding of water-resource and coal-hydrology issues have been realized. Results of these studies have been published in more than 500 reports. However, until now a consolidated summary of the major findings of these nationwide investigations has not been published. A nationwide summary will be of considerable use to Federal and State agencies concerned with land-use planning and with regulation and enforcement of land-use and resource-development plans. In addition, an important result of the many coal-hydrology investigations was to indicate additional hydrologic information and research needs that warrant further study.

This report describes the Nation's coal- and water-resource issues related to coal development; the history, objectives, and program design of the Federal coal-hydrology program; and the Federal government's role in coal- and water-resource issues. The report summarizes the major findings and accomplishments that have resulted from the nationwide studies concerned with the effects of coal mining on water resources. Finally, this report includes a discussion concerning application of the results obtained from the many multidisciplinary studies that were undertaken during the Federal coal-hydrology program regarding land-use planning, coal leasing, and land reclamation.

This report is based primarily on information contained in a series of reports that generally characterize the hydrology of individual coal areas throughout the Nation. These reports are referenced, as is other pertinent literature on the various subjects discussed, and the reader is urged to consult the literature for a more thorough discourse.

Manuscript approved for publication August 20, 1986.

COAL RESOURCES

By WILBUR PALMQUIST[1]

Coal is the most abundant fossil fuel in the United States. Knowledge of the quantity, quality, and location of coal resources is necessary for meeting energy needs and for solving potential environmental issues, which include air, water, and land degradation.

The basic unit of coal is a bed, seam, or vein. One or more beds meeting minimum criteria of thickness, quality, extent, and depth of burial constitute a coal field. One or more coal fields are combined into coal regions, which are further grouped into the coal provinces shown on plate 1 (modified from Fenneman and Johnson, 1946; Trumbull, 1960).

Coal occurs in at least 39 States and underlies 13 percent of the land area in the United States. The majority of the coal deposits occur primarily in 17 States and are divided among 11 Eastern and 6 Western States.

In most areas, the coal-bearing rocks and enclosed coal beds are in broad, shallow, structural basins or synclines. In the Eastern Province, the coal generally is classified as high-volatile bituminous (fig. 1) and occurs less than 3,000 feet below the surface. In the Interior Province, the coal generally is classified as high-volatile bituminous (fig. 2) and occurs less than 2,000 feet below the surface. In the Northern Great Plains Province, the coal generally is classified as subbituminous and lignite (fig. 3) and occurs less than 1,500 feet below the surface. In the Rocky Mountain Province, the coal generally is classified as subbituminous and high-volatile bituminous (fig. 4) and sometimes occurs at great depths—more than 6,000 feet deep in the Uinta and Southwestern Utah regions of Colorado and Utah, as much as 15,000 feet deep in the Green River region of southwestern Wyoming, and 20,000 feet deep in the Wind River and Bighorn Basin regions of central and northern Wyoming (pl. 1). However, shallower coal beds also exist in the Rocky Mountain Province.

The U.S. Bureau of Mines and the U.S. Geological Survey are responsible for estimating and analyzing the Nation's coal resources. During 1974, Averitt (1975) estimated that at least 4 trillion tons of coal existed in the United States; this estimate did not include coal deposits deeper than 6,000 feet or coal on continental shelves. Averitt (1975) showed the reserve base, the quantity of coal deemed to be economically and legally available for mining, to be 434 billion tons.

Because of increasing needs for more accurate information about coal resources, a detailed and uniform classification system has evolved (Wood and others, 1983). The current system defines coal reserves as all coal that is currently economically recoverable and coal resources as coal that is potentially recoverable but subject to more favorable economic conditions and development of advanced technology.

The U.S. Energy Information Administration of the U.S. Department of Energy annually determines the demonstrated reserve base, a continuation of a U.S. Bureau of Mines function redelegated to the U.S. Department of Energy during 1977. The demonstrated reserve base, which is equivalent to the reserve base determined by the U.S. Geological Survey, is the tonnage of coal that can be extracted economically at the present time and the tonnage of coal that potentially could be extracted in the future using advanced technology and improved economic conditions. The demonstrated reserve base changes with time, decreasing as coal is mined and increasing as new coal is discovered. The U.S. Energy Information Administration determined the demonstrated reserve base of coal in the United States to be 489.5 billion tons on January 1, 1983—55.5 billion tons more than the U.S. Geological Survey's estimate (Averitt, 1975) of 434 billion tons for 1974 (fig. 5). Of the estimated coal reserves, 24.5 billion tons can be recovered at producing mines that were active at the end of 1984 (U.S. Energy Information Administration, 1984).

During the year 1900, coal provided 93 percent of all the energy used in the United States (Perry, 1983). By 1972, coal was providing only 17.3 percent of the Nation's energy because of increased use of oil and gas. The oil embargo of 1974 and the consequent quadrupling of oil prices caused a shift to coal for energy production. By 1983, coal was providing 22.1 percent of the Nation's energy (fig. 6). There is enough coal in the demonstrated reserve base to meet all the energy needs of the Nation for more than 10 centuries at the present rate of consumption. Although the dollar price of coal historically has increased, overall coal costs relative to wages have decreased (Simon, 1981). Increased coal demand and the relatively inexpensive cost of coal from the Western United States have caused production of Western United States coal to increase substantially. Coal production in the Eastern United States has remained relatively stable, even though transportation costs have increased.

The Federal Government may own as much as 60 percent of the coal in the Western United States, but it owns very little coal in the Eastern United States. The U.S. Bureau of Land Management has identified about 17 million acres of land in the Western United States that contain coal deposits. Federally owned coal occurs beneath 11.5 million acres of land in the Western United States, of which 4.8 million surface acres are under

[1]U.S. Bureau of Land Management.

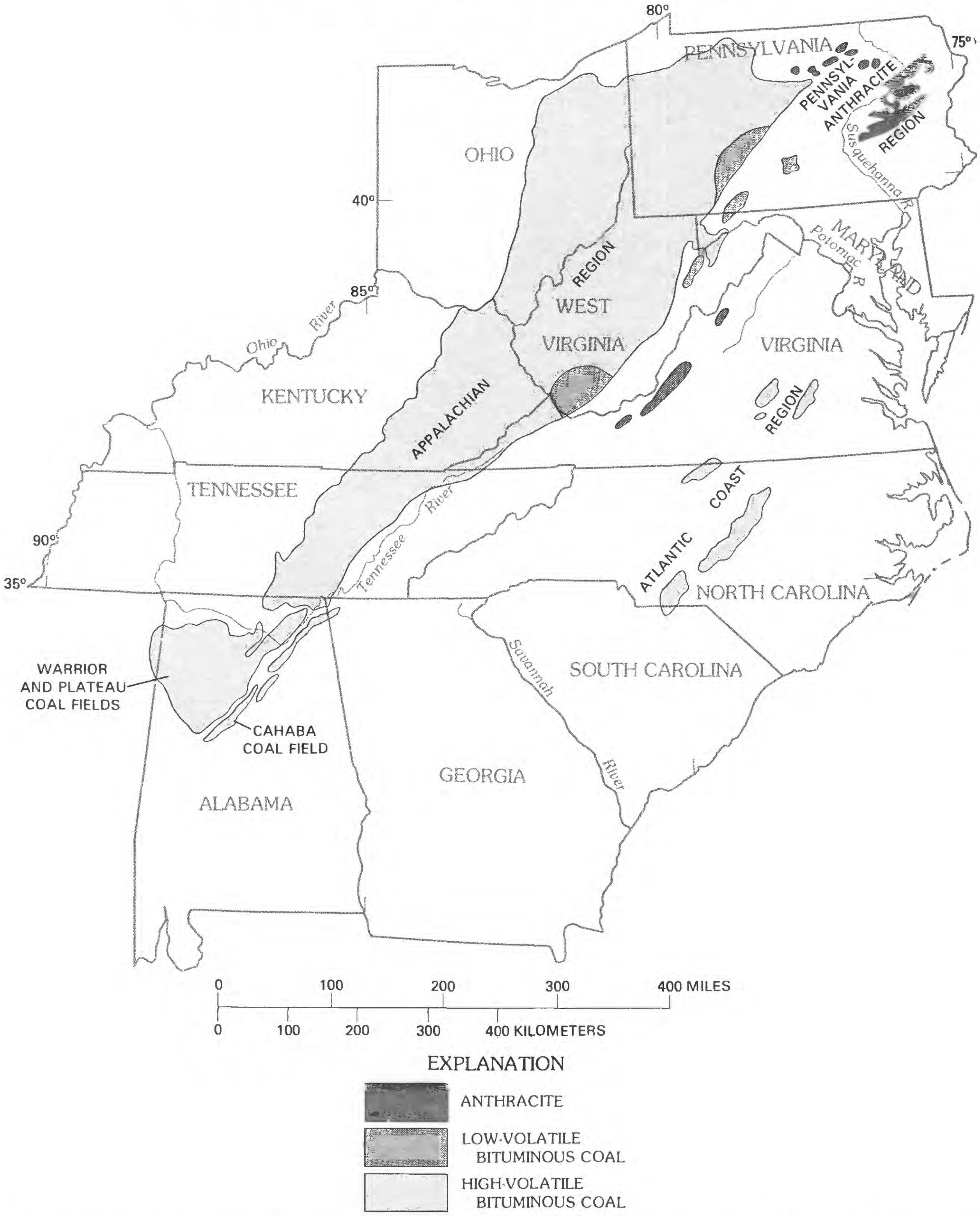


FIGURE 1.—Eastern Province: coal regions, selected coal fields, and dominant types of coal (modified from U.S. Department of the Interior, 1975).

FIGURE 2.—Interior Province: coal regions and dominant types of coal (modified from U.S. Department of the Interior, 1975).

Federal management and 6.7 million surface acres are privately owned (U.S. National Research Council, 1981b).

By the end of 1983, the U.S. Bureau of Land Management had issued 655 coal leases that had a combined surface area of 0.95 million acres in 14 States and contained an estimated 18 billion tons of recoverable reserves of Federal coal (U.S. Bureau of Land Management, 1984). The Powder River region of Wyoming and Montana and the Uinta and Southwestern Utah regions of Colorado and Utah contain 84 percent of the leased coal (pl. 1).

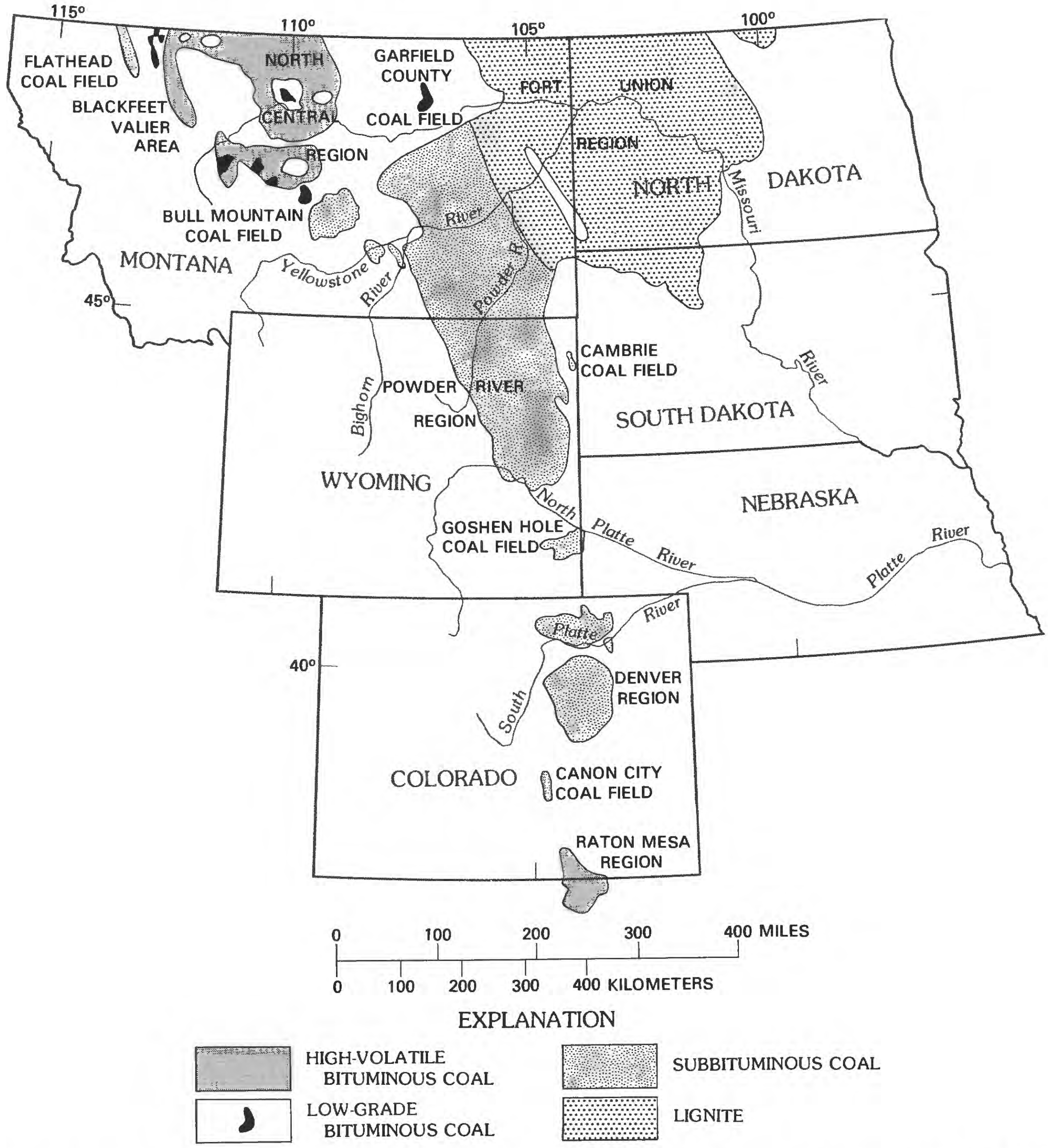


FIGURE 3.—Northern Great Plains and Rocky Mountain Provinces (part 1): coal regions, selected coal fields, and dominant types of coal (modified from U.S. Department of the Interior, 1975).

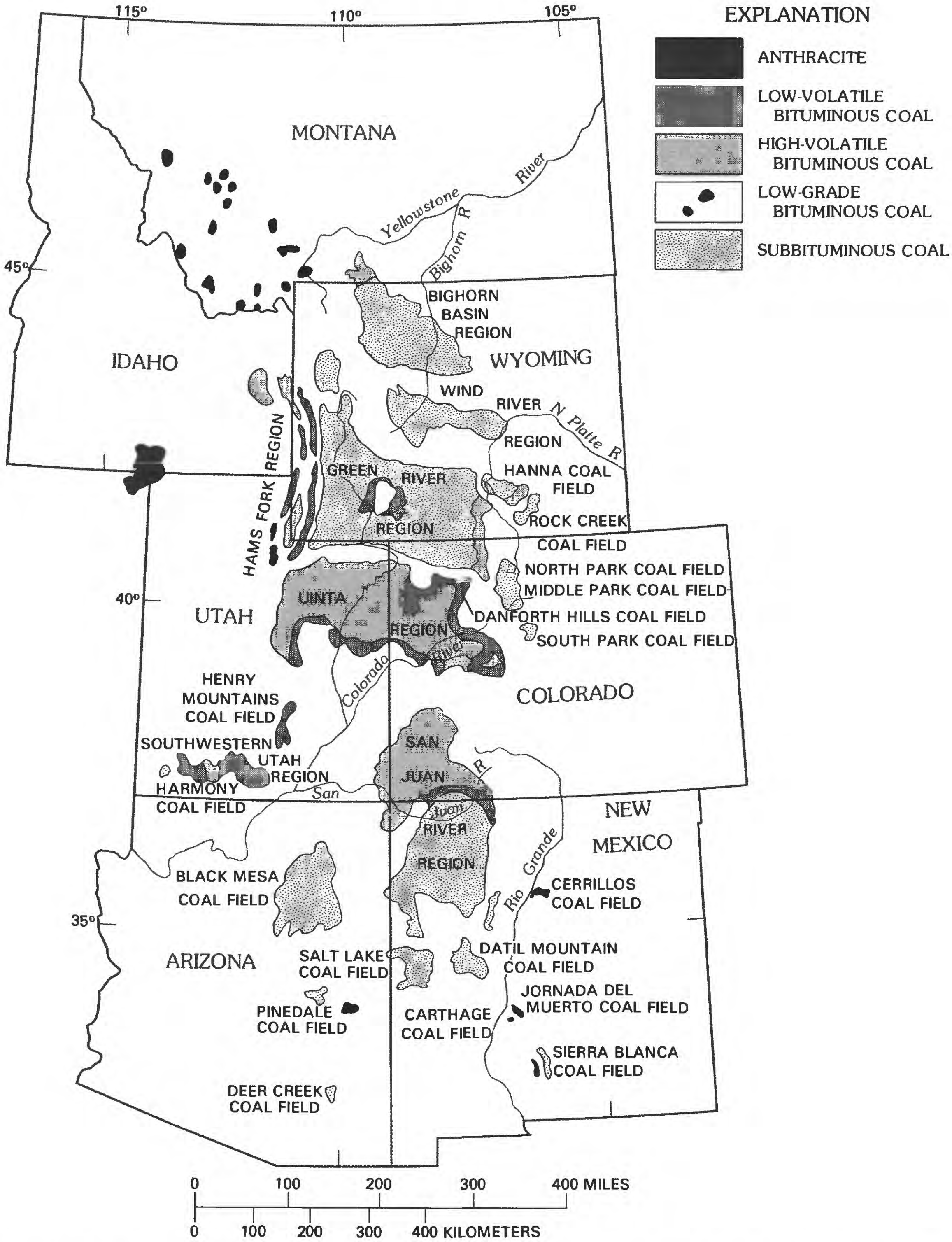


FIGURE 4.—Northern Great Plains and Rocky Mountain Provinces (part 2): coal regions, selected coal fields, and dominant types of coal (modified from U.S. Department of the Interior, 1975).

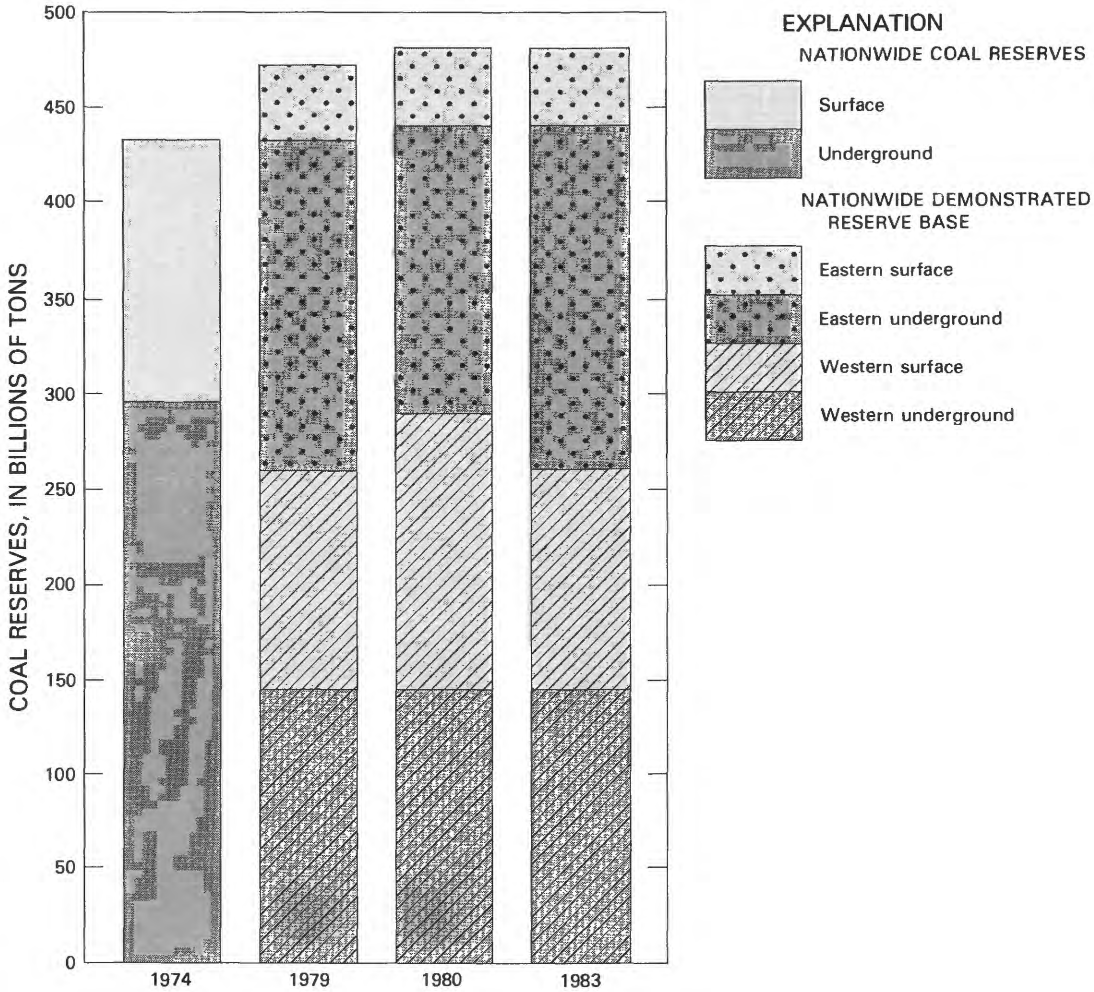


FIGURE 5.—Coal reserves (1974) and demonstrated reserve base (1979, 1980, and 1983) (modified from Averitt, 1975; U.S. Energy Information Administration, 1984).

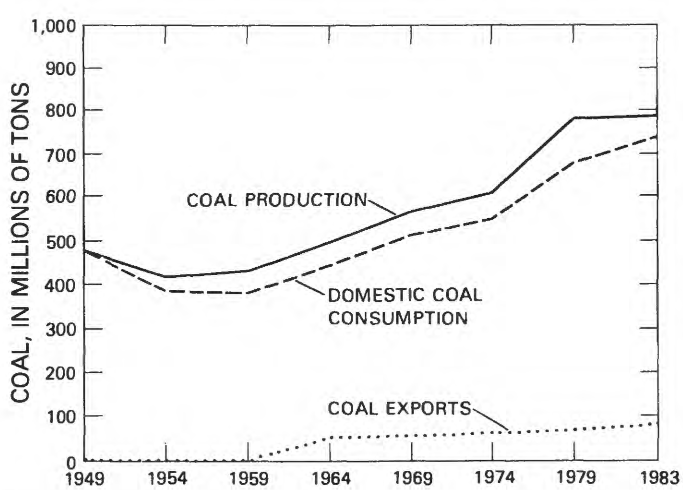


FIGURE 6.—Coal production, domestic coal consumption, and coal exports, 1949-83 (modified from U.S. Energy Information Administration, 1984).

WATER RESOURCES

By Hugh H. Hudson

A close relation exists between water and coal; it begins prior to coal mining and persists even after the land is reclaimed. Water may be pumped from the mine and used in the mining and coal-handling operations to cool condensers and to dispose of wastes. The effects of coal development on water resources vary as greatly as do the hydrologic and geologic conditions in the Nation's major coal regions. There are obvious physical differences in the coal-water relation between the humid eastern coal regions of the United States and the more arid western coal regions. There also are more subtle differences that result from the relative abundance or scarcity of water, the intensity of competition for its use, and the traditional uses of water in different parts of the Nation.

This part of the report is intended only to identify the major water-resource characteristics of the coal regions, to illustrate differences, and to provide a basis for comparing the coal-water relations between eastern and western coal regions.

The major rivers associated with the coal regions have helped determine locations of population centers and industrial developments and have shaped patterns of water use in those regions. The Eastern and Interior Provinces are drained by the Nation's largest rivers (pl. 1). The Eastern region of the Interior Province is bordered along its western edge by the Mississippi River, and the Ohio River flows across its southern tip, transporting water from the coal fields of the northern and central parts of the Appalachian region. The Tennessee River originates in and drains most of the southern part of the Appalachian region. The Missouri River flows across the north-central part of the Western region of the Interior Province; the Arkansas River flows across its southern part. The principal rivers of the Northern Great Plains and Rocky Mountain Provinces are the Colorado, Missouri, North Platte, and Yellowstone Rivers.

The large rivers in the Eastern and Interior Provinces and the many reservoirs that regulate the flow of these rivers provide routes for barge transportation and, with some exceptions, ample supplies of water for power generation and other uses. The population centers and industrial developments that require large volumes of water from dependable sources derive most of their supplies from the rivers and reservoirs. Thermoelectric and hydropower generation substantially uses the largest quantity of water; most of this water is supplied from surface-water sources.

In the Northern Great Plains and Rocky Mountain Provinces, irrigation is extensive in the valleys of the perennial streams, in the plains areas, and even in near-desert areas. Irrigation is supplied primarily by water from surface sources, and throughout the Western United States, streams and reservoirs supply most of this water. Agriculture, including irrigation, uses the largest quantity of water.

Some small streams in the Eastern and Interior Provinces are not dependable sources of supply. Typically, the small streams that occur in the coal fields drain thin soils that overlie dense, impermeable rocks and tend to cease flowing during dry spells. Runoff, especially from hilly or mountainous areas, is rapid, and little water remains in ground-water storage to sustain base flows. The base flows of many streams, especially those in the northern part of the Appalachian region, are sustained, in part, by seepage from mines that often is acidic and consequently problems may occur downstream and in hydraulically connected aquifers.

In the Northern Great Plains and Rocky Mountain Provinces, streams much larger than many perennial streams in the Eastern States are ephemeral. Those that head in the mountains transport large volumes of snowmelt during the spring and early summer; at other times of the year, low flows are maintained by springs and seeps from shallow ground-water storage. Those streams that originate at lower altitudes characteristically flow only during periods of snowmelt or summer thunderstorms. Evaporation and transpiration substantially diminish quantity of flow, especially in the drier Colorado River basin.

Regional dependence on surface water tends to obscure the critical local importance of ground water. Beyond the distribution limits of surface water, ground water supplies the needs of industry, communities, and farms and ranches. But in large areas, especially in the Eastern and Interior Provinces, the geologic conditions that curtail low streamflows also produce an inhospitable ground-water environment. Water may be obtained from bedrock at almost any location, but yields typically are small, and the water sometimes is very mineralized.

In parts of the Northern Great Plains and Rocky Mountain Provinces, saturated coal seams and associated sandstones are used as aquifers and provide adequate quantities of water to supply local needs. Elsewhere, alluvial aquifers or deeper sandstones are the principal sources of domestic and stock supplies.

There are, however, fortunate exceptions to otherwise meager opportunities for the development of ground-water supplies. Large wells developed in thick deposits of sand and gravel in the valleys of major streams and in buried ancestral valleys or in solution zones of carbonate rocks yield copious quantities of water; the occurrence of such aquifers is not common, however, and is of limited regional importance.

Even a cursory description of the water resources of hydrologically diverse coal regions is incomplete—possibly misleading—without acknowledging the institutional and legal constraints on water use. In the Eastern and Interior Provinces, streamflows are available to users in unquantified amounts under the riparian system of water allocation. However, in the Northern Great Plains and Rocky Mountain Provinces, the prior-appropriation doctrine applies; water use not only is quantified but also must be determined to be beneficial. Beneficial uses commonly are ranked by priority, and first priority usually is given to domestic and agricultural needs with an occasional bias against the use of water for energy development. At least two Western States have either banned or required legislative approval for the use of water to transport coal out of State via slurry pipeline.

Use of water in the Northern Great Plains and Rocky Mountain Provinces also is constrained by interstate compacts or by court adjudications that apportion the flow of rivers between States. The Colorado, North Platte, and Yellowstone, and several other western interstate streams are subject to such constraints. Apportionment of Colorado River water among the upper-basin States is by compact, but a separate compact between the States of the upper and lower basins and a treaty with Mexico also have to be satisfied.

The legal systems that control ground-water development and use in the Eastern and Interior Provinces vary from absolute ownership of water with the overlying land in one State to reasonable use of water with or without a permit in the other States. Western States contain large tracts of land administered by the U.S. Departments of Agriculture and the Interior or owned by native Americans. Proprietary, reserved water rights that are, as yet, unquantified are associated with both groups. Prior appropriation and permit is the universal system in the Northern Great Plains and Rocky Mountain Provinces.

HYDROLOGIC ISSUES RELATED TO COAL DEVELOPMENT

By Hugh H. Hudson

The major hydrologic issues associated with mining and use of coal generally may be categorized as mine drainage, water withdrawals, land disturbance and reclamation, and waste disposal. Each hydrologic issue is a product of local climatic, geologic, and hydrologic conditions, and rarely do all issues occur simultaneously.

Acid mine drainage is the most acute issue associated with coal mining in the northern part of the Appalachian region. In the Western United States, saline drainage is an issue, although much less severe and far more localized than acid mine drainage in the Eastern United States. In the central and southern parts of the Appalachian region, land disturbance and its attendant erosion and sedimentation is the major issue. Mine drainage and erosion result from mining in a humid environment, and the severity of each diminishes as precipitation lessens in a westward direction. The issue of water withdrawals is a function of the abundance or scarcity of water and of competition for its use. Withdrawals of water for coal-development purposes attract little attention in the Eastern United States where water is plentiful, but these withdrawals may become an intense issue having political, social, economic, legal, and institutional dimensions in the more arid Western United States. Land disturbance and reclamation and waste disposal may create hydrologic issues in any environment.

MINE DRAINAGE

Acid is produced when iron sulfides come in contact with water in the presence of oxygen. Acid formation is a natural geochemical process, but the process is greatly accelerated by mining operations. When acid forms where carbonate rocks are present, as in much of the southern part of the Appalachian region, or where alkaline soils are common, as in the Western United States, the acid becomes neutralized, and most of the process is controlled. Acid-neutralizing rocks are deficient in the northern part of the Appalachian region, and ample rainfall there not only provides a continuous supply of water for the chemical process but also furnishes the means of transporting the acid into streams and reservoirs.

The course of flow taken by the contaminated mine drainage is not always direct. Under suitable geologic conditions, nearby alluvial and bedrock aquifers also may become contaminated. Pollution of an aquifer may occur throughout a period of years; however, many more years would be needed for the aquifer to cleanse itself, even in the unlikely event that the source of pollution was eliminated.

When the acid- and iron-laden water reaches an unaffected stream, chemical and physical changes degrade the water. A rust-colored coating called "yellow boy" may form in the streambed (fig. 7), and trace elements such as manganese and zinc become solubilized. Acid mine water characteristically contains large concentrations of trace elements and sulfate, even after acid has been neutralized. For example, there are streams downstream from coal fields in Arkansas that have abnormally large concentrations of trace elements—an indication of acid mine drainage in the headwaters (Bryant and others, 1983).

Acid mine drainage can impair or destroy aquatic habitats and has adverse effects on water for industrial, municipal, and recreational uses. Costs of using or treating acid-contaminated water are great, and even after acid neutralization, dissolved-solids concentrations and hardness may limit its use for some purposes. Although recent years have seen some improvement, about 2,000 miles of streams in West Virginia were identified as being substantially affected by acid mine drainage during 1983 (U.S. Geological Survey, 1983a).

Not all the acid is attributed to drainage from mines; some of the acid is due to drainage from refuse piles. About half of mined coal is cleaned prior to use. Approximately 20 percent of the raw coal is rejected and consists primarily of iron sulfide compounds, rock, and coal particles. In the Pennsylvania Anthracite region, refuse piles in 10 counties were estimated to contain nearly a billion cubic yards of refuse (MacCartney and Whaite, 1969). Drainage from the refuse piles had pH measurements as acidic as 2.

Acid mine drainage is an issue where coal is mined, precipitation is ample, and calcareous rocks are absent. Fish kills have been reported in streams in Missouri downstream from holding pits that overflowed after heavy rains (Detroy, Skelton, and others, 1983). Final-cut lakes in Illinois were acidic and contained concentrations of trace elements such as aluminum, cobalt, copper, and lead at least one order of magnitude larger than nonacid lakes (Zuehls and others, 1981b).

Acid mine drainage is virtually unknown in the Northern Great Plains and Rocky Mountain Provinces. Coal in these provinces has fewer sulfide minerals, and the semiarid climate here results in there being less moving water to transport the acid, should it form. In addition, the natural alkalinity of water and soil in the Western United States neutralizes acid, should it form.

FIGURE 7.—Reddish-yellow precipitates, "yellow boy," in streams draining eastern coal-mine areas. *A*, Stream near Burgesstown, Pennsylvania; *B*, Tributary of Short Creek near Dillonvale, Ohio; note underground mine at top of photograph (from Roth, Engelke, and others, 1981).

There is, however, another type of drainage common to mines in the Western United States. Water that accumulates in and drains from mine spoils contains large sulfate concentrations. Thus far, the issue is localized, and when the sulfate-enriched water reaches a flowing stream, dilution occurs rapidly. The addition of salts to a river system, particularly the Colorado River system, aggravates the issue of delivering water of acceptable quality downstream. Water that drains or is pumped from surface or underground mines typically is more mineralized than nearby surface or ground water, but the volume of drained or pumped water and, hence, the issue thus far are relatively minor.

WATER WITHDRAWALS

Water withdrawals may be in the form of mine dewatering that provides a dry working face in the mine or may be a means of supplying water from a surface- or ground-water source for condenser cooling, slurry pipeline, or any of the water-dependent phases of coal use. Water withdrawals may produce hydrologic effects, depending on the quantity of withdrawal and on local hydrologic and geologic conditions.

Where dewatering of a mine occurs as gravity flow, the water level declines to the floor of the mine. The water-level decline is greatest in the immediate vicinity of the mine, and the effect of dewatering decreases rapidly with distance away from the mine. Where air shafts in the Appalachian region have been constructed without pregrouting, large volumes of ground water drain into the mine, and shallow wells within a mile of the shaft have failed within a few months. There are mines in the Appalachian region that routinely pump more than 1 million gallons of water per day (U.S. National Research Council, 1981a).

In the drier Western United States, mine dewatering presently (1985) is not a major issue, although short-term, local effects may be severe. However, large volumes of water flow into underground mines in Utah (coal area 56), and mine dewatering was the largest source of man-made discharge from coal-bearing aquifers during 1980 (Lines and others, 1984). The largest volumes of water usually flow from areas where the mines intercept faults or fractured rocks. Water draining from a bolt hole in an underground mine roof is shown in figure 8. Some mines require continuous dewatering, and others discharge water intermittently (Lines and others, 1984). The possibility of a longer term, more severe issue, also in Utah, exists where dewatering an underground mine may induce the flow of more mineralized water into a fresh-water aquifer, and continued pumping may degrade the quality of water in the receiving streams (Price and others, 1987). Wherever mine dewatering occurs, flows of springs that are sources of domestic, stock, and wildlife water may be affected.

FIGURE 8.—Water draining from a bolt hole in the sandstone roof of an underground mine in Utah (from Lines and others, 1984).

Water may be withdrawn to supply any of several needs of the coal-energy industry. Estimates of the volume of water needed vary greatly and depend on the planned use and the conversion technologies envisioned by the investigator. Without exception, however, water used for condenser cooling accounts for the largest volume needed and, nationwide, is exceeded only by water used for irrigated agriculture. However, there are enormous regional differences. During 1983 in West Virginia, water for power generation accounted for 82 percent of the total water used, but in Wyoming, irrigated agriculture accounted for 93 percent of the total water used (U.S. Geological Survey, 1983a).

Water may be used for dust control, sanitary purposes, supplemental irrigation to revegetate mined lands, and transportation of coal as slurry. Volumes of water estimated for several of the uses are quite site dependent, and the estimates vary greatly.

Transportation of coal as slurry is advocated as being less expensive than transportation by rail. However, slurry is water-intensive, requiring about a ton of water to transport each ton of coal. Coal-slurry pipelines have been proposed to transport coal from western Virginia to eastern Virginia (Hollis, 1982) and from West Virginia and Illinois to powerplants in the Southeast (Yucel, 1982). No difficulty in obtaining or disposing of water is anticipated, but political pressures at National and State levels have curtailed development.

In the arid Western United States, however, the export of water merely to transport coal is considered questionable. Several coal-slurry pipelines have been proposed to transport coal out of the Western States, and reactions of State governments have ranged from legislative bans on such uses to reciprocity requirements. The most publicized proposal was one that would have transported coal from northeastern Wyoming to plants in the mid-South. The Madison aquifer in the Mississippian Madison Limestone first was selected as the source of water, then Oahe Reservoir on the Missouri River in South Dakota was selected. However, the political issue of water exportation remained, and the proposal was cancelled.

LAND DISTURBANCE AND RECLAMATION

Erosion and sedimentation, like acid mine drainage, are natural processes. In the central and southern parts of the Appalachian region, the processes have been accelerated by disturbing large tracts of steeply sloping land in a region characterized not only by large quantities of precipitation but also by frequent and severe flooding. In this region, erosion and sedimentation are the most adverse effects of mining on the local and regional water resources. Erosion and sedimentation also are considered to be severe issues in the Interior Province where surface mining is intensive and the quantity of precipitation is relatively large.

Extreme effects of erosion include excessive deposition of sediment in reservoirs (fig. 9*A*) and streams (fig. 9*B*, *C*) that increase the cost of maintaining navigation channels and of treating water for industrial and municipal use. Other adverse effects include the destruction of fish and wildlife habitats, increased flooding because of the decreased efficiency of stream channels and flood plains (fig. 9*C*), and a decrease in recreational use and aesthetic value of riparian lands.

West of the Appalachian region, the limited precipitation in coal-mining areas seems to minimize erosion. There are mine spoil piles in Montana, for example, where coal was mined more than 50 years ago that show little evidence of erosion.

A common consequence of surface-mine construction is the disruption of one or more aquifers (fig. 10). Where the base of the mine is above saturated rocks, there will be little or no effect on water levels, but where excavation penetrates one or more water-yielding zones, there likely will be a decrease in production of wells and springs in the vicinity of the mine (fig. 11). Where multiple aquifers are intersected by mining, water of degraded quality from one aquifer may blend with and possibly degrade the quality of water in another aquifer. Water probably will return to approximately premining levels after mining ceases, but dissolved-solids and trace-element concentrations may be increased.

When surface mining has been completed, Federal surface-mining regulations require that the land be restored to its approximate original contours. Throughout mining and reclamation, the emphasis is on protection of the hydrologic system and especially of the water quality. In practice, however, reclamation is limited to controlling the geochemistry and hydraulic properties of the fill material. Consequently, there will be reclaimed mines where the natural processes of infiltration, lateral inflow, and leaching will produce impaired quality water, even though the reclamation requirements have been fully met.

Where precipitation is adequate, soluble salts and other objectionable elements and compounds will be diluted and leached below the soil and root zone. Where precipitation is deficient, however, such as in some areas of the Western United States, exchangeable salts and sulfur may occur in delicate balance, moving upward into the soil during certain conditions or downward into the ground-water system during other conditions. If movement is upward, productivity of the soil may suffer, and if downward, ground-water quality may deteriorate.

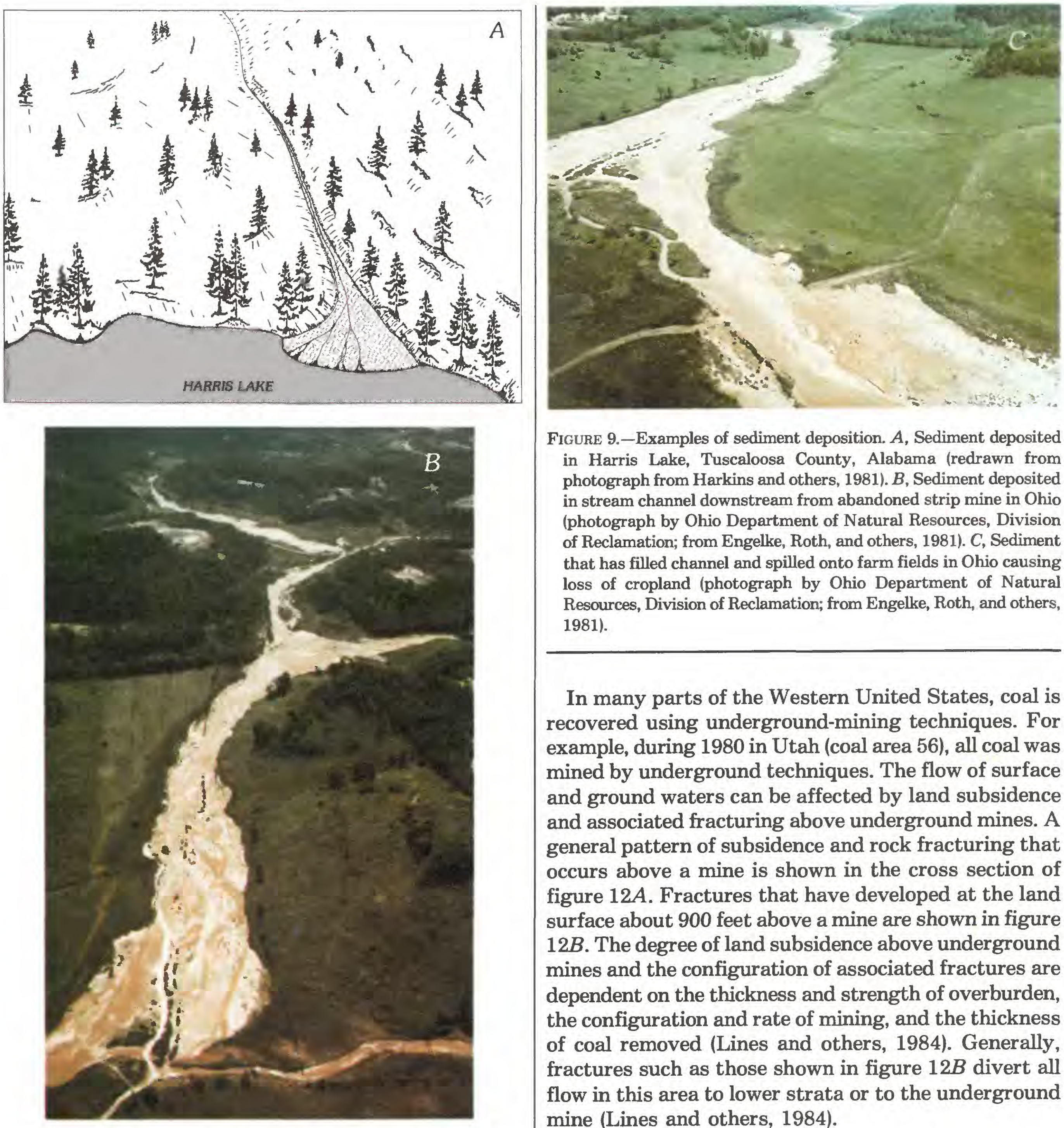


FIGURE 9.—Examples of sediment deposition. *A*, Sediment deposited in Harris Lake, Tuscaloosa County, Alabama (redrawn from photograph from Harkins and others, 1981). *B*, Sediment deposited in stream channel downstream from abandoned strip mine in Ohio (photograph by Ohio Department of Natural Resources, Division of Reclamation; from Engelke, Roth, and others, 1981). *C*, Sediment that has filled channel and spilled onto farm fields in Ohio causing loss of cropland (photograph by Ohio Department of Natural Resources, Division of Reclamation; from Engelke, Roth, and others, 1981).

Determinations, thus far, indicate that where coal is removed from below the water table and is replaced by mine spoil, the hydraulic properties of the new aquifer usually are as good or better than those of the original material. Water levels usually recover, and the values of porosity and transmissivity usually increase greatly. Quality of the water is quite variable but generally deteriorates moderately to substantially.

In many parts of the Western United States, coal is recovered using underground-mining techniques. For example, during 1980 in Utah (coal area 56), all coal was mined by underground techniques. The flow of surface and ground waters can be affected by land subsidence and associated fracturing above underground mines. A general pattern of subsidence and rock fracturing that occurs above a mine is shown in the cross section of figure 12*A*. Fractures that have developed at the land surface about 900 feet above a mine are shown in figure 12*B*. The degree of land subsidence above underground mines and the configuration of associated fractures are dependent on the thickness and strength of overburden, the configuration and rate of mining, and the thickness of coal removed (Lines and others, 1984). Generally, fractures such as those shown in figure 12*B* divert all flow in this area to lower strata or to the underground mine (Lines and others, 1984).

WASTE DISPOSAL

Where evaporation rates permit, modern coal-fired thermoelectric powerplants are designed to operate cooling and water-handling systems as closed loops, and no effluent is allowed to reach streams. In other plants, sludges containing fly ash and flue-gas scrubber wastes

FIGURE 10.—Water in mine pit from dewatering of aquifer in Colorado (from Kuhn and others, 1983).

are piped to ponds, and the effluent, unless reclaimed, flows into streams. The effluent typically has large chemical oxygen demand, an alkaline pH, and large concentrations of trace elements. It also typically contains large concentrations of sulfates and may contain biocides that can be more damaging to the environment than the salts.

Disposal of fly ash and scrubber waste is a growing issue. During 1975, 58 million tons of fly ash were produced at powerplants, and this quantity is expected to increase to 134 million tons per year by 1995 (Argonne National Laboratory, 1982). Production of scrubber waste is increasing much more rapidly. Only 0.8 million tons required disposal during 1975, but 51 million tons are expected to be produced annually by 1995. A measure of the increased effect on water resources is indicated by the dissolved-solids loadings of streams receiving water from powerplants. During

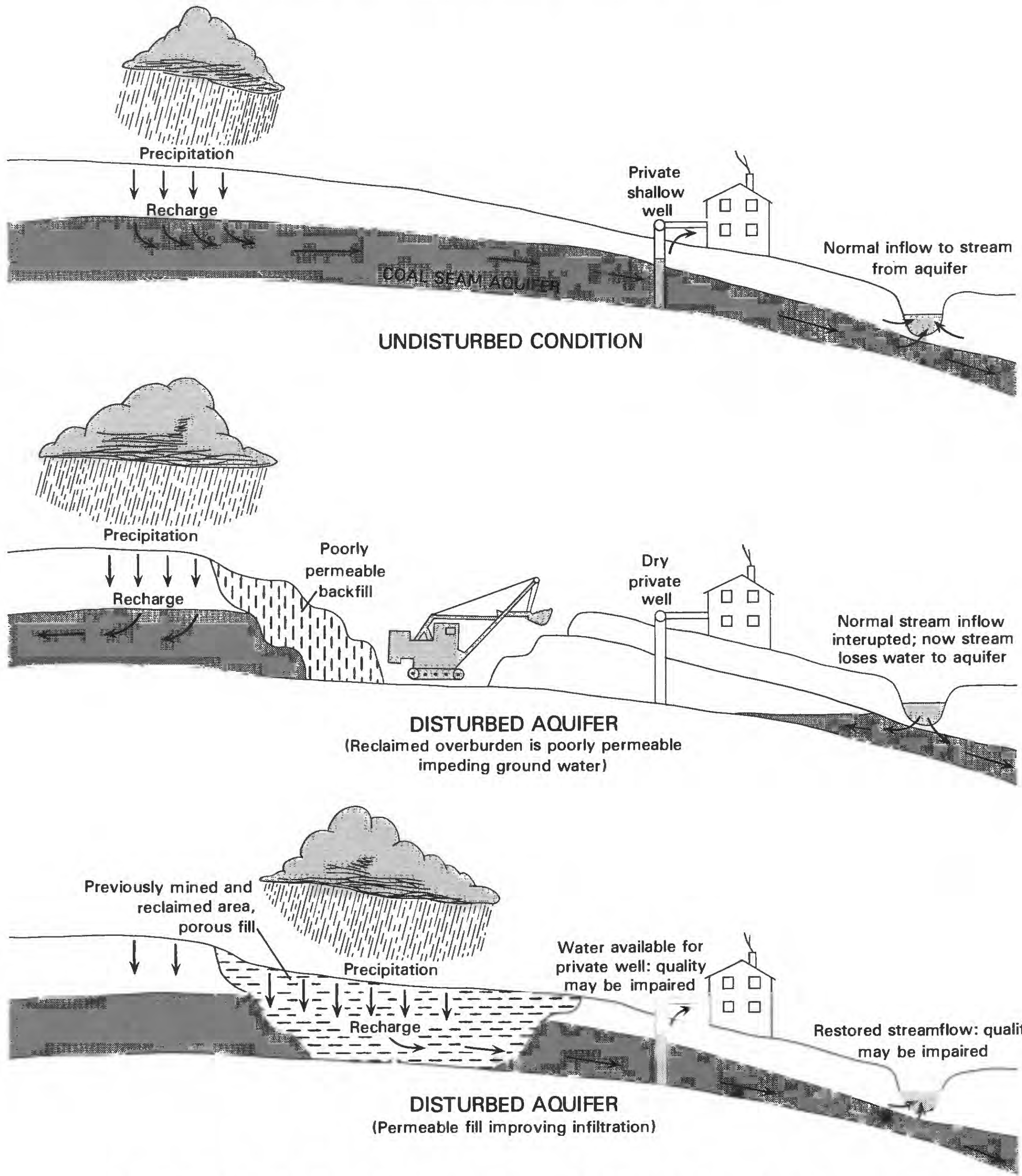


FIGURE 11.—Possible effects of mining aquifers (modified from Harkins and others, 1981).

1975, power generation produced nearly 6 million tons or nearly 2 percent of the dissolved solids that occur in the Nation's rivers. This is expected to increase to 10 million tons per year by 1990 (Argonne National Laboratory, 1982).

Little is known about the long-term hydrologic effects of burying powerplant wastes in surface-mine pits, yet the practice of including fly ash and scrubber waste with spoils is increasing as mine-mouth powerplants become more prevalent, particularly in the Western United States. If hydrogeologic conditions are favorable for containment, the potential contaminants will remain isolated. However, if conditions are not favorable, leaching may occur and contaminants may reach the ground-water system, wells, springs, and streams after years, or even centuries, have elapsed.

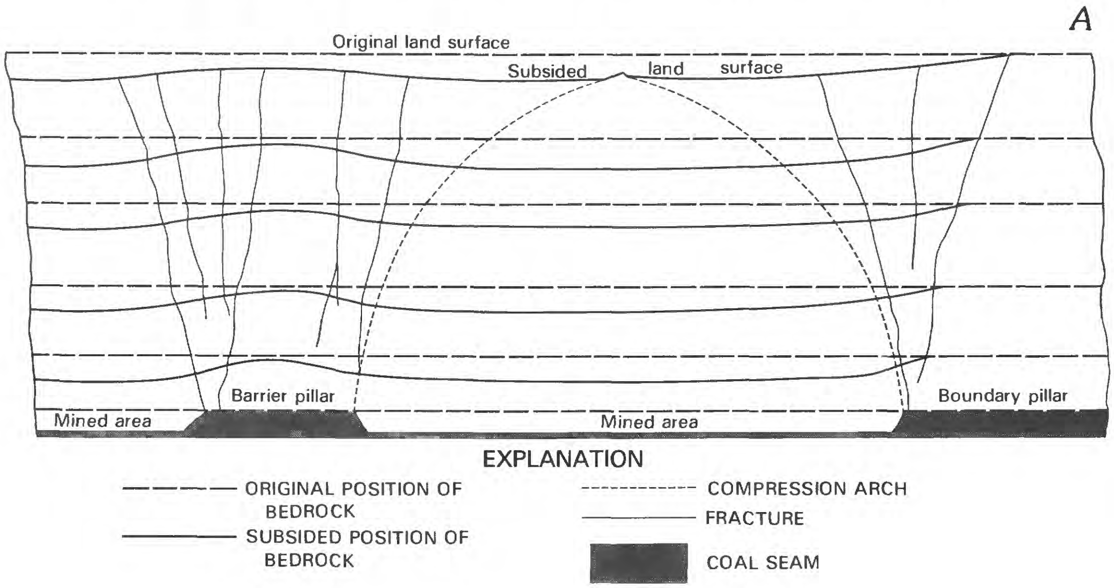


FIGURE 12.—Effects of underground coal mining on land subsidence. *A*, Generalized cross section showing subsidence and fracturing that occurs above an underground coal mine (modified from Lines and others, 1984). *B*, Fractures resulting from subsidence at the surface above a barrier pillar in an underground mine in Utah (from Lines and others, 1984).

FEDERAL ROLE IN COAL AND WATER ISSUES[2]

By HUGH H. HUDSON

Water issues that are concurrent with coal development involve the statutory functions and responsibilities of several Federal agencies. Laws, regulations, and policies concerned with natural resources, public-lands management, energy, mining operations, and the environment are shared by the U.S. Departments of Agriculture, Energy, and the Interior and by the U.S. Environmental Protection Agency.

The U.S. Department of Agriculture's interests in coal and water issues are contained largely in programs of the U.S. Forest Service, which manages lands containing economically attractive coal deposits, and of the U.S. Agricultural Research Service. The U.S. Science and Education Administration was established during 1978 to include the U.S. Agricultural Research Service and its studies of soils and water. The agency name was changed back to Agricultural Research Service in 1980. The U.S. Department of Energy was established during 1977 by consolidating major Federal energy functions previously managed by other departments, commissions, and agencies, including the Energy Research and Development Administration.

The U.S. Department of the Interior, with its traditional administration of or trust responsibilities for more than one-half billion acres of public and Indian-owned land and its role in the conservation and development of natural resources including fish and wildlife, has the most diverse interests in coal and water issues. Within the U.S. Department of the Interior, the major agencies involved in the coal-hydrology program during the 1970's were the U.S. Bureau of Land Management, the U.S. Bureau of Mines, the U.S. Fish and Wildlife Service, and the U.S. Geological Survey. In addition, the Office of Surface Mining Reclamation and Enforcement was established during 1977 as part of the U.S. Department of the Interior. The U.S. Environmental Protection Agency, within the context of coal and water issues, exercised Federal advocacy of energy technologies that minimized water-quality impairment. Brief descriptions of the functions of the Federal agencies that were involved most actively in the coal and water issues follow.

U.S. Department of Agriculture:

U.S. Agricultural Research Service does research activities in the use and improvement of soil and water under a varied range of geographic, climatic, and environmental conditions. The Agricultural Research Service's work includes studies of soils, vegetation, and water requirements relative to mined-land reclamation.

U.S. Forest Service manages 154 National forests and 19 National grasslands that comprise 188 million acres using the principles of multiple use and sustained yield, not only for timber but also for other resources associated with the lands. To ensure that the management and development of the coal and other mineral resources within the National forests and grasslands were accomplished within the framework of its traditional policy to protect and improve the quality of air, soil, water, and natural beauty, the Surface Environment and Mining program was established within the U.S. Forest Service. The Surface Environment and Mining program's initial emphasis was on coal areas in the Western United States and protection of the water resources of those areas.

U.S. Department of Energy:

U.S. Department of Energy continued and expanded the research, development, and demonstration of energy technologies that were administered largely by the Energy Research and Development Administration prior to 1977 and in which the national laboratories such as those at Oak Ridge, Tennessee, Los Alamos, New Mexico, and Argonne, Illinois, continue to be actively involved. The U.S. Department of Energy's function includes the sponsorship of major regional assessments of the water requirements of non-nuclear energy development.

U.S. Department of the Interior:

U.S. Bureau of Land Management is responsible for the total management of 417 million acres of public land located primarily in the Western United States and the subsurface management of 169 million acres throughout the Nation where mineral rights have been reserved by the Federal Government. Resources managed by the U.S. Bureau of Land Management include not only the coal beneath the surface but also the wildlife, rangeland soils and vegetation, water, and other natural resources. Its programs provide for the orderly development and use of resources while maintaining and enhancing the quality of the environment. In order to focus its efforts on those responsibilities associated with coal, the U.S. Bureau of Land Management began an Energy Minerals Rehabilitation, Inventory, and Analysis (EMRIA) program, which guided and supported hydrologic-data collection and analysis and water-resources studies and research in the hydrology of coal development.

U.S. Bureau of Mines for many years has been developing technologies for coal extraction at reasonable cost

[2]Much of the following material describing the statutory functions of the U.S. Departments of Agriculture, Energy, and the Interior and the U.S. Environmental Protection Agency was abstracted from the Office of the Federal Register, National Archives and Records Service (1982).

and without harm to the environment. The U.S. Bureau of Mines has a responsibility to abate pollution and land damage caused by minerals extraction and processing operations and consequently has helped administer environmental reclamation programs such as the Appalachian Regional Development Act, which is intensely involved in remedying mine-drainage issues. The U.S. Bureau of Mines also has supported assessments of the effects of surface mining on shallow ground-water systems in coal areas of the Western United States.

U.S. Fish and Wildlife Service includes among its major responsibilities the protection and improvement of fish and wildlife habitats and the assessment of the environmental effects of energy development on living natural resources. Faced with the possibility that water withdrawals for energy development in the Western United States may seriously deplete the flows of streams, the U.S. Fish and Wildlife Service undertook studies to determine the flow requirements of western streams considered minimal to sustain fish habitats.

U.S. Geological Survey does surveys, investigations, and research in geology and mineral and water resources and publishes the results of those activities. The U.S. Geological Survey provides basic information about the character, magnitude, location, and distribution of mineral resources, including coal, and about the occurrence, distribution, and quality of the Nation's water resources. The U.S. Geological Survey conducted the hydrologic-data collection, areal and site water-resource studies, and hydrologic research to acquire the hydrologic information associated with coal development. This water-resources information is needed by other agencies, particularly the U.S. Bureau of Land Management and the Office of Surface Mining Reclamation and Enforcement, to support coal planning, management, and development activities.

Office of Surface Mining Reclamation and Enforcement was established by the Surface Mining Control and Reclamation Act of 1977 to protect society and the environment from the adverse effects of mining operations. The agency promulgated mining and land-reclamation standards and, in collaboration with State Governments, administers a mining-permit system designed to minimize the adverse effects of mining on the hydrologic environment.

U.S. Environmental Protection Agency:

U.S. Environmental Protection Agency uses its headquarters staff, national laboratories, and regional offices in the continuing effort to control and abate water pollution as coal usage increases. The U.S. Environmental Protection Agency's programs include numerous studies of water requirements and wastes generated by coal-conversion processes.

HISTORY OF THE COAL–HYDROLOGY PROGRAM[3]

By HUGH H. HUDSON and BRUCE P. VAN HAVEREN[4]

ISSUES

The Arab oil embargo focused national attention on coal from the Western United States as a source of energy that is not affected by the unreliable aspects of imported oil. Coal from the Western United States contains less sulfur than coal from the Eastern United States and occurs largely in thick deposits near the surface and, therefore, is easily mined. Most of the coal is federally owned, is managed by the U.S. Bureau of Land Management, and normally is available to be leased and developed under the provisions of the Mineral Leasing Act of 1920.

Plans to increase use of coal from the Western United States were developed at a time of intense and active public interest in the environment, and these plans coincided with or closely followed the enactment of Federal legislation designed to protect and restore environmental quality. The National Environmental Policy Act that became law during 1969 required an environmental analysis of all Federal activities "***significantly affecting the quality of the human environment***." The Clean Air and Clean Water Acts included a requirement that Federal resource management agencies be more cognizant of their activities that affect water quality.

During 1970, the U.S. Bureau of Land Management determined that since 1955 the tonnage of coal under lease had increased substantially, while the tonnage of coal produced from Federal leases had declined. A moratorium was imposed on the issuance of new leases and was continued until 1979. Lease sales resumed, temporarily, during 1981.

During the time the moratorium was in effect, environmental groups sued the U.S. Department of the Interior because the Department lacked a comprehensive, regional environmental impact statement for coal development in the Northern Great Plains Province. Also, during the moratorium, the U.S. Bureau of Land Management designed a new coal-leasing procedure, the Energy Minerals Activity Recommendation System. The Energy Minerals Activity Recommendation System received opposition from western governors and from environmental and agricultural groups. In 1977, the environmental impact statement for the Energy Minerals Activity Recommendation System was judged to be inadequate by a Federal district court, and the U.S. Bureau of Land Management was enjoined from implementing the coal-leasing procedure until the National Environmental Policy Act requirements were met.

Plans for larger scale development of coal from the Western United States included hypothetical plants in the West and elsewhere to convert the coal to other forms of energy. By 1975, several plans had been prepared that included thermoelectric powerplants, synthetic fuels plants, and coal-slurry transportation systems that had an eventual requirement of millions of acre-feet of water per year. The use of such large quantities of water for energy production in a dry region raised questions about the physical, legal, and institutional availability of the water and about the effects of such large withdrawals on water resources in the Western United States.

The prominent visibility of the environmental, legal, and judicial issues led to Congressional intervention and passage of the Federal Coal Leasing Amendment and the Federal Land Policy and Management Act in 1976. The amendment required lessee compliance with the Clean Air and Clean Water Acts, and the Federal Land Policy and Management Act required that the U.S. Bureau of Land Management give top priority to the designation and protection of areas of critical environmental concern in its overall land-use planning.

The legal and hydrologic issues that surrounded the coal-hydrology program initially were of concern only to the Western States, but with passage of the Surface Mining Control and Reclamation Act during 1977, the issues and the program became of National concern. This Act and its operating regulations were written to protect the hydrologic environment and required detailed mining and reclamation plans from companies planning to open mines and established performance standards to ensure minimal damage from surface-mining operations. Adherence to the Act required certain types of hydrologic information that generally were not available. A requirement of the Surface Mining Control and Reclamation Act, for example, was that the hydrologic functions of surface-mined areas be restored, which implied knowledge of their functions prior to mining. The Act also prohibited mining in flood plains, alluvial valley floors, and other hydrologically sensitive areas unless it could be shown that mining would not cause irreparable damage.

Policy changes were made by the U.S. Department of the Interior during 1982 and 1983 to streamline the leasing program and to make more coal available for

[3]Much of the foregoing discussion of legal, judicial, and administrative issues was condensed from U.S. Congress (1984).

[4]U.S. Bureau of Land Management.

leasing. The changes were controversial and prompted Congress to mandate during 1983 the establishment of an Advisory Commission on Fair Market Value for Federal coal leasing. The Commission's report was delivered in February 1984. The U.S. Bureau of Land Management began preparation and has since (1987) completed a supplemental coal environmental impact statement. Most coal leasing was suspended during this time, but in January 1986, the Secretary of the Interior again permitted coal leasing in most of the coal regions.

PROGRAM OBJECTIVES AND INFORMATION NEEDS

In 1974, the U.S. Bureau of Land Management established the Energy Minerals Rehabilitation Inventory and Analysis (EMRIA) program to systematically obtain the technical information needed for the several preleasing activities required by law, court decisions, and administration policies. Not having the in-house capability to do the specialized multidisciplinary studies that were envisioned as being needed, the U.S. Bureau of Land Management requested assistance from the U.S. Geological Survey. Water-resources investigations were underway or had been done for many years by the U.S. Geological Survey, primarily for other Federal and State water-development and management agencies near the coal-lease sites. However, funds were not allocated in the U.S. Geological Survey budget for coal-related studies, and its personnel were committed to other projects. The U.S. Bureau of Land Management agreed to transfer funds and personnel positions to the U.S. Geological Survey. Assistance by the U.S. Geological Survey to the U.S. Bureau of Land Management began in 1974. The transfer of personnel positions was completed by adjusting the personnel ceilings assigned to each Bureau rather than by the actual reassignment of people. A year later, Congress provided authorization and funds to the U.S. Geological Survey to investigate the water-resource aspects of coal development in the Western United States, without regard to specific lease or mine sites or coal ownership. In 1976, the U.S. Geological Survey was funded to determine the regional effects of large volumes of local pumping from the Madison aquifer in the Northern Great Plains. Water from this aquifer was to be used for coal-slurry pipeline. With passage of the Surface Mining Control and Reclamation Act in 1977, the U.S. Geological Survey was requested by Congress to expand the coal-hydrology studies that had begun 2 years earlier in the Western United States to other coal provinces nationwide.

The information needs of the U.S. Bureau of Land Management and the U.S. Geological Survey were similar, although the ultimate objectives of each agency differed somewhat in scope and application. In a sense, the scope of the U.S. Bureau of Land Management responsiblities, and hence program objectives, ranged in size from large coal regions to the smaller specific tracts and sites and were applicable where the coal was federally owned. The scope of the U.S. Geological Survey's program objectives generally was regional or topical, unconstrained by coal ownership, and included developing an understanding of the principles and processes involved in coal hydrology.

Information was needed to characterize the water resources of areas likely to be mined in order to support general planning and to prepare environmental impact statements and, later, the issuance of permits for mining. During the early 1970's, little was known about the occurrence and quality of ground water associated with coal, particularly the shallow aquifers that may be interrupted by surface mining. Specifically, information was needed about the availability and chemical suitability of water for possible supplemental irrigation of lands to be reclaimed in the Western United States or about deeper regional aquifers that may be used to provide water for other coal-development purposes. Except for the larger perennial streams that flow across or near the coal fields, virtually nothing was known about the natural flow patterns of the smaller streams that drain the coal areas nor about the chemical and sediment characteristics of those streams. In the past, there had been virtually no hydrologic studies of coal areas; consequently, ground-water and streamflow data collected from coal areas were meager or nonexistent.

The U.S. Bureau of Land Management objectives and corresponding hydrologic information needed for support of coal-leasing decisions have fluctuated as agency policies have changed because of court decisions, new legislation, and changes in administration during the 10 years of the coal-hydrology program. Four phases of objectives are identified here; the listing is somewhat arbitrary, but it illustrates the changing program emphasis at different times.

Period	Objectives
1974–77	To determine rehabilitation potential of mined lands.
1977–78	To describe the water resources of coal areas, including lease areas and potential mine sites, and to estimate the general coal and water relation.
1978–81	To determine the effects of coal mining on local water resources and to increase the capability to predict the hydrologic effects of coal development.
1981–84	To detail appraisals of the water resources of high-priority coal-leasing areas and

to develop and apply simulation models for predictive purposes.

The earliest needs for information were those that would assist in determining reclamation potential. During the early 1970's, data about infiltration, erodibility, sediment production, and precipitation-runoff relations were obtained at several study sites in coal regions of the Western United States. When it became apparent that effects of mining on water resources would overshadow reclamation as a coal-development issue, the focus of the studies was changed accordingly.

As the coal-hydrology program of the U.S. Geological Survey and U.S. Bureau of Land Management matured, it became increasingly evident that descriptions of steady-state coal and water relations, regardless of the detail provided, were inadequate. Planners, land managers, and water-resources administrators needed predictions, not only of quantitative changes in streamflows and ground-water levels that might result from mining but also of changes in water chemistry and sediment production and deposition. Digital models were being used to simulate ground-water flow and hydraulic-head changes, but the development of other models was largely in its infancy.

Advances in the other simulation models, especially those needed to predict water-quality changes depended, in turn, on improved understanding of the natural processes. For example, the geochemical processes operative in mine spoils and the microbial function in those processes were, at best, conjectural.

Even if all the surface-water and ground-water flow and quality simulation models were available for use, combining the individual model results might have been erroneous because of possible synergistic effects. Therefore, the ultimate need was for an integrated set of simulation models, each designed to identify and incorporate the hydrologic changes derived from the other models. Such an advanced set of integrated simulation models was envisioned as necessary to assess the overall hydrologic effects of extensive land-use changes that accompany surface mining.

The enactment of the Surface Mining Control and Reclamation Act resulted in information needs that were ahead of technological capabilities. Adherence to the Act's regulations required a determination of the cumulative hydrologic effects of multiple mines operating in a single hydrologic basin. The means necessary to do such analyses were unavailable or unreliable.

The information and means needed to meet the objectives of the coal-hydrology program ranged from basic data to complex simulation models. Technological means were needed to transform the hydrologic data into results usable by planners, land managers, mining companies, and natural resource agencies at all levels of government. Results of research in the hydrologic processes involved in coal mining, handling, and ultimate use also were needed.

IMPLEMENTATION

Several phases of the U.S. Geological Survey and U.S. Bureau of Land Management coal-hydrology program were implemented primarily in response to Federal legislation and major changes in funding and secondarily to internal technical and administrative decisions. The primary changes may be accounted for in chronological order; the secondary changes, only approximately in that order. For both, however, implementation of the program is best described in order of major external or internal decisions.

1974: Following Congressional approval and funding of the EMRIA program, the U.S. Bureau of Land Management requested the assistance of the U.S. Geological Survey in developing the hydrologic requirements of the new coal-hydrology program. Program objectives, however, were not certain at that time. Surface mining on the scale anticipated was new, and the tracts to be leased were not yet identified; however, environmental impact statements still would have to be prepared. Information about the general availability and quality of water associated with the coal was needed, as well as technical judgments about the probable hydrologic consequences of large-scale surface mining. Meeting those immediate needs and the more remote, and as yet undefined, objectives required hydrologic data that were scant in the coal regions. The coal-hydrology program, as initially begun, gave priority to the design, construction, and operation of hydrologic-data-collection sites.

The initially selected sites were operational within the second year of the coal-hydrology program in States in the Northern Great Plains and Rocky Mountain Provinces. Oklahoma and Alabama were included later as soon as funds and staff permitted.

The hydrologic data collected, which consisted of continuous and partial-record streamflows, levels from ground-water observation wells, and water-quality analyses, were intended to be short-term, mobile, and flexible. The data program that was begun was considered adequate for reconnaissance-level appraisal of rather large areas and for general hydrologic characterization of intermediate and large watersheds.

1975: Authorization and funding were provided to the U.S. Geological Survey by Congress for studies of water resources and coal development in the Western United States. Hydrologic-data-collection programs, which began with EMRIA funds, were supplemented, and research on the geochemical processes in coal and mine spoils was begun.

1976: The U.S. Environmental Protection Agency requested the assistance of the U.S. Geological Survey in monitoring surface- and ground-water quality at selected sites in coal areas in the Western United States. These sites further supplemented the coal-hydrology program.

Progress that had been made by the U.S. Bureau of Land Management in identifying areas where leasing was likely to occur caused a need for more detailed hydrologic studies of smaller areas of 10 to 50 square miles. A series of small-basin studies was begun, first in the Fort Union and Powder River regions, then in regions in several other States in the Rocky Mountain Province and in Oklahoma and Alabama. Each study was designed for completion in about 2 years.

Results were needed more quickly than the collection of standard time-dependent hydrologic data permitted. Techniques available included simulation models of ground-water flow systems, statistical methods to extend data application in time and space, and empirical techniques such as the estimation of surface-water characteristics from measurements of channel geometry. Deficiencies in the availability or reliability of other types of simulation models, however, impeded the program.

1977: The Surface Mining Control and Reclamation Act was enacted as Public Law 95-87. The Act initiated a coal-mine permit process that was based, in part, on a required description of the hydrology of the mining area, an analysis of the probable hydrologic consequences of the proposed mining operation, and an analysis, by the State or Federal coal-mining regulatory agency, of the cumulative effects of the overall mining operation in the area. As a result of the Act and the persistent need for hydrologic data in coal-mining areas nationwide and for advanced hydrologic techniques, funding to the U.S. Geological Survey was increased and coal-hydrology studies were expanded to other areas of the country.

Deficiencies in hydrologic data in the Eastern and Interior Provinces now were more severe with the passage of the Surface Mining Control and Reclamation Act than in the Northern Great Plains and Rocky Mountain Provinces where data collection began as much as 3 years earlier. There also was a much greater demand on the regulatory agencies because of the greater coal production and number of mines in the Eastern than in the Western United States.

The design of the hydrologic-data-collection program that was implemented in the Eastern United States in 1977 was based primarily on the large number of operating and anticipated mines, the extensive water-quality issues, and prevalent geohydrologic conditions that enabled obtaining flow measurements and samples at thousands of locations during low-flow periods. The data obtained using this program afforded a quick, synoptic view of the hydrologic conditions of a broad area without the time-consuming operation and expense of large numbers of permanent data-collection sites.

As hydrologic data were collected and progress made in reconnaissance investigations and small-area and synoptic studies, the shortcomings of established interpretive techniques became more acute. Little was known, for example, about the complex combination of hydrologic changes that may result from the extensive land-use changes associated with surface mining. A research project established to assess this particular problem already was operational in the U.S. Geological Survey, but the project had limited staff, funds, and opportunities for onsite testing under a variety of natural conditions. During 1977 and the years immediately following, the research project was expanded using EMRIA funds. Small basins in coal fields of the Western United States, Oklahoma, and Alabama were selected, instrumented, and operated by onsite personnel in close coordination with the U.S. Geological Survey research group, thus incorporating a needed and practical small-basin-modeling function in the EMRIA program.

1980: The Office of Surface Mining Reclamation and Enforcement provided funds to the U.S. Geological Survey for assistance in the mine-permitting procedure and for helping to develop methods to determine cumulative hydrologic effects from coal mining.

1981: The small-basin-modeling research project that had been reinforced with EMRIA funds in 1977 again was extended by the U.S. Geological Survey to basins in the Appalachian region and Interior Province. During 1981, 19 additional basins were instrumented and, by 1984, land-use-change models were being developed at about 40 sites representing a large variety of climatic, topographic, hydrologic, and geologic conditions (Kilpatrick, 1984).

1981-84: A decrease in funds available to the coal-hydrology program began in 1981 and has continued. The U.S. Environmental Protection Agency funds were withdrawn in 1981, and substantial decreases were made in funds appropriated to the U.S. Geological Survey beginning in 1982. Hydrologic-data collection was curtailed severely during this period. The U.S. Bureau of Land Management restructured its function in the coal-hydrology program in order to apply the more limited resources to high-priority areas where leasing seemed imminent.

HYDROLOGIC STUDIES IN COAL REGIONS

By LINDA J. BRITTON

As a result of the data-collection program and investigations done as part of the U.S. Geological Survey and U.S. Bureau of Land Management National coal-hydrology program, as well as other Federal cooperative programs, more than 500 reports have been published that discuss and summarize hydrologic information related to coal-resource development. A bibliography of coal-hydrology reports authored by personnel of the U.S. Geological Survey or U.S. Bureau of Land Management is presented in Cochran and others (1983). In addition, the U.S. Geological Survey prepared a series of reports that generally characterized the hydrology of coal areas nationwide. These reports, termed "coal-area hydrology reports," have been prepared for most of the coal areas shown on plate 1. No reports were done for coal areas 26, 36, 37, 44, and 55; therefore, these areas are not discussed in the regional sections that follow. The basic objectives were to: (1) Summarize existing knowledge of the water resources; (2) identify potential hydrologic issues; and (3) document further needs for data collection. These coal areas were delineated on the basis of hydrologic-basin boundaries within the major coal-production regions. The status of these coal-area hydrology reports is shown in table 1.

The regional discussions in the following sections of this report provide brief summaries of the individual coal-area hydrology reports, as well as the hundreds of other reports resulting from the coal-hydrology program. These summaries emphasize results of data-collection activities and studies made within the regions and specific hydrologic issues associated with coal mining within the regions. Some western regions are grouped together and some regions often include areas beyond the boundaries of any defined coal area.

TABLE 1.—*Status of U.S. Geological Survey coal-area hydrology reports*

Coal area number (shown on pl. 1)	Author(s) and publication date	Water-Resources Investigations Open-File Report number
1	Herb and others (1983a)	82–223
2	Herb and others (1983b)	82–647
3	Herb and others (1981a)	81–537
4	Roth, Engelke, and others (1981)	81–343
5	Herb and others (1981b)	81–538
6	Staubitz and Sobashinski (1983)	83–33
7	Engelke, Roth, and others (1981)	81–815
8	Friel and others (1987)	84–463
9	Ehlke and others (1982b)	81–803
10	Ehlke and others (1983)	82–864
11	Roth and Cooper (1985)	84–233
12	Ehlke and others (1982a)	81–902
13	Kiesler and others (1983)	82–505
14	Quinones and others (1981)	81–137
15	Leist and others (1982)	81–809
16	Hufschmidt and others (1981)	81–204
17	Gaydos and others (1982a)	81–1118
18	May and others (1981)	81–492
19	Gaydos and others (1982b)	81–901
20	Hollyday and others (1983)	82–440
21	May and others (1983)	82–679
22	Harkins and others (1981)	81–135
23	Harkins and others (1980)	80–683
24	Harkins and others (1982)	81–1113
25	Zuehls and others (1981a)	81–636
26	No report planned	
27	Zuehls (1987a)	84–707
28	Zuehls and others (1984)	83–544
29	Fitzgerald and others (1984)	82–858
30	Wangsness and others (1983)	82–1005
31	Zuehls (1987b)	85–342
32	Wangsness and others (1981b)	81–498
33	Wangsness and others (1981a)	81–423
34	Quinones and others (1983)	82–638
35	Zuehls and others (1981b)	81–403
36	No report planned	
37	No report planned	
38	Detroy, Skelton, and others (1983)	82–1014
39	Bevans and others (1984)	83–851
40	Marcher, Kenny, and others (1984)	83–266
41	Marcher and others (1987)	84–129
42	Bryant and others (1983)	82–636
43	Lambing and others (1987)	85–88
44	No report planned	
45	Slagle and others (1984)	83–527
46	Croft and Crosby (1987)	84–467
47	Crosby and Klausing (1984)	83–221
48	Slagle and others (1986)	84–141
49	Slagle and others (1983)	82–682
50	Lowry, Wilson, and others (1986)	83–545
51	Peterson and others (1987)	84–734
52	Lowham and others (1985)	83–761
53	Driver and others (1984)	83–765
54	Kuhn and others (1983)	83–146
55	No report planned	
56	Lines and others (1984)	83–38
57	Price and others (1987)	84–68
58	Chaney and others (1987)	85–479
59	Gaggiani and others (1987)	85–153
60	Roybal and others (1983)	83–203
61	Abbott and others (1983)	83–132
62	Roybal and others (1984)	83–698

An attempt has been made to standardize the format and content of the following regional summaries. Similar types of data were not uniformly available for every region because the emphasis on hydrologic-data-collection activities and objectives of studies varied depending on prevalent hydrologic issues in each region. However, the format of the regional summaries is uniform and is organized as follows: (1) Introduction, which includes a discussion of general features, geology, and land and water use; (2) coal resources; (3) hydrology, which is divided into surface-water and ground-water components; (4) coal-hydrology studies; and (5) hydrologic issues. The introduction is self-explanatory, but the hydrology sections require an understanding of various hydrologic principles and relations that are used to describe surface- and ground-water characteristics. The following discussions in this section of the report briefly define some of the principles and relations used to describe the hydrology of the coal regions.

HYDROLOGIC CHARACTERISTICS

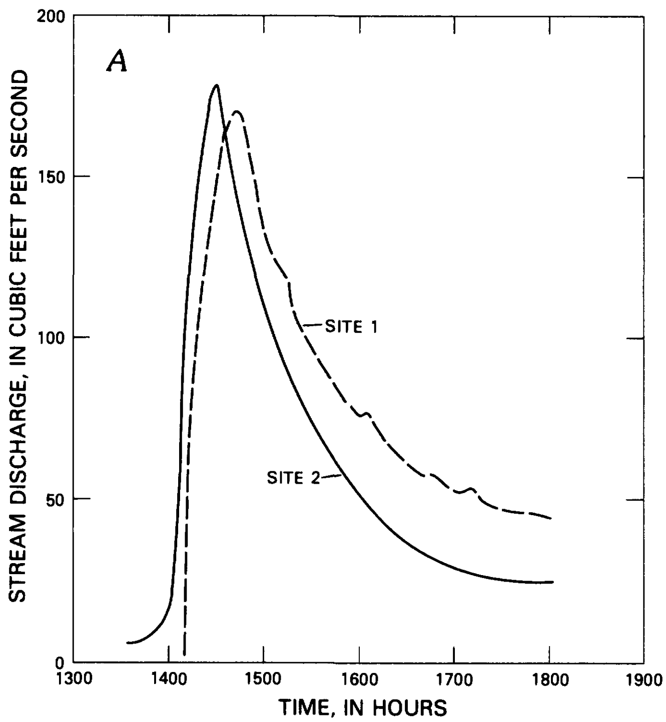
Surface-water quantity (discharge, flow, or streamflow) varies from stream to stream because of variations in altitude, precipitation, vegetation, temperature, drainage basin size, and consumptive use by man. As a result, stream discharge varies seasonally in a pattern similar to seasonal variations in precipitation and snowmelt. The hydrograph of a stream is a graph that shows how the stage, stream discharge, velocity, or other properties of water flow vary with time. As such, the hydrograph indicates those characteristics of the drainage basin that affect runoff. A typical hydrograph produced by a concentrated storm event (fig. 13*A*) is a single-peaked, skewed distribution curve. Hydrographs with multiple peaks (fig. 13*B*) may indicate abrupt variation in rainfall or snowmelt-runoff intensity, a succession of storms, abnormal ground-water recessions, or other causes (Chow, 1964). Volumes have been written on the distribution of runoff and on hydrograph analysis. For example, multiple-peaked complex hydrographs can be separated into a number of single-peaked hydrographs so that the specific contributions of surface runoff, interflow, and ground-water flow to the total runoff can be determined (Chow, 1964). However, the hydrographs presented in the regional summaries that follow are shown only to indicate representative flow patterns for streams in the region.

Flow-duration curves, or cumulative-frequency curves, are another technique used to graphically present stream-discharge data. The curves show the percentage of time a specified stream discharge is equaled or exceeded. The shape of the curve gives an indication of the characteristics of the drainage basin. If the curve has an overall steep slope, the drainage basin has a large quantity of direct runoff and greater variability of stream discharge than does a drainage basin represented by a flat curve. If the curve is fairly flat, there is substantial storage, either on the surface or as ground water, which tends to equalize the discharge. In some instances, different parts of the curve indicate various flow characteristics. For example, the lower two-thirds of the curve for site A (fig. 14) is rather steep, indicating the small recharge and (or) storage qualities of the ground-water system of that region, which results in small yields during dry periods (May and others, 1981). The curves for sites B and C (fig. 14) have flatter slopes on the lower end, indicating larger sustaining flows from the ground-water system. The upper ends of all three curves have essentially the same slope and positioning, indicating that the high-flow runoff per square mile from all three sites is nearly the same. Flow-duration curves can be considered to represent the distribution of stream discharge during the period of record, without regard to when a particular discharge occurred. These curves generally are plotted on log-normal probability paper with the flow on logarithmic scale and percentage of time on normal-probability scale.

The shape of a flow-duration curve may change with the period of record. The curves can be used to extend the discharge information on a given stream for which short-term records are available and for which simultaneous and long-term records are available on at least one adjacent stream that is believed to be affected by similar hydrologic conditions.

Stream-discharge data also can be used to estimate mean annual discharge at ungaged sites using predictive equations developed for different regions and to indicate primary sources of runoff. These relations have been developed for many areas included in the regional summaries.

Estimates of the magnitude and frequency of flood peaks and volumes also can be predicted from equations developed for many ungaged stream sites. Magnitudes of flood discharges are described in terms of recurrence intervals of 2, 5, 10, 25, 50, and 100 years. A 2-year flood is expected to be equaled or exceeded, on the average, once in 2 years (50 percent chance of occurring in any given year), and a 100-year flood once in 100 years (1 percent chance of occurring in any given year). However, changes in climatic patterns can increase or decrease the magnitude of a designated recurrence. Information about high-flow and flood-flow characteristics of a stream is useful in the design of dams, bridges and culverts, reservoirs, and flood-control and navigation channels.



Low-flow frequency information can be used to evaluate the ability of a stream to supply adequate water for various uses. A common statistic used is the 7-day, 10-year low flow, which is the stream-discharge value at the 10-year recurrence interval obtained from a frequency curve of annual values of the lowest mean discharge for 7 consecutive days. The probability is 1 chance in 10 that the 7-day low flow in any given year will be less than the 7-day, 10-year low flow. Even though the effects of regulation or diversion on flood flows may not be substantial, their effects on low flows may be very substantial.

Specific conductance is a measure of the ability of water to conduct an electric current. The standard units of measurement are microsiemens per centimeter at 25 °C. As ion concentrations (dissolved solids) increase, specific conductance of the water increases; therefore, specific-conductance measurements provide an indication of dissolved-solids concentrations. Because specific-conductance measurements can be measured directly onsite, they are less expensive to obtain than measurements of dissolved-solids concentrations, which must be obtained from laboratory analysis.

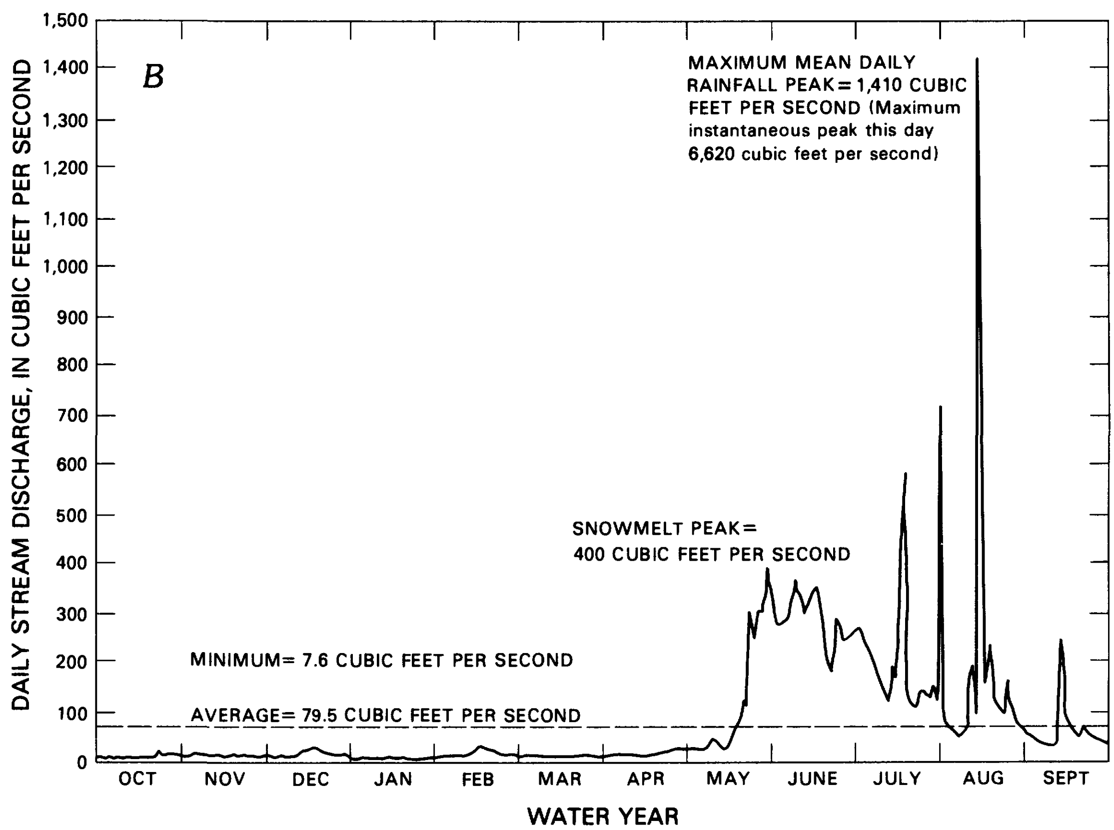


FIGURE 13.—Typical hydrographs showing *A*, single-peaked, skewed distribution from storm event at two sites (modified from Jarrett and Veenhuis, 1984); and *B*, multiple-peaked distribution from variations in storm events and snowmelt runoff (modified from Abbott and others, 1983).

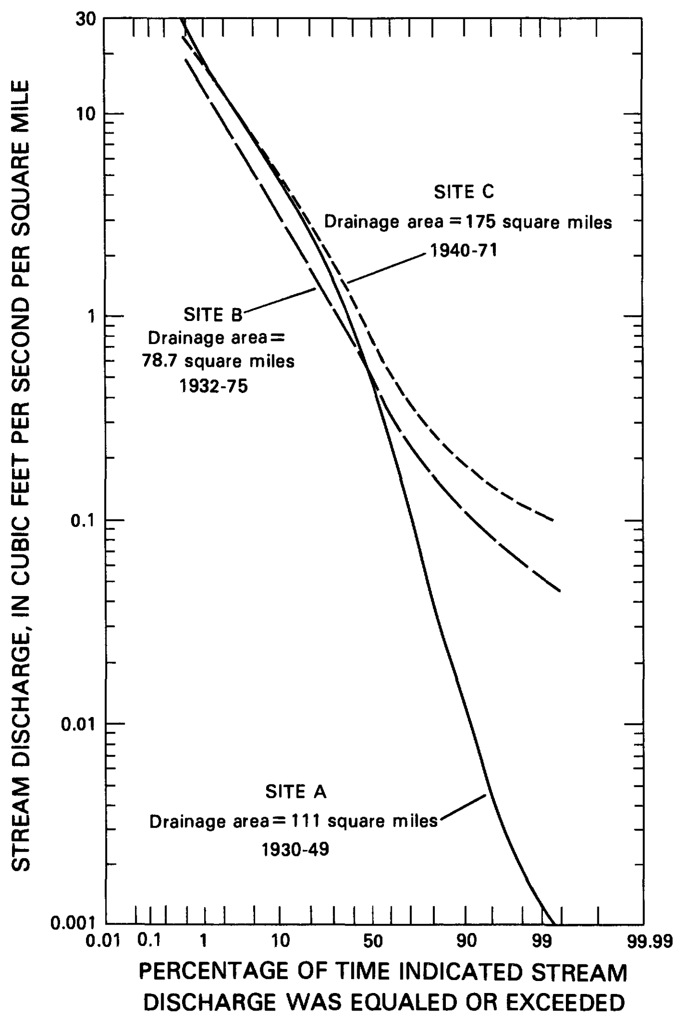


FIGURE 14.—Typical flow-duration curves (modified from May and others, 1981).

The relation between specific conductance and dissolved solids generally is simple and direct and can be expressed by an equation of the following form:

$$DS = A \times K_{sc},$$

where

DS = dissolved-solids concentration, in milligrams per liter;

A = a coefficient; and

K_{sc} = specific conductance, in microsiemens per centimeter at 25 °C.

According to Hem (1985), the coefficient A usually ranges from 0.55 to 0.75; the larger values generally are associated with waters containing large sulfate concentrations. For example, figure 15 shows the relation of dissolved-solids concentration to specific conductance from sites in coal area 25 of the Eastern region. An

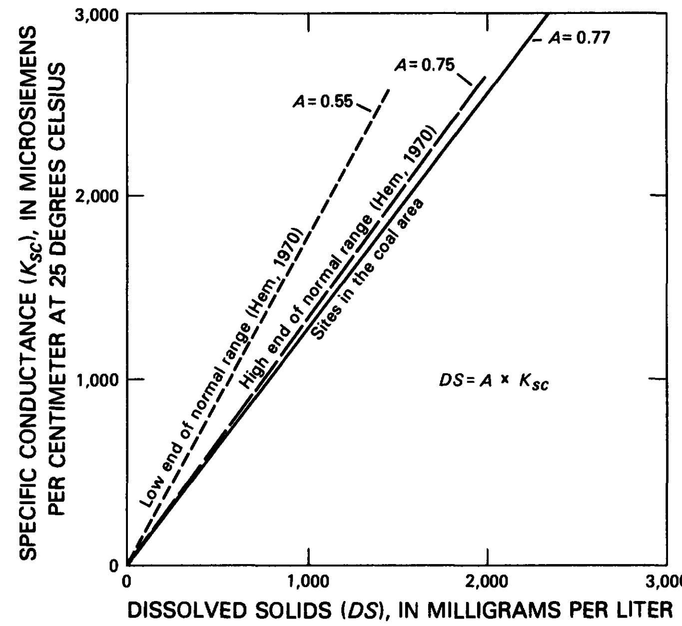


FIGURE 15.—Typical relations of dissolved-solids concentration to specific conductance (modified from Zuehls and others, 1981a).

equation of the form $DS = 0.77 \times K_{sc}$, was developed from 36 measurements. The large value of A is attributed to large sulfate concentrations (Zuehls and others, 1981a). Using data to develop relations of dissolved solids to specific conductance, the dissolved-solids concentrations can be calculated for sites discussed in the following regional summaries. In addition, at sites where a satisfactory relation has been developed, a continuous record of dissolved-solids concentration can be obtained by measuring specific conductance continuously.

The relation between stream discharge and specific conductance generally is inverse; as stream discharge increases, specific conductance decreases as a result of dilution. An example of relations of stream discharge to specific conductance is shown in figure 16. The positions and slopes of the lines are substantially affected by local bedrock geology (Abbott and others, 1983). The largest stream discharges shown in figure 16 generally occur as a result of direct runoff, causing the curves to slope down at large discharges. When direct runoff is not occurring, discharge may be maintained at base flow by ground-water inflows. Because ground water is in contact with geologic materials for a much longer period than is direct runoff, ground water generally has a larger specific conductance because of dissolution of rocks and minerals. The result is a larger specific conductance during base flow (Abbott and others, 1983). Furthermore, the specific conductance of base flow depends on the geologic formation or formations from which base flow is contributed, as shown in figure 16.

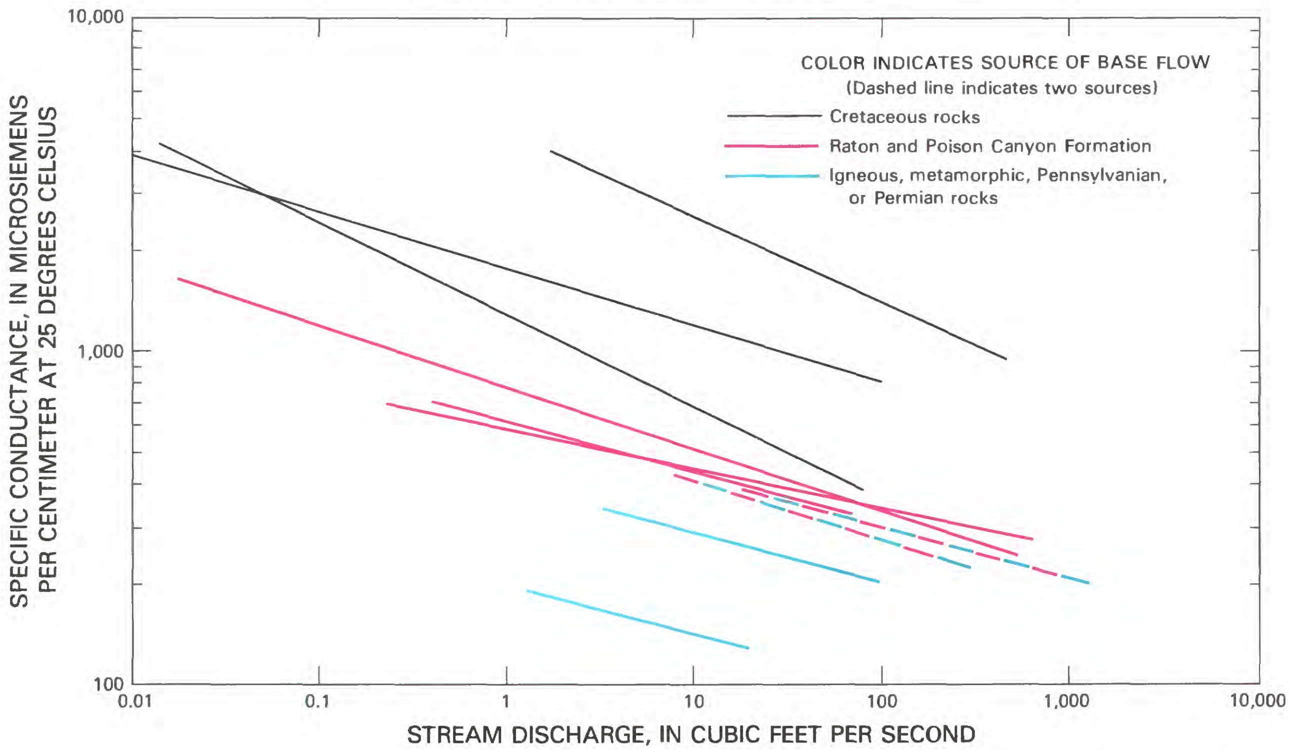


FIGURE 16.—Typical relations of stream discharge to specific conductance (modified from Abbott and others, 1983).

Ground water is water that is contained in joints, fractures, and pore spaces of rocks. It is replenished by precipitation and, consequently, varies locally in quantity and quality. The best indication of the quantity and quality of ground water is the type of rock present. Rock refers not only to hard, consolidated formations such as sandstone, limestone, granite, or lava rocks, but also to loose, unconsolidated sediments such as gravel, sand, and clay. The layer of rock that has a usable supply of water is an aquifer. Gravel, sand, sandstone, and limestone generally are the best aquifers, but they form only a fraction of the rocks in the Earth's outer crust, and not all of them yield usable supplies of water. The bulk of the rocks in the Earth's outer crust consists of clay, shale, and crystalline rocks, which are all poor aquifers although they may yield enough water for domestic and stock uses in areas where better aquifers are not present.

An aquifer may be only a few feet thick or thousands of feet thick. An aquifer may be located just below the surface or hundreds of feet below the surface. In addition, an aquifer may underlie only a few acres or hundreds of square miles. For example, the Dakota Sandstone in the West underlies several States, but most aquifers are local in extent.

The water table is the top of the zone of saturation—the zone in which all the rocks are saturated with water. When precipitation occurs, the first water entering the soil is contained by capillary action, replacing water that has evaporated or has been consumed by plants. After the soil is saturated, the excess water will reach the water table, and all the openings (joints, fractures, and pore spaces) below the water table become completely saturated. Any well that extends below the water table will fill with water up to the level of the water table. The quantities yielded to a well from a water-bearing rock can range from a few hundred gallons a day, suitable for use where only a domestic supply is needed, to as much as several million gallons a day.

The quantity of water that rock openings contain depends on the porosity (the space between the grains or the cracks that can fill with water) of the rock. A rock that will be a good source of water must contain many pore spaces, joints, and fractures, or combinations of these types of openings. If water is to move freely through the rock (permeability), the openings must be connected to one another. Large quantities of water are available to a well from saturated permeable rocks. In addition, water will move faster in certain kinds of rocks. A clayey silt that has only small pore spaces will not transport water readily, possibly only a few inches a day. However, a coarse gravel containing many large interconnected pore spaces will transport water freely and rapidly, possibly at rates of thousands of feet per day.

The flow of ground water from rocks onto the land surface (discharge) occurs in several ways: (1) Water may seep into a stream through the bed and banks; (2) water may emerge as a spring; or (3) water may seep out to the surface in a swampy area. The area where the aquifer is recharged with water is higher than the area of discharge, so that water moves through the aquifer by gravity. The recharge area usually is where a layer of permeable material is close to land surface.

Withdrawal of water from a well lowers the level of the water table around the well. There are several areas where ground water is being withdrawn faster than it is replenished, and the water levels are declining. One of the effects of coal mining can be the total or partial loss of an aquifer by removal of overburden or coal. After reclamation, these aquifers may or may not be reestablished in the spoil material. Dewatering of aquifers adjacent to mines results in a decline in water levels in those aquifers, and water-supply wells can be affected.

Because ground water is in contact with rocks and soil longer than surface water, it usually contains more dissolved minerals. Water that contains more than 500 milligrams per liter of dissolved solids is not considered desirable for domestic supplies. Not only the length of time of contact but also the type of rocks and soils in contact determine natural effects on ground-water quality. The quality of water from gravel and sand likely would differ from clay and fine silt, because the permeability of the material through which the water moves affects the quantity of dissolved minerals it accumulates. Where a well taps several water-bearing materials that are interbedded, the pumped water frequently is variable in quality, depending on the depth of the well and other considerations. For example, wells drilled into interbedded sand, shale, clay, siltstone, sandstone, and lignite deposits in parts of northwestern North Dakota normally yield hard water at shallow depths and soft water at greater depths (hard water does not readily form a lather with soap).

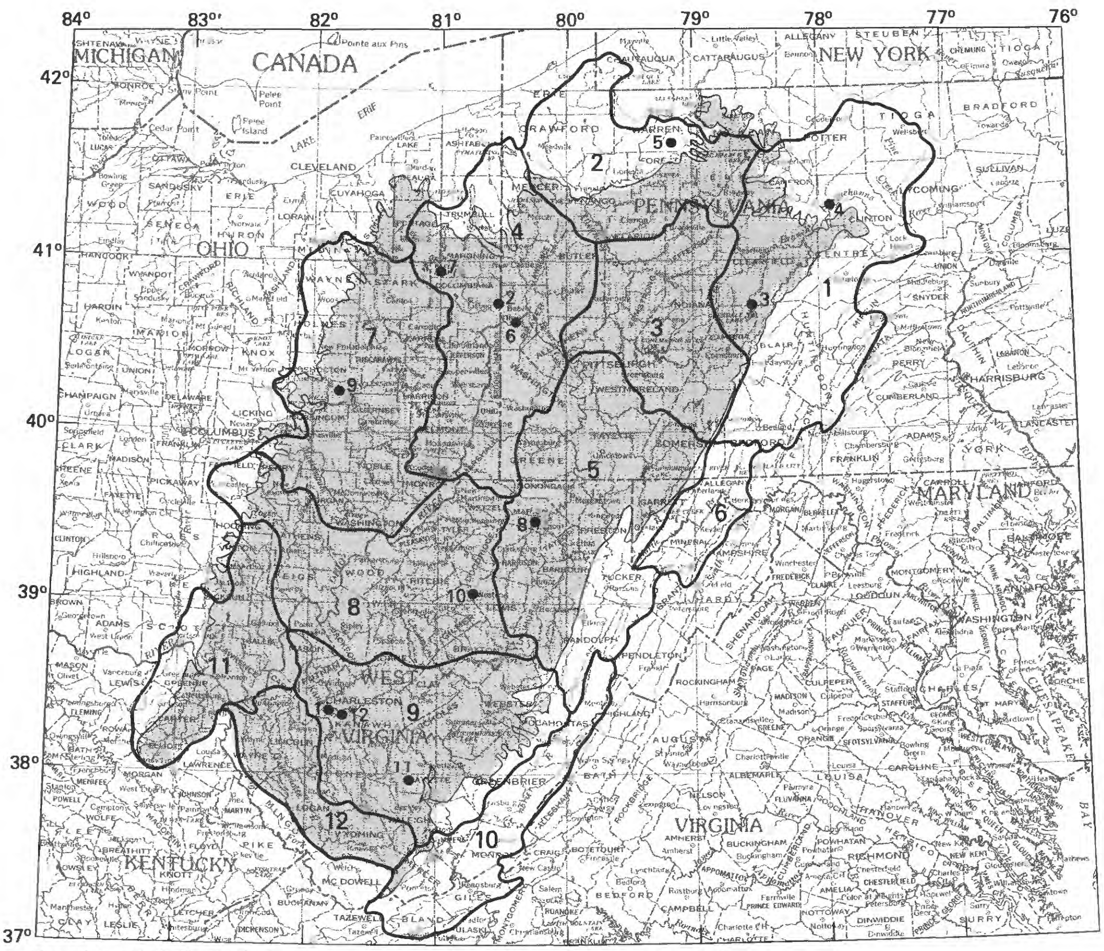
Disruption of aquifers and related effects due to surface mining may affect ground-water quality. The rock material exposed and fragmented by mining primarily is unweathered. As water moves through the spoils, increases in dissolved-solids and trace-element concentrations are likely. The water usually is in contact with the spoils for a long time, and dissolved-solids concentrations may increase substantially in aquifers in mine spoils. Also, prior to mining, two or more aquifers that have very different water-quality characteristics may be separated by relatively impermeable layers. Disruption by mining could effectively join these aquifers, resulting in degradation of water quality in some aquifers.

EASTERN PROVINCE—NORTHERN APPALACHIAN REGION

By David H. Appel

The Northern Appalachian region, an area of about 58,400 square miles in parts of Kentucky, Maryland, New York, Ohio, Pennsylvania, Virginia, and West Virginia (fig. 17), includes coal areas 1–12 (table 1). The land surface varies from rolling farmlands in the glaciated areas along the northern and northwestern edge of the region to rugged, deeply incised, mountainous terrain with narrow valleys in the central section of the Appalachian Plateaus physiographic province (pl. 1) to long, sharp-crested mountain ridges with broad valleys in the Valley and Ridge physiographic province along the eastern edge of the region.

The climate of the region can be classified as humid continental. Average annual precipitation in the region is about 42 inches, but ranges from 36 inches in the eastern panhandle of West Virginia and in the



Base from U. S. Geological Survey 1 : 2,500,000 United States base map

0 50 100 MILES

0 50 100 KILOMETERS

EXPLANATION

COAL REGION

5 COAL-AREA BOUNDARY—Number refers to local areas (Cochran and others, 1983)

•3 SAMPLING SITE AND NUMBER—See figures 18 and 19 for site descriptions

Figure 17.—The Northern Appalachian region, coal areas 1–12, and sampling sites.

northwestern section of the region to more than 60 inches in the higher mountains of West Virginia.

Geologically, the Northern Appalachian region is part of an enormous structural trough or basin. The basin contains a great mass of sedimentary rocks that fill an elongated depression in the crystalline basement complex. The stratified rocks in this enormous basin form a large, locally mineral-rich, wedge-shaped mass that is thickest near the eastern edge of the basin and becomes progressively thinner to the west. The deepest part of the basin, the area of greatest thickness, is in northern West Virginia and southern Pennsylvania.

Strata along the eastern margin of the region are extensively folded and broken by faults. Intensity of folding and faulting decreases to the west, and in the western part of the region, strata are nearly horizontal. Because of these structural features, erosion has exposed the rock systems at the land surface in the eastern part of the region, but only the rocks of Mississippian, Pennsylvanian, and Permian age are exposed at the land surface in the western part of the region.

Forests, predominantly of deciduous trees, cover approximately 68 percent of the total area in the region; agricultural lands cover about 23 percent; and the remaining 9 percent is a combination of urban and barren lands and water. Most of the surface lands and coal in the region are privately owned; approximately 10 to 15 percent of the surface land is publicly owned. An even smaller percentage of the coal is publicly owned; most of the coal under Federal lands is privately owned. Most of the area is rural, although there are 11 cities with populations greater than 35,000. The 1980 population of the region was approximately 7.4 million people.

Although precipitation in the region normally is abundant, it is distributed unevenly throughout the year and generally is deficient during late summer and fall when demand for water is great. Surface water is the principal source of water for public supply and industrial uses in the region. Thermoelectric power generation is by far the largest use of water in the region, 72 percent of the total. However, most of the water is not consumed but is returned to the river after use. Ground-water sources supply only about 3 percent of the total water withdrawn in the region. About 30 percent of the total population of the region and 92 percent of the rural population depend upon ground-water sources of supply. Ground water also is used by many industries.

COAL RESOURCES

Approximately 234 million tons of bituminous coal (fig. 1) were mined from the coal-producing area of the Northern Appalachian region during 1980. Of this total, 93 million tons (40 percent) were mined from about 2,550 surface mines, and 141 million tons (60 percent) were mined from about 1,150 underground mines.

The region contains many mineable coal seams; as many as 62 occur in West Virginia alone. Recoverable reserves from coal seams more than 28 inches thick are estimated to be 80 billion tons. Most mined coal seams commonly are 3 to 6 feet thick, although coal seams reach a maximum, exceptional thickness of 22 feet in Maryland (Nielsen, 1984).

The quality of the coal varies by coal seam and areally. Generally, average sulfur content for any one coal seam tends to increase westward or northwestward and, in any one area, the stratigraphically lower coals tend to contain more sulfur. An imaginary hinge line can be drawn through West Virginia dividing the region into a northern and a southern section. The hinge line represents an approximate sulfur content of 1.5 percent and an ash content of 6 percent (Babu and others, 1973). Generally, better quality coal (greater heating value and smaller percentages of sulfur and ash) is in the southern section. The imaginary hinge line dividing the sections is not distinct; a gradual decline in coal quality occurs for many miles on either side of the line. Better quality coals south of the hinge line mostly are metallurgical coals used for steel making, and coals north of the hinge line primarily are "steam" coals used for generating electric power.

HYDROLOGY

The terrain in much of the Northern Appalachian region is very steep and rugged, and the area receives relatively large quantities of precipitation. As a result, any land disturbance such as mining, clearing, dumping of mine spoils, or road building may cause large increases in erosion and sedimentation, degradation of surface water, and changes in the quantity of streamflow. Quality and quantity of surface and ground waters may be affected by surface and underground mining.

The region has been mined actively since the late 1700's, and many of the hydrologic issues or effects of mining have been recognized for many years. Two early regional studies were by Schneider and others (1965) and Biesecker and George (1966). However, most older studies were problem- or site-oriented and locally funded. As National interest in coal increased, interest in the effects of coal mining on the hydrologic environment and the need for more hydrologic information about the Northern Appalachian region correspondingly increased.

SURFACE-WATER NETWORK

Prior to 1979, approximately 200 stream-discharge measurement sites and special-project sites already were operative as part of other ongoing programs. The number of sites was increased to 266 after 1979, and primary emphasis was on small watersheds where the effects of mining would be identified more readily.

In addition to expanding the number of stream-discharge measurement sites, more than 1,200 new synoptic measuring sites were established in the region. Synoptic sites are those that are located on small streams where water quality and stream-discharge data are collected at specific times and during certain flow conditions, in particular during periods of low flow.

SURFACE-WATER CHARACTERISTICS

Stream discharge in the Northern Appalachian region varies seasonally in response to precipitation and evapotranspiration. The hydrograph shown in figure 18*A* illustrates monthly stream discharge and is typical of an unregulated stream in the region. The greatest mean monthly stream discharge usually occurs during March because of snowmelt, increased precipitation, and minimal evapotranspiration. Stream discharge during spring and early summer usually is high because of increased thunderstorm activity but decreases during late summer and early fall because of increased evapotranspiration losses and decreased precipitation. Stream discharge usually increases again during November and December because of increased precipitation and decreased evapotranspiration. The mean monthly and annual mean stream discharges for one specific year (1974) compared with the mean monthly and annual discharges for 30 years of record (1931–60) are shown in figure 18*B*. This hydrograph also illustrates characteristics of the typical streamflow cycle for unregulated streams in the region. Mean monthly stream discharges of regulated streams generally are less variable and do not typify natural streamflow conditions.

Equations are available to estimate average annual stream discharge at ungaged sites in Pennsylvania (Herb, 1981) and for other sites in the Northern Appalachian region (Wetzel and Bettandorff, 1986). Average annual stream discharge is quite variable in the region but is well correlated with annual precipitation and temperature and drainage area. The average annual stream discharge for gaged streams in the area ranges from less than 1.0 cubic foot per second per square mile to more than 2.5 cubic feet per second per square mile. Thus, the average annual discharge of a stream draining 100 square miles probably will range from 100 to 250 cubic feet per second, depending on location.

Low-flow characteristics of streams in the region also are quite variable and difficult to predict, especially for small drainages. Low flows are affected by factors that are difficult to quantify, such as the storage and transmission capacity of the rocks, which are affected not only by geology but also by mining. Soil types and depths and vegetation also affect low flows. Low-flow regression equations are available for Ohio (Johnson and Metzker, 1982), Pennsylvania (Flippo, 1982), and Kentucky (Sullavan, 1984). Standard errors of estimate in Pennsylvania typically were determined to be 20 to 40 percent when using basin characteristics of drainage area, annual precipitation, and a geologic index. However, the equations are not applicable to streams that have underflow. Underflow may occur in areas of fractured bedrock, which is common where underground mines have collapsed.

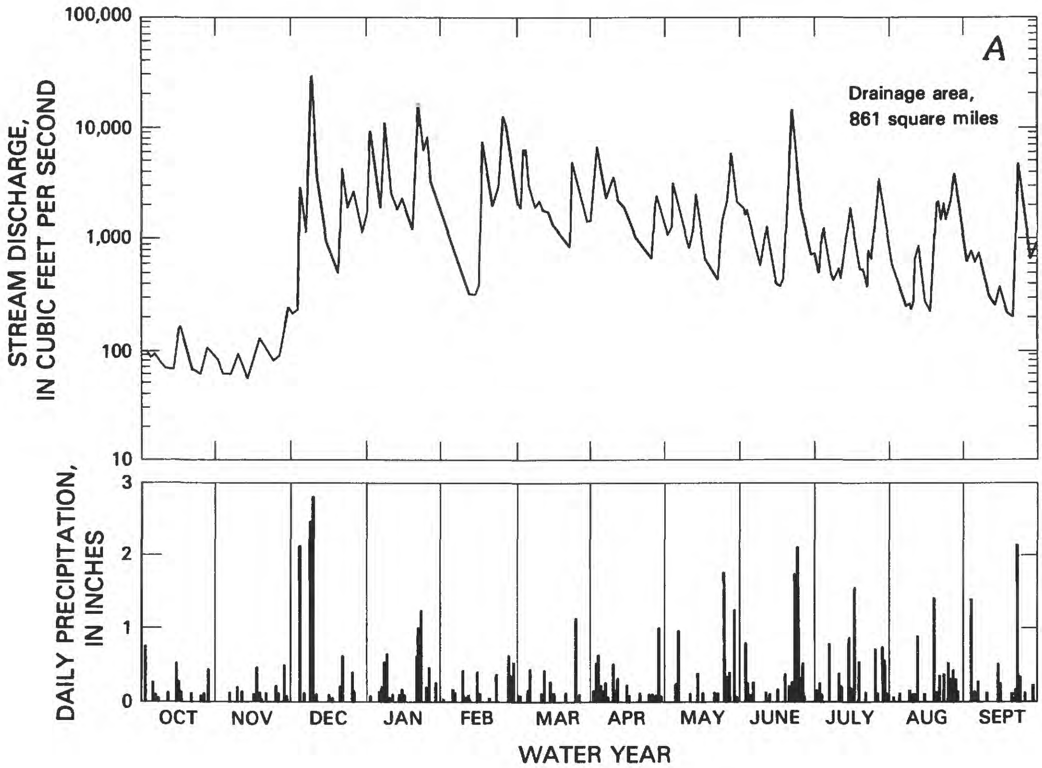
Equations for estimating flood magnitude and frequency at ungaged sites are available for some States in the region: Kentucky (Hannum, 1976); Maryland (Carpenter, 1983); Ohio (Weber and Bartlett, 1976); Pennsylvania (Flippo, 1977); Virginia (Miller, 1978); and West Virginia (Runner, 1981).

SURFACE-WATER QUALITY

Surface-water-quality data are available at approximately 1,350 sites that are primarily synoptic sites in the region. Water in streams draining mined areas in the southern part of the region generally was of better quality than water in streams draining mined areas in the northern part. These data also indicate that the water in mined areas generally is of poorer quality than in unmined areas. In the northern half of the region, specific conductance and dissolved-solids concentrations were determined to be 2 to 3 times greater, and sulfate was as much as 10 times greater in streams draining mined areas than in those draining unmined areas. However, specific conductance, pH, and concentrations of total iron, total manganese, and dissolved sulfate can vary considerably from stream to stream and with time in a single stream.

Median values and the ranges of specific conductance at selected surface-water-quality sites are shown in figure 19. Drainage areas at these sites range from 2.67 to 4.61 square miles. Specific conductance of surface water at all sampled sites in the region ranged from 6 to 14,500 microsiemens per centimeter; pH ranged from 2.0 to 9.3; and sulfate concentrations ranged from 1.0 to 4,700 milligrams per liter. Total recoverable iron concentrations were as large as 730,000 micrograms per liter, and total recoverable manganese concentrations were as large as 160,000 micrograms per liter. The largest concentrations almost always were from small streams draining old or existing mined areas.

Increase in sediment loads of streams from mined areas may be one of the most significant effects of coal



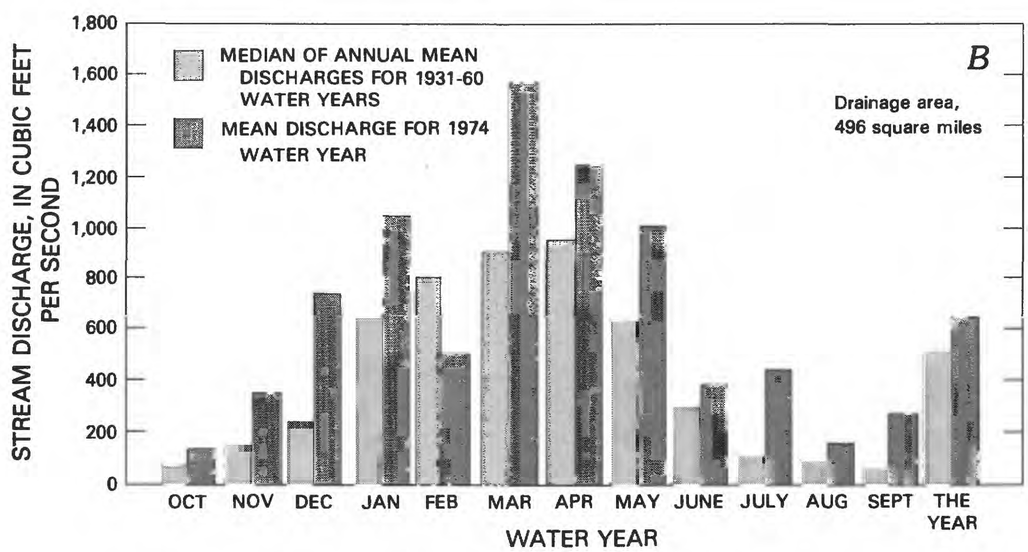
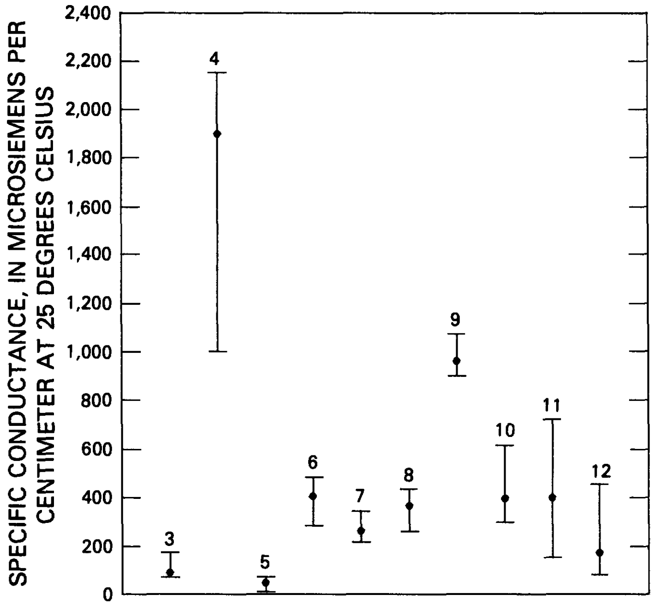


FIGURE 18.—Typical hydrographs showing variation of stream discharge in the Appalachian region. *A*, Discharge and precipitation for Coal River at Tornado, West Virginia, site 1, for October 1, 1978 to September 30, 1979 (modified from Ehlke and others, 1982b). *B*, Seasonal pattern of discharge for Little Beaver Creek near East Liverpool, Ohio, site 2 (modified from Roth, Engelke, and others, 1981). Location of sites shown in figure 17.



EXPLANATION

3 SITE NUMBER
MAXIMUM
MEDIAN
MINIMUM

SITE NUMBER IN FIGURE 17	SITE NAME AND DRAINAGE AREA
3	Sandy Run at Van Ormer, Pennsylvania (2.80 square miles)
4	Crowley Hollow near Keating, Pennsylvania (2.67 square miles)
5	Upper Sheriff Run near Lynch, Pennsylvania (4.44 square miles)
6	Service Creek near Shippingport, Pennsylvania (4.50 square miles)
7	Naylor Ditch near Sebring, Ohio (3.96 square miles)
8	Thomas Fork at Santiago, West Virginia (4.50 square miles)
9	No name tributary Wills Creek near Conesville, Ohio (3.00 square miles)
10	Stewart Creek at Baldwin, West Virginia (3.33 square miles)
11	Packs Branch at Packs Branch, West Virginia (4.61 square miles)
12	Trace Fork at Ruth, West Virginia (2.82 square miles)

DATA IN FIGURE REPRESENT 3 TO 7 SAMPLES PER SITE DURING 1979-81

FIGURE 19.—Maximum, median, and minimum specific conductance at selected surface-water-quality sites in the Northern Appalachian region.

mining. Stream discharge is the main factor affecting the sediment yield of a given watershed. Sediment concentrations and loads generally are largest during high flows and smallest during low flows. Increased precipitation not only increases stream discharge and its ability to transport sediment, but also increases erosion and, therefore, the supply of transportable material.

Average annual suspended-sediment yields for large streams in the region range from 20 to 800 tons per square mile (Schneider and others, 1965, sheet 8). This range may not include the extremes that occur in smaller tributaries in the region. Yields tend to increase in a southerly direction, ranging from 20 to 250 tons per square mile in the northern part of the region to 100 to 800 tons per square mile in the southern part. The glaciated area in the northwestern corner of the region is an exception to the above statement; here, yields range from 100 to 800 tons per square mile.

Sediment yields of streams are affected by numerous other factors, including physiography, soils, climate, and land use. Land-use activities that disturb the land surface, such as surface mining, construction, agriculture, and silviculture, increase erosion and sediment yields. Although the network of daily suspended-sediment sites is not adequate to correlate sediment load with specific land uses, active surface mining is known to produce some of the largest rates of erosion. In west-central Pennsylvania (coal area 3) the synoptic-site data indicate that for any given instantaneous unit stream discharge, the instantaneous suspended-sediment discharge may vary by a factor of 1,500 with no appreciable change in land use (Herb and others, 1981a).

GROUND-WATER NETWORK

The 1983 ground-water observation-well network in the region consisted of 83 wells that were measured on a routine basis. Water-level and water-quality data also are available for many thousands of short-term project wells. These data consist of one or more samples and were collected as part of specific studies or projects.

GROUND-WATER OCCURRENCE

Two principal types of aquifers underlie the region—unconsolidated alluvial and glaciofluvial deposits and consolidated bedrock aquifers composed of sedimentary rocks. Unconsolidated aquifers are the best sources of ground water for municipal and industrial uses in the region. Water production from wells in these aquifers depends on permeability, areal extent, saturated thickness of the sand and gravel materials, and proximity of wells to rivers. The quality of water in alluvial aquifers generally is suitable for most uses but often requires some treatment. In some locations, however, wastes from chemical and industrial plants have contaminated local ground water.

Major sources of ground water in the Appalachian Plateaus physiographic province part of the region (pl. 1) are the Pennsylvanian aquifers. The Upper Pennsylvanian aquifers consist of nearly horizontal layers of mostly shale and thin interbeds of fine-grained sandstone, siltstone, coal, and limestone. The Lower Pennsylvanian aquifers consist mostly of massive coarse-grained sandstone and shale, siltstone, coal, and thin limestone beds.

The primary permeability of the Pennsylvanian bedrock aquifers generally is negligible. Ground water flows through and is stored in joint systems, fractures, and bedding planes and in carbonate rocks in dissolution channels. These aquifers commonly are very local in extent. In some areas, these local aquifers are perched and are under a single hilltop.

Mississippian aquifers in the southeastern part of the region are similar in lithology and permeability to the Pennsylvanian aquifers but are gently to moderately folded. Parts of the sandstones are saturated and confined by overlying and underlying shales. The aquifers can yield moderate to large quantities of water.

The predominantly carbonate Greenbrier Limestone of the Mississippian aquifers has good potential for large-scale withdrawal of ground water. Fracture openings in these strata generally are enlarged by solution, and wells that penetrate enlarged openings may have large yields.

Farther to the east, in the Valley and Ridge physiographic province part of the region (pl. 1), the aquifers are faulted and compressed into steep folds that greatly affect the occurrence and movement of ground water. In these areas, ground-water conditions are more variable than in the rest of the region. The principal carbonate units of the Devonian and Ordovician aquifers and some of the massive sandstone units of the Devonian aquifers have potential for providing large quantities of ground water. The carbonate units also are sources of springs and have large yields (as much as 15,000 gallons per minute) that supply small water-supply systems and light industry.

GROUND-WATER QUALITY

Quality of water in the Pennsylvanian aquifers generally is suitable for most purposes. However, the water usually varies from soft (60 milligrams per liter calcium carbonate) to very hard (as much as 400 milligrams per liter calcium carbonate). In some locations, specifically where drainage from coal mines is a source of recharge to underlying aquifers, the water may be very hard (1,300 milligrams per liter calcium carbonate) and may contain large concentrations of iron (180,000 micrograms per liter), manganese (9,900 micrograms per liter), sulfate (2,500 milligrams per liter), and chloride (2,300 milligrams per liter). Brine underlies freshwater in most areas of the Appalachian Plateaus physiographic province part of the region (pl. 1), but generally it is located deeper than is accessed by usual drilling practices (300 feet in valley areas).

Water quality of the Mississippian aquifers generally is suitable for most uses. Hardness and locally large iron concentrations (greater than 300 micrograms per liter) are common issues. Because of sink holes and large solution openings that may be in direct hydraulic connection with sources of contamination in outcrop areas, the carbonate unit is very susceptible to biological and chemical pollution.

COAL-HYDROLOGY STUDIES

Economic interest in coal resources and hydrologic issues associated with coal mining resulted in several coal-hydrology studies in the region. For example, in February 1972, the most destructive flood in West Virginia's history occurred when a coal-waste dam collapsed on Buffalo Creek in the southwestern part of the State. Davies and others (1972) reported the hydrology and engineering geology of the disaster. The large loss of life, human suffering, and property damage focused attention on an aspect of coal hydrology that often is overlooked. Many of the coal-waste dams in existence at that time were not engineered dams and simply were unsafe.

Several studies that investigated the effects of various mining practices on the hydrology of small basins were done in the region. Reed (1980) determined that acidity of water in a drain in an area in northern Pennsylvania that previously had been deep-mined, but now was being strip-mined, had increased nearly 600 percent during a 3-year period. The acidity of the water in the two other drains in the same area increased by 100 and 45 percent.

The effects of underground mining and mine collapse on areal hydrology were determined by Hobba (1981) at one site where the mined bed of coal is topographically above major streams and at two other sites where the mined bed of coal is below major streams. The mining and associated subsidence cracks increase hydraulic conductivity and interconnection of overlying water-bearing rock units that, in turn, cause increased infiltration of precipitation and surface water, decreased evapotranspiration, and increased base flows in some small streams. Gaining and losing streams occur in deep-mined areas, depending on local conditions. Mine pumpage and drainage can cause diversion of water underground from one basin to another. Aquifer tests indicated that near-surface rocks have greater transmissivity in a mine-subsided basin than in unmined basins. Increased infiltration and circulation of ground water through shallow subsurface rocks increased dissolved-solids loads in streams, as did treated and untreated contributions from mine pumpage and drainage.

A study in cooperation with the U.S. Bureau of Land Management was started in 1981 in West Virginia to calibrate deterministic rainfall-runoff models for various land-use conditions in coal areas of the region and to develop water-quality regression models for simulating water-quality constituent concentrations in West Virginia.

As a continuation of studies in the coal areas of Alabama by Puente and others (1982), studies in West Virginia indicate that water-quality properties and constituents such as specific conductance, sulfate concentrations, noncarbonate hardness/total hardness ratio, and magnesium/calcium ratio can be used to identify streams substantially affected by coal-mine drainage (Celso Puente, U.S. Geological Survey, oral commun., 1985). Concentrations of these chemical constituents varied greatly on a statewide basis. However, the water quality of streams draining coal areas underlain by the same rock type were similar, and the coal areas were delineated into two distinct geochemical zones.

A study was done from 1979 to 1980 to monitor the water quality of streams within the coal-mining areas of western Maryland and adjacent areas of Pennsylvania and West Virginia. The report (Staubitz, 1981) contains streamflow, water-quality, and biological data for various river basins in the Eastern Province.

Ground-water conditions that occurred during coal strip mining in two small watersheds in eastern Ohio are described in a report by Helgesen and Razem (1981). Water levels in the top aquifers declined as mining increased near the watersheds. Depletion of the top aquifer was indicated by decreased stream base flow and by increased mineralization after mining. Helgesen and Razem (1981) concluded that no immediate substantial effects of mining were evident on ground-water levels or ground-water quality beneath the strippable coal.

An assessment of water quality in streams draining coal-producing areas in Ohio is reported by Pfaff and others (1981). A reconnaissance of water quality at 150 sites and a study of 4 small basins indicated that acid mine drainage generally occurred where abandoned drift or strip mines were located; areas characterized by reclaimed or active strip mines indicated few occurrences of acid mine drainage.

The preimpoundment water quality of the Tioga River basin (fig. 17), Pennsylvania and New York, is described in reports by Ward (1976, 1981). Water quality in the Tioga River is degraded by acid mine drainage entering the river downstream from strip- and deep-mined coal areas. Diel measurements indicated that acid mine drainage has decreased biological activity in the Tioga River (Ward, 1981). Relations between selected water-quality constituents were developed for the sampling sites throughout the basin. Downstream trends also were analyzed and reported.

A study in the Tug Fork basin (fig. 17), Kentucky, Virginia, and West Virginia, used a rainfall-runoff model to determine if land-use changes associated with surface mining in the basin affected basin streamflow characteristics (Doyle and others, 1983). The model was calibrated and verified for two periods, one representing 1980 land use and one representing 1950 land use. Statistical tests made for the two periods indicated no difference in streamflow characteristics at any of the locations. In addition, analyses were made to determine if future increases in surface coal mining might affect basin stream discharge. The modeling results indicated that increasing mining in an upland watershed by as much as 200 percent had little effect on stream discharge (Doyle and others, 1983).

Additional coal-hydrology reports for counties, basins, States, or parts of the region that contain information about flood frequency, runoff characteristics, water quality, ground water, and water use are available. Two recent compilations of coal-hydrology studies and sources of data for this area, prepared in cooperation with the U.S. Bureau of Land Management, are by Grason (1982) and Cochran and others (1983).

HYDROLOGIC ISSUES RELATED TO COAL MINING

Coal-mining activities may affect all aspects of water resources in the Northern Appalachian region. Runoff characteristics of streams may be changed. Changes are more noticeable during low flows when, depending on local mining and geology, mining may cause a stream to lose or gain water (Hobba, 1981).

The chemical quality of water in more than 6,000 miles of streams in the region has been identified as being substantially affected by coal-mine drainage. In many of the affected stream reaches, the water is not suitable for most uses without expensive treatment. The pH of water draining from mined areas commonly ranges from 2.0 to 5.0 in the northern part of the region where rocks generally contain few calcareous minerals and coal contains a substantial quantity of sulfur. In contrast, the pH of mine drainage often is neutral or alkaline in the southern part of the region where calcareous minerals are common and coal contains little sulfur. Specific-conductance values and concentrations of total iron, total manganese, dissolved sulfate, and dissolved solids usually are larger in mined areas than in unmined areas.

Sources of sediment in surface mines include newly cleared areas, haul roads, mine-spoil piles, and newly reclaimed land. Strip-mine spoil is a mixture of freshly exposed sandstone, limestone, shale, and soil. Mine spoil rapidly weathers and decomposes into unconsolidated particles that are easily eroded. If a mine site is not reclaimed, mine-spoil piles may remain sources of large sediment yields for many years. However, after a mine site is properly reclaimed, erosion decreases substantially, and sediment yield from the mine site is a short-term issue (Staubitz and Sobashinski, 1983).

Ground-water resources may be affected by surface and underground mining. However, underground mining and related mine collapse usually cause the largest changes. If a mine collapses, subsidence fractures develop along or parallel to weak zones such as existing joints and fractures. The effect on hydrology apparently is the greatest near the land surface. Hobba (1981) indicated that the underground mining process may cause:

1. Lowered water tables above the underground mine and drying up of shallow wells;
2. Fluctuations as much as 100 feet annually of water levels in some wells;
3. Increased infiltration of precipitation, causing decreased evapotranspiration and resulting in higher base flows or increased leakage into mines;
4. Interbasin transfer of ground water because of mine pumpage or drainage;
5. Increased dissolved-solids concentrations and generally more acidic conditions; and
6. Large underground voids that can store large volumes of water.

Some of the changes in hydrology caused by mining are beneficial. Numerous underground coal mines, for example, store plentiful supplies of potable ground water, and many are being used as sources of public supply. Lessing and Hobba (1981) determined that 72 public water systems in West Virginia pump more than 7 million gallons of potable water per day from abandoned coal mines to supply 81,600 people and various establishments.

EASTERN PROVINCE—SOUTHERN APPALACHIAN REGION

By WILLIAM J. SHAMPINE

The Southern Appalachian region, an area of about 42,500 square miles, extends in a southwesterly direction from Kentucky through Tennessee into central Alabama and northwestern Georgia (fig. 20) and includes coal areas 13–24 (table 1). The region is within four physiographic provinces (pl. 1). From east to west these provinces are Valley and Ridge, Appalachian Plateaus, Interior Low Plateaus, and Central Lowland (Fenneman and Johnson, 1946). The Valley and Ridge province is characterized by long, steep-sided ridges separated by northeast-trending valleys. The Appalachian Plateaus province generally is a rolling upland area, and it has a steep escarpment separating it from the lower altitudes of the Valley and Ridge province. The Interior Low Plateaus province is characterized by nearly level to gentle slopes, and it has an escarpment along the western edge separating it from the Central Lowland province. The Central Lowland province is characterized by gently sloping lowlands and many knobs or rounded hills. The major stream systems in the region include the Kentucky, Licking, Clinch, Holston, Tennessee, Coosa, and Cahaba Rivers (pl. 1, fig. 20).

The region has a moist, temperate climate, and mean annual precipitation ranges from about 40 inches in parts of Kentucky to 60 inches in Tennessee. Precipitation is fairly well distributed throughout the year, although some areal variations can be noted during the rainy season. October consistently is the driest month of the year throughout the entire region. During the rainy season in the northern half of the region, the wettest month of the year is July and the second wettest is March. In the southern half of the region, the wettest month of the year is March and the second wettest is January or February. Thunderstorms occur throughout the year but are most frequent during the spring and summer months.

The Valley and Ridge physiographic province part of the region is underlain by Ordovician and Cambrian rocks that predominately are carbonate rock, siltstone, shale, and some sandstone. Karst topography formed by solution of carbonate rocks is common in this province. The Appalachian Plateaus physiographic province part of the region is underlain by gently dipping sandstone, shale, siltstone, and coal of Pennsylvanian age; these rocks have a thickness of about 1,500 feet. Below the rocks of Pennsylvanian age are the rocks of Mississippian age, predominately limestone, calcareous shale, and siltstone. The Interior Low Plateaus physiographic province part of the region is underlain by carbonate rocks of Mississippian age, which average 600 to 700 feet in thickness. These rocks are underlain by shale of Devonian age and limestone of Ordovician age. The Central Lowland physiographic province part of the region is underlain by limestones of Ordovician age.

Land in the Southern Appalachian region ranges from flat farmland to poorly accessible, heavily forested mountains. Most of the area is rural, although some major urban areas are included. Land use is estimated to be about 80 percent forest, 15 percent agriculture (cropland and pasture), 3 percent urban, and 2 percent mining.

Although quantitative water-use data are sparse throughout the region, some use patterns are apparent. The large-volume users are industry and public supply, the majority of which use water from surface sources, streams, and reservoirs. Most of the rural supplies use ground water pumped from local wells.

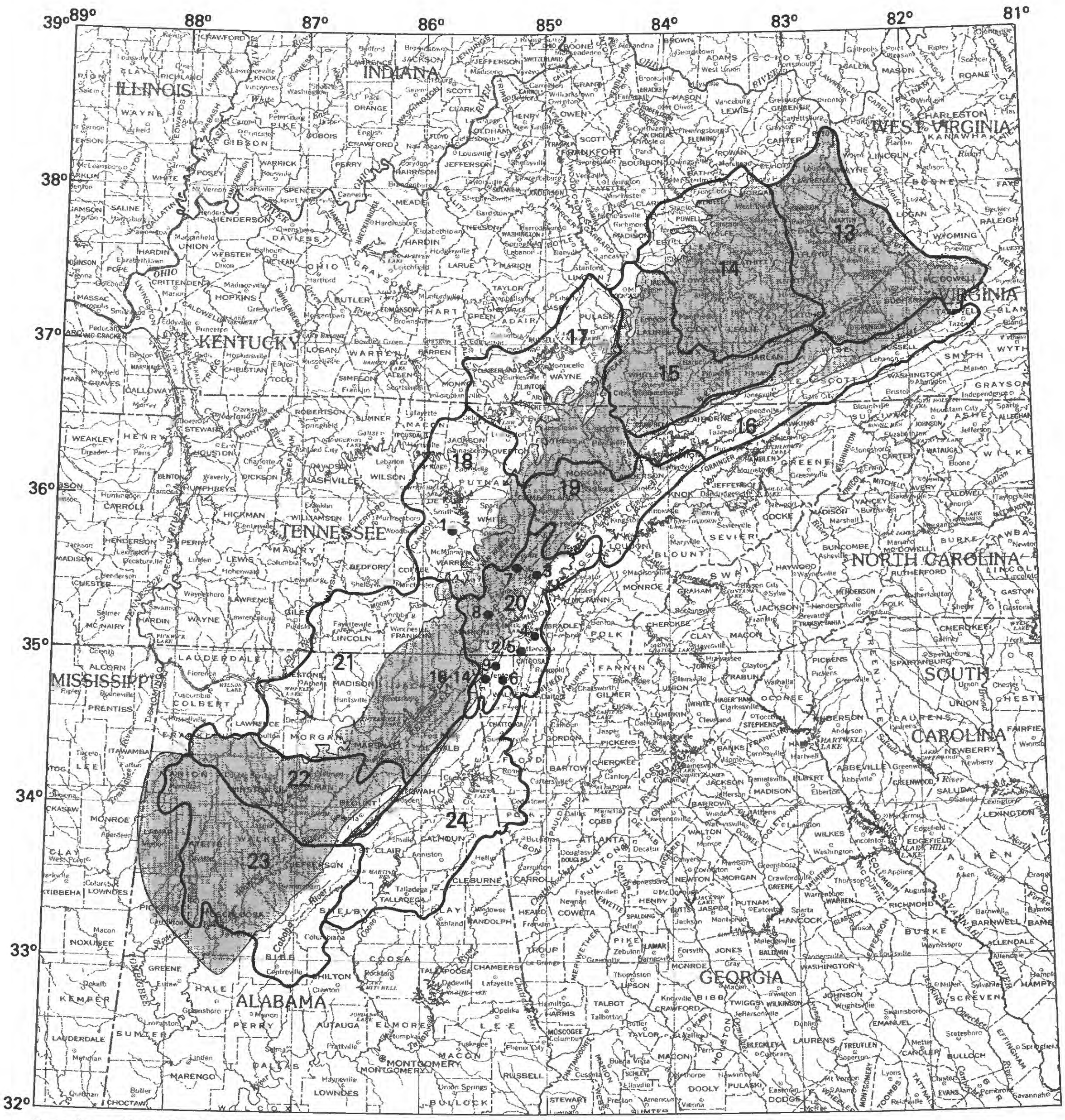
COAL RESOURCES

Coal in the Southern Appalachian region is high-volatile bituminous (fig. 1) and occurs in rocks of Pennsylvanian age in the Appalachian Plateaus physiographic province. More specifically, in the northern part of the region, most of the mineable coal occurs in the Breathitt Formation and, to a much lesser extent, in the Lee Formation. In the southern part of the region, most of the mineable coal occurs in the Pottsville Formation. The occurrence of coal throughout the region is characterized by multiple coal seams of relatively wide lateral extent and varying thicknesses, ranging from 6 inches to as much as 19 feet. However, most of the seams are relatively thin, typically less than 5 feet in thickness. The number of coal seams varies locally. Typically, there are about 25 coal seams in an area; however, as many as 60 coal seams have been identified in the Cahaba coal field (fig. 1) in Alabama. The coal seams occur at intervals ranging from a few feet to more than 300 feet.

More than 4,200 coal mines are located in the Southern Appalachian region. Most of these mines are located in Kentucky, but mining is done throughout the region. Two-thirds of the mines are surface mines, but underground methods also are used to mine the coal. The method of mining varies according to the geology and topography of the mine site. Only limited quantitative data are readily available about coal production in the region. In Kentucky, more than 140 million tons of coal were mined during 1978; most of the coal was produced in six counties: Bell, Buchanan, Harlan, Perry, Pike, and Wise (fig. 20).

HYDROLOGY

Increased national interest in coal during recent years has caused substantial increases in the quantity of



Base from U. S. Geological Survey 1:2,500,000 United States base map

0 50 100 MILES

0 50 100 KILOMETERS

EXPLANATION

COAL REGION

16 COAL-AREA BOUNDARY—Number refers to local areas (Cochran and others, 1983)

•6 SAMPLING SITE AND NUMBER—See figures 21-23 for site descriptions

FIGURE 20.—The Southern Appalachian region, coal areas 13–24, and sampling sites.

hydrologic data collected in the Southern Appalachian region. Additional work has been funded through a variety of sources at national and local levels. One major impetus for the increase in data collection came from passage of the Surface Mining Control and Reclamation Act of 1977, which established environmental laws associated with mining. This Act established a need for expanded data bases to ensure compliance.

As coal became a more important source of energy, the issue of how coal mining might affect water resources also became more important. A need developed to assess the basic hydrologic information that was available and to supplement deficiencies in the data base as needed. Coal-area hydrology reports have been published for all 12 of the coal areas (13–24) in the Southern Appalachian region (table 1).

SURFACE-WATER NETWORK

The Surface Mining Control and Reclamation Act of 1977 resulted in an increase in the quantity of hydrologic data collected after 1977 in the Southern Appalachian region. During 1976, stream-discharge data were collected at 281 sites in the region. After passage of the Act in 1977, a total of 320 new sites were established to meet specific data requirements associated with new coal-related studies. Most of these sites were intended for short-term use, although a few have been maintained to study the long-term effects of mining.

The greatest quantity of data collected consisted of a continuous record of water stage and a calculation of the daily stream discharge at a site. The period of record for continuous-record data at specific sites extends as far back as the late 1800's, although a record of 20-to-30-years duration is more typical. For many sites, however, the data were collected for a specific study, and the period of record may be for a few years only. Data also were collected at partial record sites where 8 to 12 instantaneous-discharge measurements were made annually during a period of several years.

One of the largest increases in the data-collection program occurred in the area of water quality. There were 209 active water-quality sites in the region during 1976, and an additional 535 sites were established after 1976. The data collected include measurement of major cations and anions, physical properties, trace elements (both dissolved and sorbed on the bottom materials), and some biological data.

Most of the water-quality sampling was done synoptically to provide generalized areal coverage. Most of the specific studies began during the late 1970's included a series of samples collected on a periodic basis, commonly monthly, and at least one site where a continuous record was made of the temperature, pH, and specific conductance.

Because of the importance of sediment, there was a substantial increase in the number of sediment-data-collection sites in the region after passage of the Surface Mining Control and Reclamation Act of 1977. During 1976, there were only 35 sites where sediment data were being collected. After 1976, the number of sites increased to 213. The most common type of data collected was suspended-sediment concentrations, although particle-size analyses were done on some samples.

SURFACE-WATER CHARACTERISTICS

A stream discharge hydrograph of a stream located near the middle of the Southern Appalachian region is shown in figure 21. The flow variability illustrated by this hydrograph is typical of streams throughout the region. The general shape of the hydrograph would be similar for basins of varying sizes, although the absolute values of the stream discharge would increase as the basin size increases.

Figured on a unit basis, many surface-water characteristics are relatively uniform throughout the region. For example, the average annual discharge of a stream is equal to about 2 cubic feet per second per square mile of drainage area; thus, a stream in a drainage basin of 100 square miles would have an average annual stream discharge of about 200 cubic feet per second.

Low flows are affected by several factors that are difficult to measure quantitatively, such as the storage and transmission capacity of the rocks of the area, the perviousness of the soil, and the type and density of vegetation. Low-flow frequency is expressed as the lowest average stream discharge for a given number of consecutive days for a given recurrence interval. The 3-day, 20-year low flow and the 7-day, 10-year low flow are common indices. Specific low-flow data are available from the individual coal-area hydrology reports listed in table 1. One generality that can be made, however, is that most streams draining less than about 100 square miles in the region approach zero discharge during the low-flow season.

Techniques have been developed for estimating the magnitude and frequency of floods at gaged and ungaged sites throughout the region. These techniques are represented by generalized regression equations from which estimates can be made of flood flows at any site. These equations are reported by McCabe (1962) and Hannum (1976) for Kentucky, Randolph and Gamble (1976) for Tennessee, and Peirce (1954), Gamble (1965), Hains (1973), and Olin and Bingham (1977) for Alabama.

If the flows are arranged according to frequency of occurrence and are plotted as a flow-duration curve, the resulting curve shows the integrated effect of the various factors that affect runoff in the basin. Typical flow-duration curves for two streams in the region are shown in figure 22. The curves are plotted in unit stream discharge so that a more direct comparison can be made. The shapes of the curves illustrate the differences in flow characteristics between streams draining rocks of

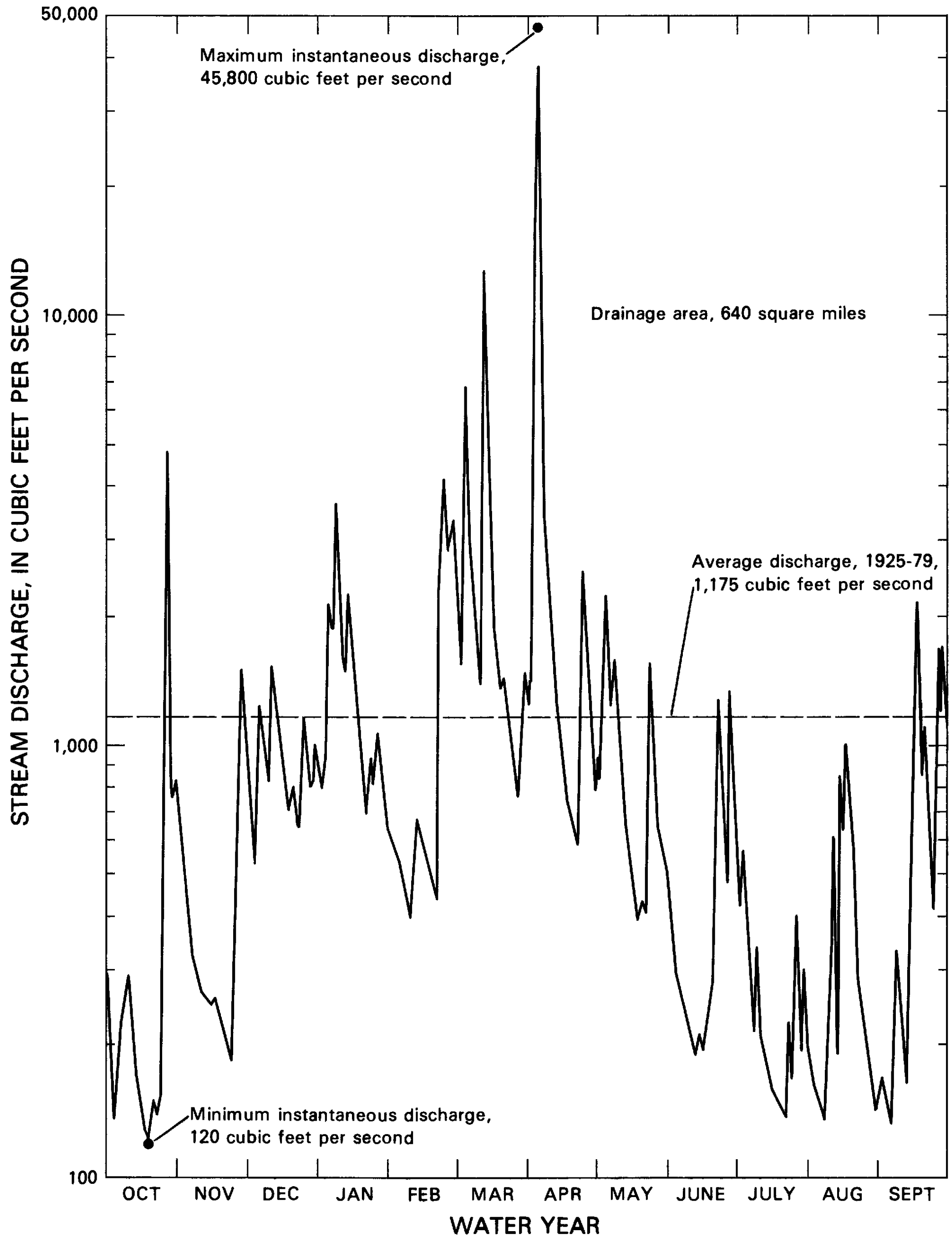


FIGURE 21.—Typical hydrograph showing variation of stream discharge for Collins River near McMinnville, Tennessee, site 1 (fig. 20), during the 1977 water year in the Southern Appalachian region (modified from May and others, 1981).

Pennsylvanian age that contain coal reserves and rocks of other ages in this area. Richland Creek is typical of streams draining uplands of the Appalachian Plateaus physiographic province that contain coal reserves. The flow-duration curve for Richland Creek is steep at stream discharges less than 1 cubic foot per second per square mile because of the small ground-water contribution to the stream. South Chickamauga Creek, however, is typical of the Valley and Ridge physiographic province, and its flow-duration curve has a flatter slope on the lower end, indicating larger yields from the ground-water system. The slope of the curves at the upper end essentially is the same, indicating that the high-flow runoff per square mile is similar for both streams.

SURFACE-WATER QUALITY

The range and median of specific-conductance measurements for selected streams in the central part of the region are shown in figure 23. These data are divided

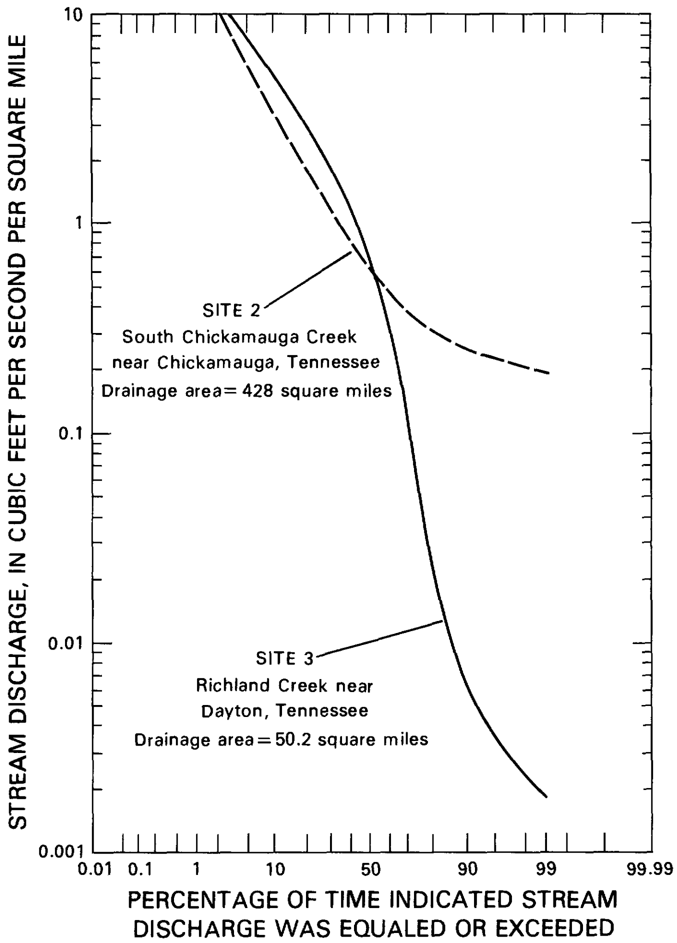
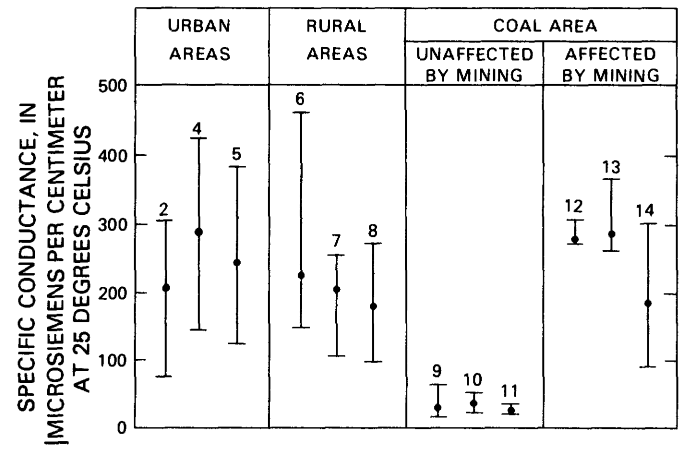


FIGURE 22.—Typical flow-duration curves for selected streams in the Southern Appalachian region (modified from Hollyday and others, 1983; see figure 20 for location of sites).

into groups that clearly illustrate the effect of human activity. The ranges illustrated also are typical of the entire region, although localized sources of pollution have caused the specific conductance occasionally to be as much as 26,000 microsiemens per centimeter.

Water-quality issues associated with coal mining in the region include increased concentrations of sulfate, manganese, and iron. Acid waters and large concentrations of trace elements that typically are associated with coal mining generally are not issues in the region. Sulfate concentrations in streams draining undisturbed basins typically range from 20 to 40 milligrams per liter. Streams draining areas disturbed by coal mining, however, typically contain sulfate concentrations ranging from 100 to 2,000 milligrams per liter. Concentrations of total recoverable manganese in streams in the region range from 0 to about 25,000 micrograms per liter, although the median values generally are less than 100 micrograms per liter. Total recoverable iron concentrations in streams range from 0 to 510,000 micrograms



EXPLANATION

2 SITE NUMBER
MAXIMUM
MEDIAN
MINIMUM

SITE NUMBER IN FIGURE 20	SITE NAME AND DRAINAGE AREA
2	South Chickamauga Creek near Chickamauga, Tennessee (428 square miles)
4	Wolftever Creek above Ooltewah, Tennessee (24.5 square miles)
5	South Chickamauga Creek at Chickamauga, Tennessee (428 square miles)
6	West Chickamauga Creek near Kensington, Georgia (73.0 square miles)
7	Sequatchie River near College Station, Tennessee (154 square miles)
8	Sequatchie River near Whitwell, Tennessee (402 square miles)
9	Long Branch near Hinkle, Georgia (3.73 square miles)
10	Daniel Creek at SR 143 near Trenton, Georgia (4.80 square miles)
11	Bear Creek at SR 157 near Durham, Georgia (7.98 square miles)
12	Rock Creek at SR 170 near Durham, Georgia (0.80 square mile)
13	Rock Creek below SR 170 near Durham, Georgia (0.80 square mile)
14	Rock Creek at Nickajack Road near Hinkle, Georgia (7.40 square miles)

FIGURE 23.—Maximum, median, and minimum specific conductance at selected surface-water-quality sites in the Southern Appalachian region (modified from Hollyday and others, 1983).

per liter and have a median value greater than 1,000 micrograms per liter in the northern part of the region and less than 500 micrograms per liter in the southern part.

Basins draining surface-mined areas generally yield 5 to 10 times as much sediment as basins draining undisturbed areas. Although suspended-sediment yields vary considerably because of topography, mining activity, rainfall intensity, and so forth, unmined areas in the region commonly yield 500 to 3,000 tons per square mile per year, and mined areas commonly yield 3,000 to 20,000 tons per square mile per year. It also is typical for 60 to 70 percent of the total annual sediment load at a given site to be transported during one major storm during the year.

GROUND-WATER NETWORK

The effects of mining on ground water are not as obvious as the effects on surface water, but they do exist. The network of data collected about ground water in the region also was increased in response to the increased interest in coal hydrology. During 1976, water-level or water-quality data were collected at 102 wells in the region. After 1976, data were collected at an additional 261 wells. Because conditions affecting ground water are not as variable as those of surface water, the frequency of data collection is not as often. Water levels may be measured daily, but more typically, monthly or even annually is sufficient. Water-quality samples may be collected as infrequently as annually. Water-quality analyses generally measured the concentrations of the major cations and anions.

GROUND-WATER OCCURRENCE

Fractured sandstones and conglomerates supply most of the water for wells in the region. Yields of wells in these rocks range from 5 to 300 gallons per minute, although most wells yield only 10 to 20 gallons per minute. Wells in the carbonate rocks that overlie or underlie the coal areas have yields ranging from 1 to 3,000 gallons per minute; most of these wells yield less than 30 gallons per minute.

Water levels in wells throughout the region are not affected by mining except for wells located close to mining operations. In some instances, the area immediately adjacent to a mine is dewatered to prevent flooding in the mine. The dewatering process is temporary, however, and would cease at the time of termination of the mining and reclamation operations.

Coal mining in the Southern Appalachian region seems to have less effect on the ground-water resources than it does on the surface-water resources. This may be because of fewer underground mines than surface mines but also may be an indication of less available data about ground-water resources to properly define the extent of problem areas compared to the more available data about surface-water resources.

GROUND-WATER QUALITY

The quality of water from ground-water systems in the region typically is very good; dissolved-solids concentrations generally are less than 500 milligrams per liter. Ground water that is moderately to very saline occurs in the region, although it tends to be sporadic and localized.

The quality of water from wells in the Valley and Ridge physiographic province generally is suitable for drinking. However, contamination of ground water is a potential issue throughout those areas of this province that are underlain by carbonate rocks. These carbonate rocks, primarily limestones and dolomites, are subject to dissolution along fractures, joints, and bedding planes (Hollyday and others, 1983), which can cause large, interconnected conduits that facilitate the rapid, extensive spread of contaminants.

Water from most wells in the Appalachian Plateaus physiographic province is a soft to moderately hard, mixed type (calcium bicarbonate, sodium bicarbonate, or calcium sulfate) and contains relatively small concentrations of dissolved solids. Locally, acidic water may occur and some large concentrations of manganese, iron, and chloride have been reported (May and others, 1981).

Water from wells in the Interior Low Plateaus physiographic province generally is a moderately hard to hard, calcium bicarbonate type and contains moderate concentrations of dissolved solids. Large iron or manganese concentrations are not a widespread issue, but locally, large concentrations of both constituents have been reported (May and others, 1983).

Water from most wells in the Central Lowland physiographic province is a very hard, calcium bicarbonate type and contains moderate concentrations of dissolved solids. Iron and manganese concentrations generally are within maximum contaminant levels for drinking water (U.S. Environmental Protection Agency, 1986c).

COAL-HYDROLOGY STUDIES

Economic interest in coal resources and potential hydrologic issues associated with coal mining have prompted several hydrologic investigations in the region. The most intensive work has been done in the coal areas of Alabama where the U.S. Bureau of Land Management is responsible for managing extensive Federal Mineral Ownership lands. The U.S. Bureau of Land Management has been involved in cooperative studies with the U.S. Geological Survey in Alabama from 1976 to present (1985). These studies have included formation and compilation of hydrologic data bases on mineable lands, assessment of hydrologic changes resulting from mining, and computer simulation modeling.

Knight and Newton (1977) reported that the degradation of water quality is the most serious and widespread coal-mining-related issue in Alabama. Their work assesses the extent of the issue in Alabama and describes work needed to further define the issue and to provide the data needed to develop potential solutions. Data indicate that water draining from mined areas commonly has a pH that ranges from 2.1 to 5.0, generally has large sulfate and dissolved-solids concentrations, is hard to very hard, and may contain objectionable concentrations of iron.

Puente and Newton (1982) analyzed climatic, physiographic, hydrologic, and land-use data for 67 basins in the Warrior coal field and derived equations for assessing water quality in streams that drain unmined areas and mined areas that have been reclaimed. Their data indicate that water-quality effects in mined basins reclaimed under present mining laws are less severe than in basins reclaimed under previous systems. In addition, dissolved-solids concentrations varied in response to the age of the mine. Generally, the concentrations maximized after about 7 years of mine operation and returned to pre-mining levels after about 15 years of mine operation. Some recent work, as yet unpublished (L.J. Slack, U.S. Geological Survey, written commun., 1987) indicates that reclamation efforts in Alabama are effective and will shorten this time cycle.

An assessment of hydrologic conditions in potential coal-lease tracts in the Warrior coal field (fig. 1), Alabama, was done by Puente and others (1982). Climatic, physiographic, hydrologic, and land-use data were analyzed to derive relations for assessing and predicting water quality in streams that drain mined and unmined areas. An equation was derived estimating specific conductance. The independent variables included stream discharge, percentage of basin mined, channel distance between stream sampling site and mined area, and relative age of mined areas. By using additional equations, based on relations between specific conductance and other constituents, estimates can be made of water-quality variables commonly used as mine indicators, such as hardness and dissolved-solids and sulfate concentrations. Using these relations, hydrologic assessments of the coal-lease tracts were made. Based on limited verification data, these assessments proved to be reasonably accurate. The effects of future mining activities in tracts also were estimated. The methods used to estimate future effects on surface-water quality were described and examples were included. In addition, Kidd and Hill (1983) prepared a report summarizing the major coal-hydrology publications and project activities related to hydrology in the Warrior and Plateau coal fields of Alabama (fig. 1).

Lake Tuscaloosa, a water supply for Tuscaloosa, Alabama (fig. 20), is located in a drainage basin containing areas that are being surface mined for coal. Although only about 5 percent of the basin has been mined, Cole (1984) has reported that there has been a small increase in the dissolved-solids concentration of the lake since the beginning of mining. Water draining Cripple Creek basin, a mined basin, contributes an estimated 310 tons per square mile per year of dissolved solids to the lake. Water draining Binion Creek basin, an unmined basin, contributes an estimated 50 tons per square mile per year of dissolved solids to the lake. Cole (1984) also reported that in some instances, natural factors affecting sediment deposition in Lake Tuscaloosa, such as steep overland and channel slopes, may cause more sedimentation in the lake than is caused by the disruption due to coal mining.

Bradfield (1986a, 1986b) has investigated the effect of coal mining on the benthic macroinvertebrate community in Tennessee. Analysis of variance tests indicated significant trends toward decreased number of taxa, number of organisms, and sample diversity at sites that have relatively poor water-quality conditions. These trends indicate significant differences in benthic invertebrate communities at sites with increasing evidence of the effects of land use.

More than 50 reports have been published describing the hydrology of mined areas in Alabama, Tennessee, and Kentucky. In addition to the coal-area hydrology reports, ongoing studies in Tennessee and Kentucky include the collection of a large volume of hydrologic data that is used to formulate and compile data bases about mineable lands. Data are being collected on basins with premining, active mining, and postmining conditions, although reports have not yet (1985) been prepared describing the results of this work.

HYDROLOGIC ISSUES RELATED TO COAL MINING

Coal-mining activities in the Southern Appalachian region have not produced any unusual or unexpected hydrologic issues. The characteristics of streams draining basins containing extensive areas of surface mining have been modified somewhat. If the vegetation in the area is stripped, runoff and the speed with which it moves may increase, thus affecting the magnitude and timing of flood flow. By lowering the water table in an area, the ground-water contribution to a stream will decrease during periods of low flow; a stream may contain less water than during premining periods, or it even may go dry.

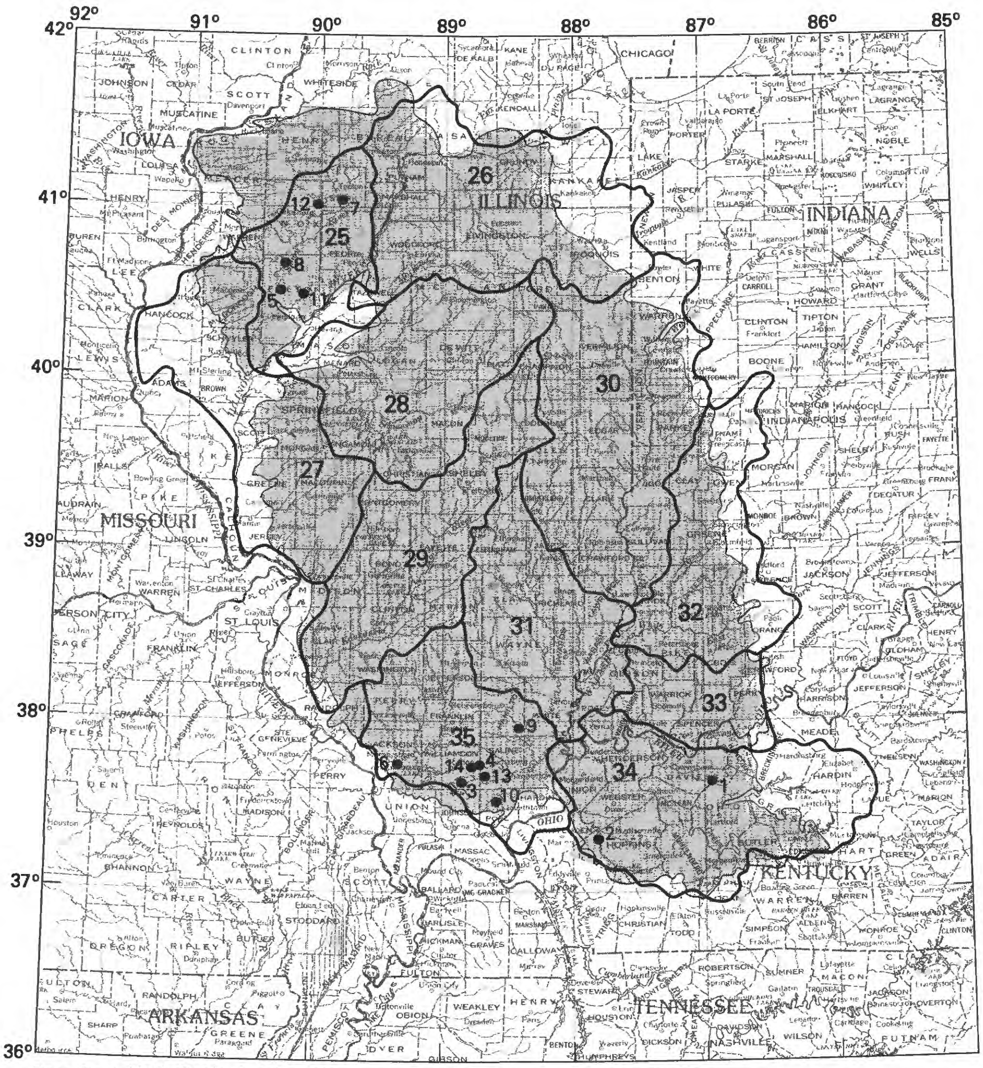
The most significant water-quality issue in the region associated with mining is the increase of suspended-sediment loads in streams adjacent to surface mines. The increase may be fivefold to tenfold and may have a serious deleterious effect on the streams and subsequent users of the water. However, retention ponds and reclamation efforts are successful and can help ameliorate the extent of the issue.

As expected, the concentrations of selected dissolved constituents are increased by coal mining. The largest concentration changes occur with sulfate and iron, which are derived from solution of the pyrite (iron sulfide) associated with coal. Other increases include manganese and possibly some trace elements associated with the suspended sediment. In general, increases in the concentrations of sodium, chloride, calcium, and magnesium in the water due to mining are not substantial enough to restrict potential uses of the water.

INTERIOR PROVINCE—EASTERN REGION

By Konrad J. Banaszak

The Eastern region, an area of about 48,500 square miles in Illinois, southwestern Indiana, and western Kentucky (fig. 24), includes coal areas 25–35 (table 1). No report was done for coal area 26, so that area is not discussed in this regional section. The region is located within two physiographic provinces (pl. 1); the Interior Low Plateaus comprises the southeastern part of the region, and the Central Lowland comprises the majority



Base from U. S. Geological Survey
1:2,500,000 United States base map

0 50 100 MILES

0 50 100 KILOMETERS

EXPLANATION

COAL REGION

28 COAL-AREA BOUNDARY—Number refers to local areas (Cochran and others, 1983)

•2 SAMPLING SITE AND NUMBER—See figures 25 and 27 for site descriptions

Figure 24.—The Eastern region, coal areas 25–35, and sampling sites.

of the region. The land is flat to gently rolling, although some ruggedly rolling hills occur. Three major rivers, the Ohio, the Wabash, and the Illinois (fig. 24) drain the area, and the Mississippi River is just west of the region. Precipitation ranges from about 34 inches per year in the northwestern part of the region to 50 inches per year in the southeastern part.

The region is a structural basin of predominantly Paleozoic sedimentary rocks generally overlain by a layer of glacial materials. The basin is asymmetric, and the deepest part occurs in extreme southwestern Illinois. Rocks are marine and shoreline deposits of alternating sandstones and carbonates with some shales from the Cambrian through Mississippian age. The Pennsylvanian is represented by sequences of terrigenous sandstones and coals alternating with sequences of marine shales and carbonates. The coal-bearing Pennsylvanian rocks indicate a major change in rock types and relation of land to sea.

The glacial material (drift) that occurs in the region is important to mining. In the northern and eastern parts of the region, the drift can be more than 200 feet thick, which makes the coal less accessible for mining. The region was last covered during the Wisconsinan glacial advance. The pre-Wisconsinan glacial debris generally is less than 50 feet thick. Major rivers are located in channels filled with glaciofluvial sands and gravels that generally are about 30 to 100 feet thick.

Because of the general topography, more than 70 percent of the land is used for agriculture, especially row crops, and about 15 percent is forest. Generally, to the north and west, the land is used more for agriculture; to the south and east, the land is forest. For example, in coal area 25 (in the northwestern part of the region), land use is 64 percent crops, 14 percent pasture, 11.5 percent forest, and 4.5 percent urban (Zuehls and others, 1981a). In coal area 34 (in the southeastern part of the region), land use is 40 percent crops, 16 percent pasture, 35 percent forest, and 30 percent urban (Quinones and others, 1983). Major cities in the region are Belleville, Carbondale, Champaign-Urbana, Danville, Decatur, Peoria, and Springfield in Illinois; Evansville, Terre Haute, and Vincennes in Indiana; and Madisonville and Owensboro in Kentucky (fig. 24).

Water-use data for the region are neither comprehensive nor uniformly categorized. It is apparent from the partial record that is available that industry (including electrical power cooling) is the major user of water in the region and that surface water is the major source. In contrast, rural water usage is for public and domestic supply, and the major source is ground water.

COAL RESOURCES

Coal in the Eastern region is high-volatile C through A bituminous coal, which is of high heating value (11,500 to more than 14,000 British thermal units per pound) (fig. 2). The coal classification depends on the maximum depth of burial and the length of time at that depth. Generally, the heating value of the coal increases toward the south, reaching a maximum value around the Ohio River at the Illinois-Kentucky border. Coal resources of the Eastern region are contained entirely in rocks of Pennsylvanian age. Most major coal beds are located in the middle of the Pennsylvanian section; some major coal beds are located in the lower part of the Lower Pennsylvanian. Only minor production occurs in the upper part of the Pennsylvanian section. The thickness of the Pennsylvanian is as much as 3,500 feet in one small area in western Kentucky. Coals from the Eastern region generally are high-sulfur coals (more than 2 percent sulfur).

The total coal resource in the Illinois and Kentucky parts of the Eastern region is at least 224 billion tons, distributed as 186 billion tons in Illinois and 38 billion tons in Kentucky. Indiana has 17 billion tons of coal reserves. Production for the three States during 1980 was about 129 million tons: 64 million tons in Illinois, 40 million tons in Kentucky, and 25 million tons in Indiana (Indiana University, 1983).

HYDROLOGY

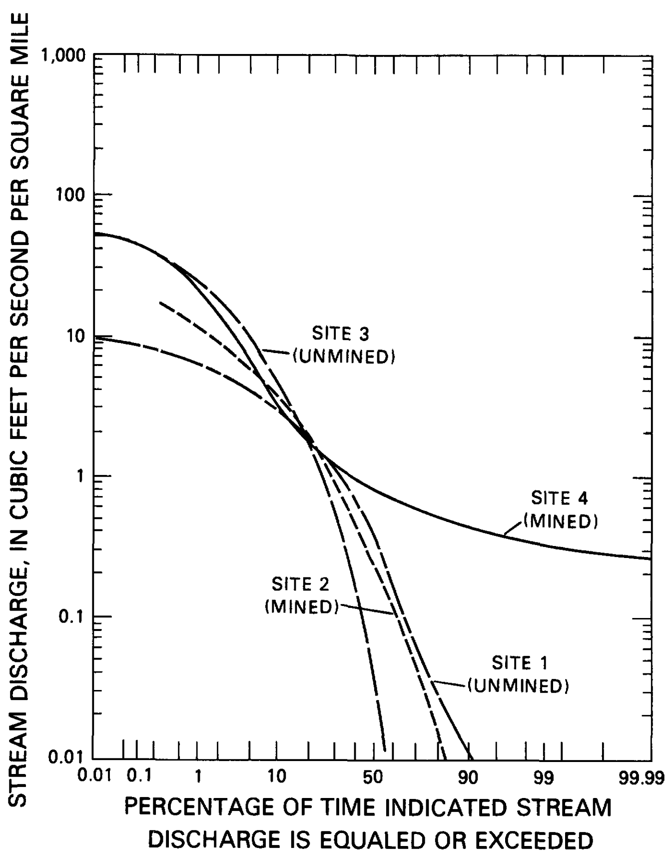
The major objective of the coal-hydrology program in the Eastern region was to quantify the effects of surface mining on surface water. The types of studies related to coal hydrology undertaken throughout the region during the coal-hydrology program may be categorized into area assessments, modeling of small watersheds, and special studies. Area assessments and extensive data-collection efforts aided in the publication of coal-area hydrology reports (table 1). Modeling of small watersheds provided a means of assessing the direct effects of coal mining as well as other land uses. Special studies considered issues having particular characteristics, such as sewage sludge amendments to coal-mined lands.

SURFACE-WATER NETWORK

Presently (1985), stream discharge and stage data are collected at approximately 175 sites, water-quality data at approximately 165 sites, and sediment data at approximately 25 sites in the region. The data-collection sites were increased to 275, 800, and 40, respectively, during the Federal coal-hydrology program, although none of the additional sites remain as parts of the permanent network. The period of record generally is in tens of years for water quantity and less than 10 years for water quality. The original long-term sediment sites are on large streams where apportioning sediment loadings to various land-use practices is difficult. The reader is referred to table 1 and to the U.S. Geological Survey District offices in the respective States for information regarding any particular site.

SURFACE-WATER CHARACTERISTICS

Typical flow-duration curves are shown in figure 25, illustrating the similarity of larger streams in the region whether unmined or mined (Quinones and others, 1983). A report by Martin and others (1987) indicates that stream discharge extremes are more moderate, high flow is not as peaked, and low flow is more sustained in small watersheds that have been mined than in unmined watersheds. Brabets (1984) showed these flow characteristics for small streams in the Illinois part of the region (fig. 25).



EXPLANATION

SITE NUMBER IN FIGURE 24	SITE NAME AND DRAINAGE AREA
1	South Fork Panther Creek near Whitesville, Kentucky (58.2 square miles)
2	Tradewater River at Ulney, Kentucky (255 square miles)
3	Little Cana Creek near Creal Springs, Illinois (1.45 square miles)
4	Bankston Fork near Crab Orchard, Illinois (1.90 square miles)

FIGURE 25.—Typical flow-duration curves for selected streams in the Eastern region. Data for sites 1 and 2 are from Quinones and others (1983); data for sites 3 and 4 are from Brabets (1984).

Using data from the existing network of surface-water sites, many estimations and conclusions can be made. Estimates of mean annual stream discharge in the region are based primarily on drainage area. These estimations are applicable to the streams in the region for which long-term stream-discharge records are available. A relation for estimating mean annual stream discharge based on 38 years of discharge records for 23 surface-water-discharge sites that have drainage areas ranging from 5.54 to 9,549 square miles in coal area 25 is shown in figure 26 (Zuehls and others, 1981a). This relation is typical for streams throughout the region. In addition, stream discharge extremes, including 7-day, 10-year high flow, 7-day, 10-year low flow, and peak discharges, can be estimated using equations developed from many years of discharge records at surface-water-discharge sites in the region and are reported in the coal-area hydrology reports (table 1).

SURFACE-WATER QUALITY

Generally, surface mining affects surface-water quality. The change almost always is a greater concentration of dissolved solids, as indicated by specific-conductance values (fig. 27). Specific-conductance data shown in figure 27 are reported for selected stream sites in coal areas 25 and 35. For all sites measured in the two areas, specific conductance ranged from 85 to 2,720 microsiemens per centimeter at sites upstream from mining and 160 to 9,200 microsiemens per centimeter at sites

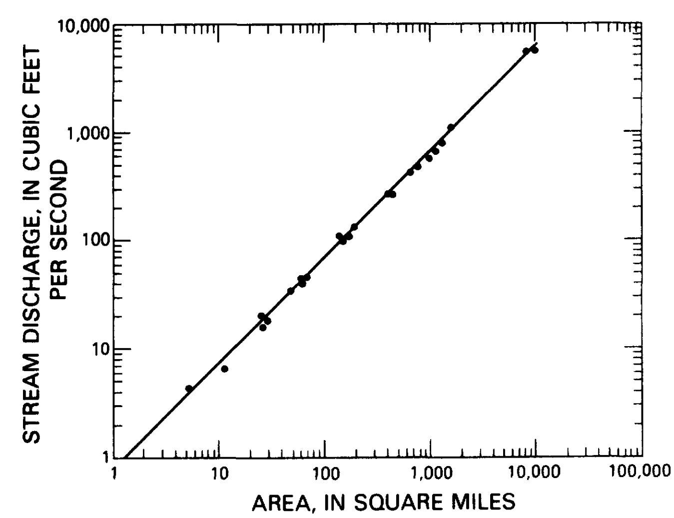
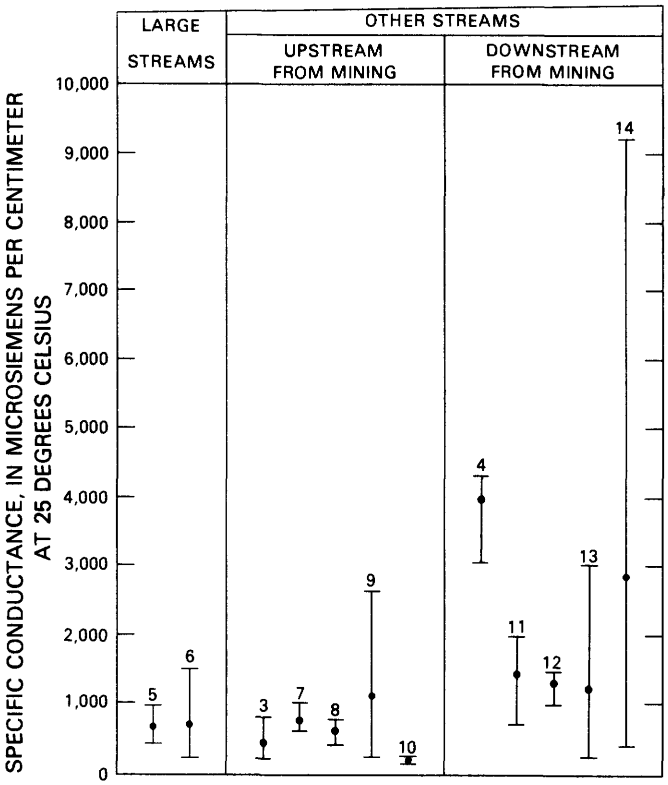


FIGURE 26.—Mean annual stream discharge for selected streams in the Eastern region (modified from Zuehls and others, 1981a).



EXPLANATION

5 — SITE NUMBER

MAXIMUM

MEDIAN

MINIMUM

SITE NUMBER IN FIGURE 24	SITE NAME AND DRAINAGE AREA
3	Little Cana Creek near Creal Springs, Illinois (1.45 square miles)
4	Bankston Fork near Crab Orchard, Illinois (1.90 square miles)
5	Spoon River at Seville, Illinois (1,636 square miles)
6	Big Muddy River at Murphysboro, Illinois (2,169 square miles)
7	Indian Creek near Wyoming, Illinois (62.7 square miles)
8	Turkey Creek near Fiatt, Illinois (11.5 square miles)
9	North Fork Saline River near Texas City, Illinois (173 square miles)
10	Lusk Creek near Eddyville, Illinois (42.9 square miles)
11	Big Creek near Bryant, Illinois (40.3 square miles)
12	Snakeden Hollow near Dahinda, Illinois (9.82 square miles)
13	South Fork Saline River near Carrier Mills, Illinois (147 square miles)
14	Sugar Creek near Stonefort, Illinois (35.4 square miles)

DATA IN FIGURE REPRESENT 5 TO 67 SAMPLES PER SITE DURING 1970-79

FIGURE 27.—Maximum, median, and minimum specific conductance at selected surface-water-quality sites in the Eastern region. Data are from Zuehls and others (1981a, 1981b).

downstream from mining. Several studies (Toler, 1982; Wilber and Boje, 1983; Brabets, 1984) indicate that representations of statistical values for a selected

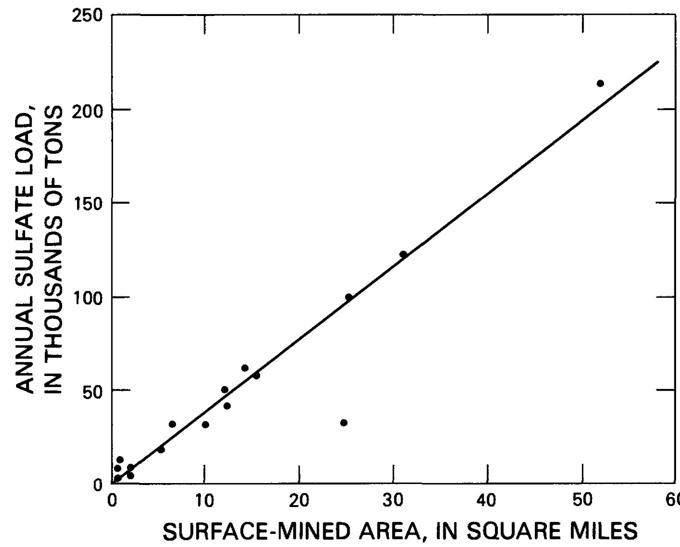


FIGURE 28.—Relation of annual sulfate load to area of surface-mined land for part of the Eastern region (modified from Toler, 1982).

constituent are not as useful as calculations of sulfate loads, for example, in evaluating water quality of surface-mined land in the region (fig. 28). Generally, streams draining mined areas also have larger concentrations of dissolved trace elements, such as iron, manganese, nickel, and zinc and smaller values of pH. Glacial geology also has an effect on stream quality. According to a report by Wilber and others (1985), streams draining Wisconsinan glacial material in Indiana generally have larger values of pH, greater alkalinity, and larger calcium concentrations than streams draining areas of bedrock or pre-Wisconsinan glacial material.

At sites where sediment data are not obtained continuously, it is difficult to determine the total loading of suspended sediment. Wilber and others (1985) concluded that on the basis of present, incomplete data, agricultural land and mined land cannot be distinguished from each other based on sediment yield, but that sediment yields are substantially larger from these lands than from forested land.

GROUND-WATER NETWORK

The U.S. Geological Survey network for collection of ground-water data consists of about 30 wells where ground-water-level information is obtained on a continuous basis and about 10 wells where ground-water-level information is collected on a semiannual basis. Although many other wells were drilled for specific projects, they have been abandoned. Thousands of wells have been drilled in the region, but only limited data are available from local agencies.

GROUND-WATER OCCURRENCE

The major aquifers in the region are unconsolidated glacial deposits; sandstones, coals, and limestones of Pennsylvanian age; limestone and dolomite of Mississippian through Silurian age; and sandstone of Cambrian age. The shallow aquifers are used mainly for domestic supplies. In the southern part of the region, large-capacity wells generally are developed in the deep sandstones. In the northern part of the region, large capacity wells generally are developed in outwash or glaciofluvial channel deposits.

The bedrock units generally are poor water-yielding aquifers, the best being the fractured sandstones and then the coals themselves (Banaszak, 1980). The overlying glacial material, especially sands and gravels in the Wisconsinan till and the glaciofluvial channel deposits, can be productive aquifers (yielding as much as 500 gallons per minute) and capable of supplying cities and towns with water supplies.

GROUND-WATER QUALITY

Generally, ground water in the region is hard to very hard, and dissolved-solids concentrations increase with depth. In the southwestern part of the region, alluvial aquifers had a median dissolved-solids concentration of 323 milligrams per liter, and bedrock aquifers had a median concentration of 519 milligrams per liter. In the eastern part of the region, alluvial aquifers had a median dissolved-solids concentration of 316 milligrams per liter, and bedrock aquifers had a median concentration of 391 milligrams per liter. Shallow waters generally are calcium bicarbonate type, whereas deep waters can be sodium bicarbonate or sodium chloride types.

COAL-HYDROLOGY STUDIES

Area assessments made during the Federal coal-hydrology program provided the general hydrologic and geologic description of the Eastern region. Wilber and Boje (1983) determined that concentrations of metals and other trace elements sorbed onto the clay fraction of streambed materials at 69 sites in coal areas of Indiana. They concluded that concentrations of aluminum, arsenic, cobalt, iron, nickel, and selenium were substantially greater for sediments from mined watersheds than from agricultural or forested watersheds. In Illinois, Brabets (1984) concluded that variability of discharge was less for mined than unmined areas, but that dissolved solids, calcium, and sulfate concentrations were greater for mined areas. Earlier, Toler (1982) determined the same result for sulfate and further noted that relatively large concentrations of dissolved aluminum, arsenic, chromium, copper, iron, manganese, and zinc commonly occur in mine drainages where sulfate concentrations are larger than 2,000 milligrams per liter. In Kentucky, Davis and others (1974) have determined that deep (as much as 1,000 feet) sandstone aquifers contained freshwater. Ground-water studies have indicated the importance of fractures in bedrock to ground-water flow (Banaszak, 1980).

A modeling effort has been directed at assessing the cumulative effects of discharge waters from several mines on a single receiving stream. A theoretical method (Bobay and Banaszak, 1985; Bobay, 1986) has been developed for predicting the chemical effects in surface water caused by the oxidation of iron and manganese. This method explicitly solves chemical reactions on a kinetic basis and mixing reactions on a thermodynamic basis. The method needs to be calibrated using onsite data collected for that purpose and then verified.

Patterson and others (1982) studied the use of sludge irrigation (the sludge used was 5 percent solids) for land reclamation, and they concluded that no difference in ground-water or surface-water quality could be attributed to the application of sludge. The effects of dewatering surface-mine pits have been studied by Weiss (1984) and Weiss and others (1986). They determined, on the basis of a finite difference model, dimensionless values that are used in simple equations applied to hydrogeologic settings typical of the Eastern region. Banaszak (1985) reported on hydrogeologic effects of a hypothetical coal mine in Indiana and concluded that a properly conducted mining operation will have minimal effects external to the mine. Finally, Wilber and others (1985) conclude that: (1) pH levels of streams draining agricultural, forested, and reclaimed mined watersheds generally range from 6.3 to 8.8; (2) pH levels in streams draining unreclaimed mined watersheds are more variable and range from 3.8 to 7.9; (3) boron, iron, manganese, nickel, and zinc concentrations generally are larger in mined watersheds than forested and agricultural watersheds; and (4) iron and manganese concentrations are less in reclaimed mined watersheds than in unreclaimed watersheds.

HYDROLOGIC ISSUES RELATED TO COAL MINING

The major issue of the coal-hydrology program was to quantify the effects of surface mining on surface-water quantity and quality. It has been substantiated that peak flows generally are decreased, low flows are increased, and water quality is degraded in streams draining reclaimed mined land. Evidence from studies in Indiana indicates that even moderate reclamation efforts can yield substantial improvements. Additional data collection and analysis are needed to determine whether regulation of reclamation efforts will make improvements to the extent needed.

The effect of dewatering of mine pits on ground water can be predicted using new techniques. These effects are increased permeability and storage but degraded quality of water.

INTERIOR PROVINCE—WESTERN REGION

By Hugh E. Bevans

The Western region, an area of about 85,000 square miles, is composed of parts of Arkansas, Iowa, Kansas, Missouri, Nebraska, and Oklahoma (fig. 29) and includes coal areas 36–42 (table 1). Although no reports were done for coal areas 36 and 37, data and results from these areas are included in this regional discussion. The region is drained by the Des Moines, Missouri, and Arkansas Rivers and by other western tributaries to the Mississippi River. Three physiographic provinces (pl. 1) occur in the region: (1) The Central Lowland, plains and low hills with local relief ranging from 100 to 300 feet, extends over most of the region; (2) the Ozark Plateaus, tablelands with local relief ranging from 300 to 500 feet, borders the eastern edge of the region; and (3) the Ouachita, high hills and low mountains with local relief ranging from 500 to 3,000 feet, occurs in the extreme southeastern part of the region.

Most of the region has a warm, temperate, rainy climate except for Iowa, which has a cold, temperate, snowy climate. Mean annual precipitation increases from northwest to southeast, averaging about 28 inches in Iowa and about 50 inches in Arkansas. Most precipitation occurs as rain during the growing season; spring and fall are the wettest. Droughts can occur any time of the year but are most severe during the summer when evapotranspiration rates are greatest.

A veneer of sedimentary rocks overlies Precambrian crystalline rock in the region (Eardley, 1951). Most structural features developed during the Paleozoic age when land movements caused the formation of broad basins and arches. During Mississippian, Pennsylvanian, and Permian time, advances and retreats of shallow seas resulted in sequences of marine strata alternating with sequences of nonmarine strata. Subsequent erosion has removed most sedimentary rocks from arches, but thick deposits remain in three prominent basins—the Forest City basin (which underlies southeastern Nebraska, south-central Iowa, northeastern Kansas, and northwestern Missouri), Cherokee basin (which underlies southeastern Kansas and northeastern Oklahoma), and Arkoma basin (which underlies east-central Oklahoma and west-central Arkansas). These basins contain the Pennsylvanian coal resources of the Western region. Bedrock of Pennsylvanian age, primarily marine shales and layers of limestone alternating with layers of coal, is exposed at the surface in most of the region. Along the eastern edge of the region, erosion has removed rocks of Pennsylvanian age, and rocks of Mississippian age (limestone, dolomite, and sandstone) crop out. Along the northwestern edge of the region, rocks of Permian age (shale and limestone) and Cretaceous age (sandstone and shale) overlie rocks of Pennsylvanian age. Rocks of Cretaceous age, sand and weakly cemented sandstone, occur at the surface at the extreme southern tip of the region in Oklahoma. The region has been glaciated generally north of the Kansas River in Kansas and the Missouri River in Missouri. Loess and glacial drift of Pleistocene age have been deposited over bedrock in these areas. Terrace and other alluvial deposits of Holocene age occur in major stream valleys, especially in the Kansas, Missouri, and Arkansas River valleys.

Some of the most agriculturally productive soils in the world have developed in this region under the native vegetation, which is primarily bluestem prairie and, in scattered areas, oak and hickory forest. Crop production, including wheat, sorghum, corn, and soybeans, is the predominant land use in Nebraska, Iowa, northeastern Kansas, and northwestern Missouri (Anderson, 1970). Most of the remaining region is cropland mixed with grazing land although forests are intermixed with cropland and grazing land along the eastern edge of the region. Principal urban areas include Des Moines, Iowa; Topeka, Kansas; Kansas City, Missouri; Kansas City, Kansas; St. Joseph, Missouri; Tulsa, Oklahoma; and Fort Smith, Arkansas.

Principal water uses in the region are electric-power generation, public supplies, industry, and irrigation. Although large volumes of water are used for electric-power generation, most of the water is returned to the streams. Excluding electric-power generation, 60 percent of the total volume of water used in the region is for public supplies, 23 percent is for industry, and 17 percent is for irrigation. Surface-water sources provide 56.5 percent and ground-water sources provide 43.5 percent of the water used.

COAL RESOURCES

The Western region has a demonstrated coal reserve base of about 16 billion tons (Averitt, 1975). The demonstrated coal reserve base consists of coal beds 28 inches or more thick that are located under less than 1,000 feet of overburden. These reserves occur in rocks of Pennsylvanian age. Most of the land containing the reserves is privately owned; however, in Oklahoma, fairly large acreages of coal lands are on Indian reservations. The coal reserves are mostly medium- to high-volatile bituminous (fig. 2), except in extreme east-central Oklahoma and west-central Arkansas where low-volatile bituminous and semianthracite reserves occur. Coal beds, reserves, historic production, and

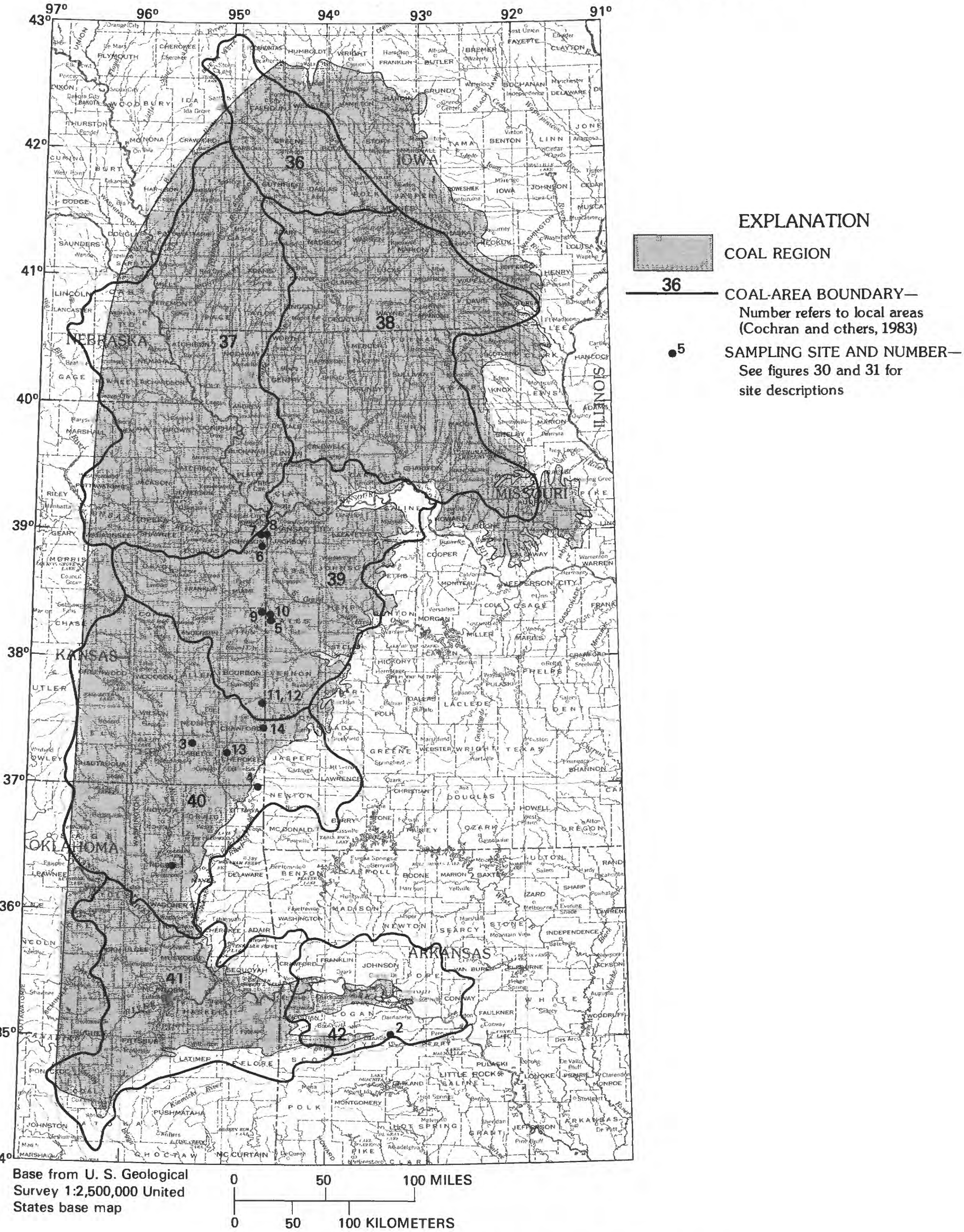


FIGURE 29.—The Western region, coal areas 36-42, and sampling sites.

average as-received analysis of major coal reserves for each State in the Western region are in table 2.

Approximately 1.3 billion tons of coal have been produced in the Western region (table 2). Coal production began in 1840 and peaked about 1920. Production generally declined from the 1920's through the 1950's. Since 1960, coal production has increased in Missouri and Oklahoma and peaked in these States during the late 1970's. Prior to the 1930's, most coal was produced by underground mining. Since the 1960's, almost all production has been from surface mines.

HYDROLOGY

The generalized objectives for the coal-hydrology program in the region were to collect hydrologic data relevant to coal mining and to use these data in conjunction with available data and reports to describe the quantity and quality of surface- and ground-water resources and the hydrologic effects of coal mining. To fulfill these objectives, the hydrologic-data network was expanded, coal-area hydrology reports were prepared, and interpretive hydrologic studies were undertaken. Coal-area investigations used available information from reports and data files to describe: (1) Physical features (climate, geology, and physiography); (2) coal mining (mining methods, coal production, locations of mined areas, and coal reserves; (3) cultural features (population, land use, and water use); and (4) hydrology (hydrologic data base, streamflow and water-quality characteristics, ground-water occurrence and quality, and hydrologic effects of coal mining).

TABLE 2.—*Coal beds, reserves, historic production, and average as-received analysis of major coal reserves for each State in the Western region*

[Btu, British thermal units; ----, data not available]

State	Coal beds	Coal reserves (millions of short tons)[1]	Historic coal production (millions of short tons)[1]	Average as-received analysis: Moisture (range, in percent)	Volatile matter (range, in percent)	Fixed carbon (range, in percent)	Ash (range, in percent)	Sulfur (range, in percent)	Heating value (range, in Btu's per pound)
Nebraska[2]	Nodaway, Elmo, Wamego, Lorton, and Honey Creek.	10	>1	17–35	26–34	21–41	8–20	1–6	4,400–9,700
Iowa[3]	Laddsdale, Carruthers, White Breast, Wheeler, Bevier, and Mystic.	2,885	370	4–13	31–37	35–47	11–29	4–8	8,800–10,500
Kansas[4]	Mineral, Bevier, Mulberry, and Nodaway.	1,388	290	5–10	----	----	10–14	3–7	11,100–12,600
Missouri[5]	Rowe, Drywood, Weir-Pittsburg, Tebo, Mineral, Fleming, Croweburg, Bevier, Mulky, Summit, Lexington, and Mulberry.	9,488	350	7–14	31–40	39–54	9–19	3–5	10,500–12,300
Oklahoma[6]	Lower and Upper Hartshorne, McAlester (Stigler, Secor, Mineral, Morris), Croweburg, and Iron Post.	1,294	200	dry–7	17–45	44–74	4–16	1–6	11,000–14,400
Arkansas[7]	Lower Hartshorne and Paris.	665	100	1.8–2.5	12–18	69–75	7–12	1–3	13,000–14,100

[1]Data from Averitt, 1975.
[2]Data from Burchett, 1977.
[3]Data from Landis and Van Eck, 1965; Avcin and Koch, 1979; Hatch and others, 1984.
[4]Data from Brady and Dutcher, 1974; Brady and others, 1976; Ebanks and others, 1979.
[5]Data from Wedge and others, 1976; Robertson and Smith, 1981.
[6]Data from Friedman, 1974.
[7]Data from Haley and others, 1979; Howard, 1984.

SURFACE-WATER NETWORK

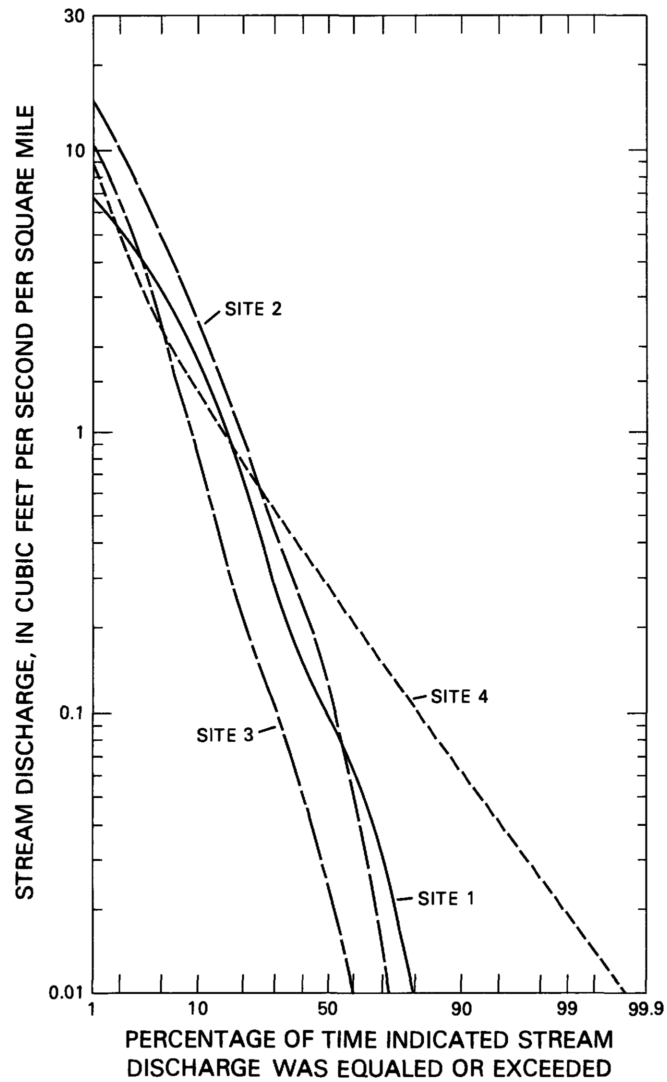
To provide hydrologic data for coal-hydrology investigations in the 1970's, approximately 115 stream-discharge and surface-water-quality sites, and 50 strip-mine-pond, water-quality sites were established in the Western region. Nearly all of these data-collection sites have been discontinued because the investigations supporting them have been completed. However, long-term data are available for many other sites. During 1982, the U.S. Geological Survey collected hydrologic data at 191 continuous-record stream-discharge and reservoir sites and at 51 surface-water-quality sites (chemical, sediment, and (or) biological data) in the Western region. High- and low-stream-discharge, miscellaneous stream discharge, and miscellaneous surface-water-quality data also were collected.

SURFACE-WATER CHARACTERISTICS

In the region, stream discharge varies over time in response to daily, seasonal, and longer term fluctuations in climatic factors (precipitation and evapotranspiration); discharge also varies spatially in response to differences in climate, topography, and geology. Daily variations in stream discharge are caused by variations in precipitation. When sufficient precipitation occurs and produces overland runoff, discharge increases to a peak and then decreases as precipitation and overland runoff diminish and cease. Seasonal variations in stream discharge primarily occur because of differences in precipitation and evapotranspiration. Stream discharge is greatest during the spring and fall when precipitation quantities are large and evapotranspiration rates are least. The least discharge generally occurs during the summer when precipitation quantities are small and evapotranspiration rates are greatest.

Average annual runoff generally increases from northwest to southeast in response to increasing precipitation in that direction (Busby, 1966). Flow-duration curves (fig. 30) indicate the percentage of time that a specified stream discharge was equaled or exceeded. The part of the flow-duration curve that shows stream discharges that are equaled or exceeded only a small percentage of the time (during high flows) represents discharge provided by overland runoff. The part of the flow-duration curve showing stream discharges that are equaled or exceeded most of the time (during low flows) represents discharge provided mainly by base flow from ground water.

The flow-duration curves for the Verdigris River (site 1), Petit Jean River (site 2), and Big Hill Creek (site 3) are characteristic of streams draining rocks of Pennsylvanian age (mainly shale). The steep slopes of the curves indicate that stream discharge primarily results from surface runoff, is quite variable, and is not well sustained by base flow. The Verdigris River has more stream discharge per square mile during low-flow periods than the other streams draining rocks of Pennsylvanian age because its drainage basin has more alluvium, which provides larger volumes of base flow.



EXPLANATION

SITE NUMBER IN FIGURE 29	SITE NAME AND DRAINAGE AREA
1	Verdigris River near Claremore, Oklahoma (6,534 square miles)
2	Petit Jean River near Booneville, Arkansas (241 square miles)
3	Big Hill Creek near Cherryvale, Kansas (37.0 square miles)
4	Spring River near Quapaw, Oklahoma (2,510 square miles)

FIGURE 30.—Typical flow-duration curves for selected streams in the Western region. Data for sites 1, 3, and 4 are from Marcher, Kenny, and others (1984); data for site 1 are from Bryant and others (1983).

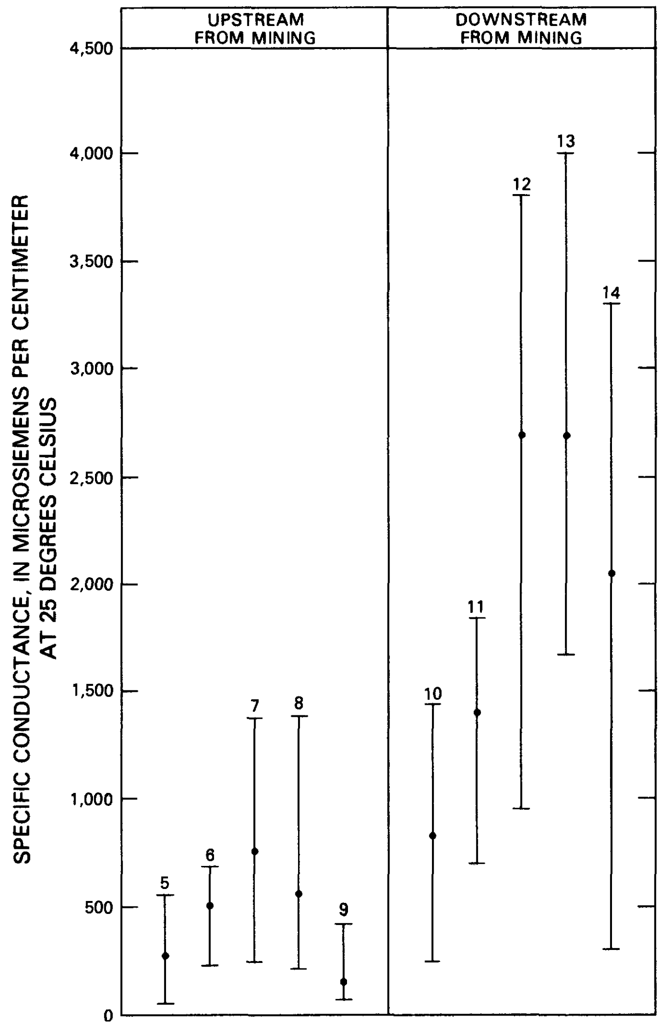
The generally greater discharge of the Petit Jean River is because of greater precipitation. The smaller streams generally have more stream discharge per square mile during high flows than large streams because smaller basins have steeper slopes and because an individual storm is more likely to cover completely a small drainage basin than a large one. The slope of the flow-duration curve representing the Spring River (site 4) is much flatter than those curves representing the other streams. The Spring River drains rocks of Mississippian age (limestone, dolomite, and sandstone), which provide greater volumes of base flow than do rocks of Pennsylvanian age.

Average-, high-, and low-flow characteristics have been determined for stream-discharge sites that have sufficient discharge records, and techniques have been developed for estimating these characteristics at ungaged sites. These characteristics, techniques, and additional information about stream discharge are available in coal-area hydrology reports for the region (table 1). For example, in coal area 38, equations for estimating average annual flows and flood peaks for selected recurrence intervals have been developed (Detroy, Skelton, and others, 1983). Also, in coal area 38, most streams that drain areas less than 50 square miles will cease to flow for 7 consecutive days during 50 percent of the years.

SURFACE-WATER QUALITY

The quality of water in streams in the region generally is dependent on the source of water providing the streamflow. Streamflow provided by ground-water discharge (base flow) usually has larger concentrations of dissolved solids than streamflow that results from overland runoff, because ground water has been in contact with minerals in the rocks for a relatively long time. As streamflow increases from overland runoff, concentrations of dissolved solids are diluted.

The types of dissolved constituents in streams during base flow indicate the mineralogy of aquifer materials. Streams draining areas where limestone or dolomite crop out generally have relatively large concentrations of calcium, magnesium, and bicarbonate. Streams draining areas where shale crops out can have relatively large concentrations of sodium, chloride, and sulfate. Generally, measured dissolved-solids concentrations in streams are less than 500 milligrams per liter and range from less than 100 milligrams per liter in Arkansas to more than 2,550 milligrams per liter in the Canadian River basin in the extreme southwestern part of the region in Oklahoma (Rainwater, 1962). A comparison of specific-conductance values for selected streams draining unmined and mined areas is shown in figure 31.



EXPLANATION

5 SITE NUMBER
MAXIMUM
MEDIAN
MINIMUM

SITE NUMBER IN FIGURE 29	SITE NAME AND DRAINAGE AREA
5	Unnamed tributary to Mulberry Creek near Amoret, Missouri (5.42 square miles)
6	Blue River near Stanley, Kansas (46.0 square miles)
7	Indian Creek at Overland Park, Kansas (26.6 square miles)
8	Tomahawk Creek near Overland Park, Kansas (23.9 square miles)
9	North Sugar Creek tributary 3, below La Cygne Lake, Kansas (1.96 square miles)
10	Mulberry Creek at Mulberry, Missouri (16.2 square miles)
11	Cox Creek tributary near Mulberry, Kansas (8.00 square miles)
12	Cox Creek 1 mile south of Arcadia, Kansas (30.0 square miles)
13	Deer Creek near Hallowell, Kansas (7.00 square miles)
14	East Cow Creek at Frontenac, Kansas (7.50 square miles)

FIGURE 31.—Maximum, median, and minimum specific conductance at selected surface-water-quality sites in the Western region. Data are from Detroy, Skelton, and others (1983) and Marcher, Kenny, and others (1984).

During high streamflow, there are increases in concentrations of suspended sediment and some constituents, such as iron and manganese, that are sorbed to suspended sediment. Mean annual suspended-sediment concentrations of streams in the region increase from less than 270 milligrams per liter in the southern and eastern parts of the region to more than 6,350 milligrams per liter in the western part (Rainwater, 1962), generally because the eastern part has more forest and woodland and the western part has more cropland.

GROUND-WATER NETWORK

To provide ground-water data for coal-hydrology investigations in the 1970's, approximately 100 ground-water-level and (or) ground-water-quality sites were established in the Western region. Nearly all these data-collection sites have been discontinued because the investigations supporting them have been completed. During 1982, the U.S. Geological Survey collected ground-water-level data at 122 observation wells in the region. Miscellaneous ground-water-quality data also were collected.

GROUND-WATER OCCURRENCE

Ground-water resources are limited in most of the region. Although ground water occurs throughout the area and there is ample precipitation to provide recharge, well yields are controlled by hydrogeologic properties of aquifers. The following discussion is based on State summaries presented in U.S. Geological Survey (1985). Bedrock of Pennsylvanian age, primarily fine-grained shale with some limestone, is present at or near the surface throughout most of the region. Wells in rocks of Pennsylvanian age generally yield less than 50 gallons per minute; wells in these rocks are shallow and frequently go dry during droughts. Cretaceous sandstones in the southwestern and northwestern parts of the region are productive aquifers and commonly yield 50 to 500 gallons per minute. Carbonate-rock aquifers of Cambrian, Ordovician, and Mississippian age, primarily limestone and dolomite with some sandstone, occur along the eastern edge of the region and commonly yield 50 to 100 gallons per minute. Alluvial aquifers of clay, silt, sand, and gravel are present in valleys of the Missouri, Kansas, East and West Nishnabotna, Platte, Grand, Thompson, Chariton, Des Moines, Osage, Canadian, and Arkansas Rivers, and yields commonly exceed 1,000 gallons per minute. Glacial-drift aquifers and buried alluvial-valley aquifers occur primarily north of the Kansas and Missouri Rivers. Water yields from these aquifers may exceed 500 gallons per minute in some parts of the region. Alluvial and glacial-drift aquifers are recharged easily by precipitation and surface drainage.

GROUND-WATER QUALITY

Water from rocks of Pennsylvanian age, which occur at the surface in most of the region, can have large concentrations of sodium, chloride, and sulfate if the water is from a shale formation. Calcium and bicarbonate generally are the major dissolved constituents in water from limestone formations. In or near outcrop areas where bedrock aquifers receive recharge, concentrations of dissolved solids usually are less than 1,000 milligrams per liter. As the strata dip toward the west, the ground water becomes more mineralized and generally is not used.

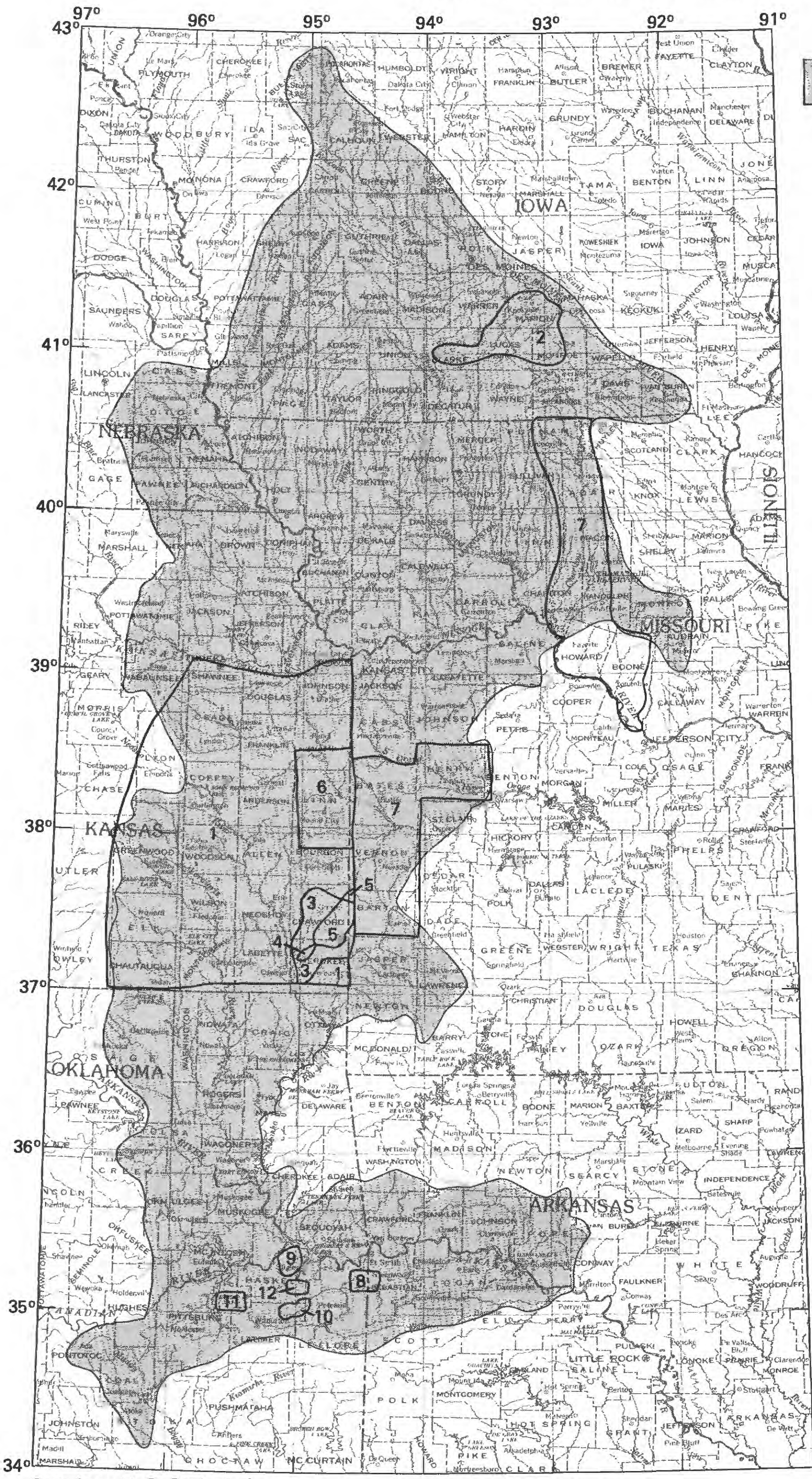
The Cretaceous sandstone aquifers yield calcium magnesium sulfate type water in the northwestern part of the region and sodium or calcium bicarbonate type water in the extreme southwestern part of the region. The limestone and dolomite aquifers of Cambrian, Ordovician, and Mississippian age generally yield calcium bicarbonate type water along the eastern edge of the region.

Water from the alluvial aquifers generally is a calcium magnesium bicarbonate type, and concentrations of dissolved solids generally are less than 500 milligrams per liter. Glacial-drift aquifers and buried alluvial-valley aquifers that occur north of the Kansas and Missouri Rivers yield calcium bicarbonate type water. Concentrations of dissolved solids generally are less than 500 milligrams per liter in water from shallow wells, but concentrations usually increase with depth. Alluvial and glacial-drift aquifers are very susceptible to contamination from surface sources.

COAL-HYDROLOGY STUDIES

Reports of U.S. Geological Survey coal-hydrology studies are available for Iowa, Kansas, Missouri, and Oklahoma (fig. 32 and table 1); some results are described briefly here. These reports contain hydrologic information necessary to determine the effects of coal mining on water resources. Several of the reports present hydrologic data collected during the investigation; the other reports are interpretive and either provide areal descriptions of the physical setting, coal-mining activities, cultural features, hydrology, and hydrologic effects of coal mining and (or) present methods used to identify, assess, or predict various hydrologic effects of coal mining.

The water quality of coal-mining areas in south-central Iowa was investigated in cooperation with the Iowa Department of Environmental Quality. The report



Base from U. S. Geological Survey 1:2,500,000 United States base map

0 50 100 MILES

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EXPLANATION

COAL REGION

LOCATION OF COAL-HYDROLOGY STUDIES

1 Estimating stream-aquifer interactions in coal areas of eastern Kansas (Bevans, 1986)

2 Baseline water quality of Iowa's coal region (Slack, 1979)

3 Statistical summaries of water-quality data for streams draining coal-mined areas, southeastern Kansas (Bevans and Diaz, 1980)

3 A procedure for predicting concentrations of dissolved solids and sulfate ions in streams draining areas strip mined for coal (Bevans, 1980)

4 Applications of remote-sensing techniques to hydrologic studies in selected coal-mined areas of southeastern Kansas (Kenny and McCauley, 1983)

5 Quality-of-water data and statistical summary for selected coal-mined strip pits in Crawford and Cherokee Counties, southeastern Kansas (Pope and Diaz, 1982)

6 Physical and hydrologic environments of the Mulberry coal reserves in eastern Kansas (Kenny and others, 1982)

6 Hydrologic responses of streams to mining of the Mulberry coal reserves in eastern Kansas (Bevans, 1984)

7 Physical environment and hydrologic characteristics of coal-mining areas in Missouri (Vaill and Barks, 1981)

8 Preliminary appraisal of the hydrology of the Rock Island area, Le Flore County, Oklahoma (Marcher and others, 1983b)

9 Preliminary appraisal of the hydrology of the Stigler area, Haskell County, Oklahoma (Marcher and others, 1982)

10 Preliminary appraisal of the hydrology of the Red Oak area, Latimer County, Oklahoma (Marcher and others, 1983c)

11 Preliminary appraisal of the hydrology of the Blocker area, Pittsburg County, Oklahoma (Marcher and others, 1983a)

12 Hydrology of an abandoned coal-mining area near McCurtain, Haskell County, Oklahoma (Slack, 1983)

FIGURE 32.—Location of areas of coal-hydrology studies done in the Western region.

of this investigation provides surface-water-quality data representing high-, average-, and low-flow conditions for White Breast, English, and Cedar Creeks (Slack, 1979).

The U.S. Geological Survey made a coal-hydrology investigation of an area underlain by strippable reserves of coal in east-central Kansas. The results of this investigation were published in two reports. The first report describes the physical and hydrologic environments of the study area based on available data and reports (Kenny and others, 1982). The second report evaluates the effects of abandoned coal mines on areal surface-water quality and the effects of an active strip mine on streamflow and water-quality characteristics of small streams (Bevans, 1984). Results of this investigation indicate that most streams contained dissolved-solids concentrations less than 500 milligrams per liter. However, streams draining abandoned coal-mined areas contained larger concentrations of sulfate than streams draining unmined areas; and a small stream draining an active strip mine had less high flow and more low flow, a 41 percent larger load of dissolved solids, a 244 percent larger load of sulfate, and a 25 percent larger load of suspended sediment than a small stream draining a nearby unmined control basin.

Stream-aquifer interactions in coal areas of eastern Kansas were investigated by Bevans (1986). Basin constants (equivalent to the aquifer transmissivity divided by the product of the aquifer storage coefficient and the squared average distance from the stream to the ground-water divide) were developed by analyzing the slopes of base-flow recession curves. The basin constants then were used in conjunction with discharge records to estimate ground-water recharge, storage, and discharge that resulted from one or more periods of recharge and to estimate the rate of evapotranspiration. A regional regression equation was developed for estimating basin constants for ungaged basins.

Channel-geometry techniques for estimating streamflow characteristics were applied to surface-mined areas in a report by Osterkamp and Hedman (1979). Simple- and multiple-power-function equations relating channel configuration and channel-material data to mean and peak stream discharge were developed for perennial streams in the Central and Western United States and for ephemeral streams in the Western United States. The equations for perennial streams also probably can be applied in the Eastern United States.

The Kansas Department of Health and Environment and the U.S. Geological Survey cooperated in a coal-hydrology investigation in Crawford and Cherokee Counties, Kansas. Reports published from this investigation present: (1) Statistical summaries of water-quality data and regression equations that relate stream discharge and specific conductance to concentrations of selected chemical constituents (Bevans and Diaz, 1980); and (2) regression equations that can be used to predict instream concentrations of dissolved solids and sulfate from the percentage of drainage basin that was strip mined (Bevans, 1980).

An investigation of the Cherry Creek basin in Cherokee County, Kansas, by the U.S. Geological Survey in cooperation with the Kansas Department of Health and Environment and the Kansas Geological Survey, applied and evaluated remote-sensing techniques for coal-hydrology studies. Color and color-infrared aerial photography were used with simultaneously collected water-quality samples to identify cause-and-effect relations between land, water, and vegetation disturbances. Types and extent of vegetation on abandoned and reclaimed mine lands, drainage patterns, point sources of acid mine drainage, and recharge areas of underground mines were determined from aerial photography (Kenny and McCauley, 1983).

The Office of Surface Mining Reclamation and Enforcement cooperated with the U.S. Geological Survey in an investigation of water-quality characteristics of coal-mine strip pits in Crawford and Cherokee Counties, Kansas. The report of this investigation contains a statistical summary of water-quality data collected from the strip pits and regression equations that relate specific conductance, concentration of dissolved solids, and acidity to concentrations of selected chemical constituents (Pope and Diaz, 1982).

The U.S. Geological Survey investigated the coal-mining areas in Missouri. The report of this investigation describes the physical environment, coal-mining practices, general hydrology, and the 1980 hydrologic-data base for the north-central and western coal-mining regions. Water in streams draining unmined areas generally had pH values near neutral (7.0) and concentrations of dissolved solids less than 400 milligrams per liter. However, water from some streams affected by coal-mine drainage had pH values less than 4.0 and concentrations of dissolved solids greater than 1,000 milligrams per liter (Vaill and Barks, 1981).

The hydrology of an abandoned coal-mining area near McCurtain in Haskell County, Oklahoma, was investigated by the U.S. Geological Survey. The report presents hydrologic data collected during the investigation, an evaluation of the water resources of the area, and an appraisal of the probable effects of reclamation (Slack, 1983). Analysis of water-quality data from a stream draining abandoned and reclaimed surface mines indicated that concentrations of dissolved constituents, principally sulfate but also calcium, magnesium, sodium, chloride, and alkalinity, were larger in reaches of the stream that drained abandoned mines. Also, instream concentrations of these constituents increased as the area of abandoned mines drained by the stream increased.

The U.S. Geological Survey, in cooperation with the U.S. Bureau of Land Management, investigated water-resources effects of coal mining on Federal coal lands in Oklahoma. Reports containing hydrologic data, descriptions of the physical settings, preliminary appraisals of hydrology, and probable hydrologic effects of coal mining have been published for the Blocker area in Pittsburg County (Marcher and others, 1983a), the Stigler area in Haskell County (Marcher and others, 1982), the Rock Island area in Le Flore County (Marcher and others, 1983b), and the Red Oak area in Latimer County (Marcher and others, 1983c). Results of these investigations indicate that streams draining unmined parts of these areas had mean concentrations of dissolved solids ranging from 50 milligrams per liter in the Red Oak area to 322 milligrams per liter in the Rock Island area. Streams draining mined parts of the areas had mean concentrations of dissolved solids ranging from 132 milligrams per liter in the Red Oak area to 1,766 milligrams per liter in the Stigler area. Concentrations of iron and manganese were larger downstream from areas of old and recent strip mining in the Red Oak area than in unmined parts of the area. Information about other coal-hydrology investigations in the Western region that are not yet completed, or for which reports are not yet published, can be obtained from U.S. Geological Survey district offices in this region.

HYDROLOGIC ISSUES RELATED TO COAL MINING

Surface and underground mining of coal disturbs the hydrologic environment, often affecting the quantity and quality of surface and ground water in the region. The clearing of land prior to surface mining causes increased runoff and erosion, which increases concentrations and loads of suspended sediment in receiving streams. Sediment ponds constructed to intercept runoff from active surface mines regulate discharge by decreasing flows. However, concentrations and loads of suspended sediment in streams draining active mines are larger than normal because colloidal clay particles often do not settle out if detention times in the sediment ponds are relatively short and flocculating agents are not used (Bevans, 1984). As mining proceeds, excavation exposes unweathered bedrock to physical and chemical weathering.

In most of the region, excess acidity generated from weathering of iron sulfide minerals increases the weathering of calcite and dolomite, leaving increased concentrations of dissolved solids (sulfate, bicarbonate, calcium, and magnesium) in solution. However, in shaft-mined areas where carbonate rocks are not exposed during mining, excess acidity decreases the pH, thereby releasing iron, manganese, aluminum, lead, zinc, and other metals into solution (Kenny and others, 1982). Median values and ranges of specific conductance often are greater in streams draining mined basins. A comparison of specific-conductance values for selected streams draining unmined and mined basins is shown in figure 31. Specific conductance and concentrations of dissolved solids increase as the percentage of drainage basin that is mined increases (Bevans, 1980).

If an aquifer is disturbed during mining, water will be pumped from the mine, and local water levels may decline. After mining ceases, the ridge-and-furrow topography and strip pits of abandoned surface mines and the mine shafts and sinkholes above collapsed tunnels of abandoned underground mines intercept runoff and increase recharge, thereby decreasing high flow and increasing base flow in streams that drain the mines. Reclaimed surface mines, which have been graded to approximate the original topography and have been planted in grass, probably will not affect ground-water levels or flow in adjacent streams within the region.

Small streams draining mined areas in the region often are contaminated during low-flow conditions by base flow that has large concentrations of sulfate and other dissolved constituents or by acid mine drainage. During runoff, the contamination is diluted (Bevans, 1980). Active and abandoned surface mines will contribute large quantities of sediment to receiving streams until vegetation is reestablished. Reclaimed surface mines yield quantities of sediment comparable to undisturbed areas. Water-quality degradation in streams that results from coal mining usually is only a local issue because runoff and base flow from unmined parts of a drainage basin dilute the coal-mine drainage.

NORTHERN GREAT PLAINS AND ROCKY MOUNTAIN PROVINCES—FORT UNION REGION

By ORLO A. CROSBY and CLARENCE A. ARMSTRONG

The Fort Union region (fig. 33), an area of about 45,000 square miles in east-central Montana (about 14,000 square miles), western North Dakota (about 30,000 square miles), and northwestern South Dakota (about 1,000 square miles), includes coal areas 45-47 (table 1). About 41,000 square miles of the region is in the Missouri River drainage basin and about 4,000 square miles is in the basins of the Des Lacs and Souris

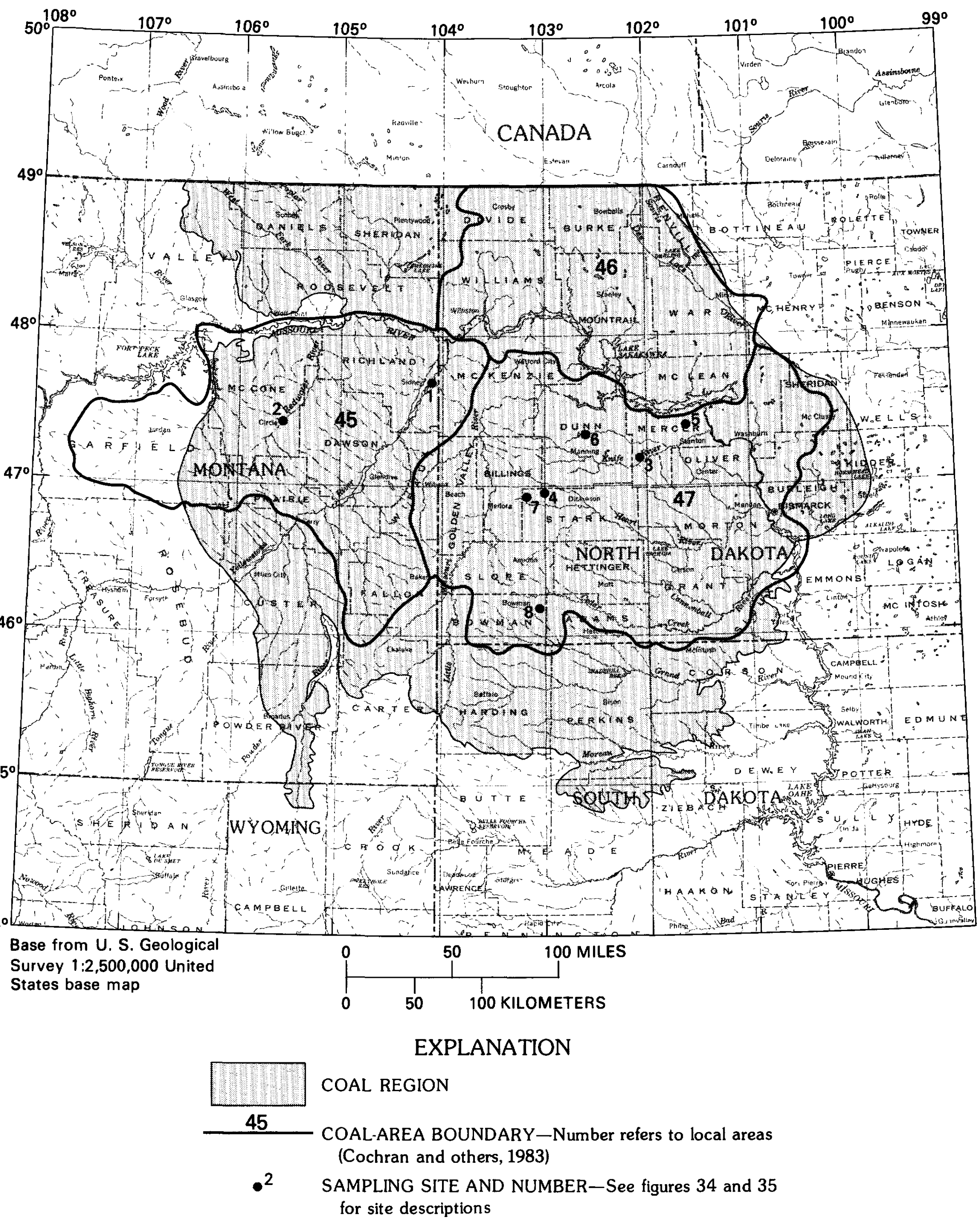


FIGURE 33.—The Fort Union region, coal areas 45-47, and sampling sites.

Rivers in northwestern North Dakota. Although generally included in the basin of the Missouri River, the Coteau du Missouri, a part of the Great Plains province in northwestern North Dakota (pl. 1), contributes little or no surface flow to the river basin, although it contains many prairie potholes, sloughs, and small lakes.

The region is in the Great Plains and Central Lowland physiographic provinces (pl. 1). The Coteau du Missouri, a part of the Great Plains physiographic province, is a series of elongated hills, ridges, sloughs, and prairie potholes that is bounded on the north by a scarp that grades into the Central Lowland physiographic province. The Central Lowland physiographic province in the region is characterized by a northeastward-sloping plain with a few low, rounded hills and shallow depressions.

Mean annual precipitation ranges from 12 inches in the western part of the region to about 18 inches in the east-central part. About 65 percent of the annual precipitation occurs during May through August. Most of the precipitation that falls during June, July, and August is the result of thunderstorm activity (U.S. Weather Bureau, 1962). Mean annual snowfall is about 36 inches. Mean annual lake evaporation ranges from about 34 inches in the northeastern part of the region to about 45 inches in the southwestern part (National Oceanic and Atmospheric Administration, 1982).

The entire region is located within the ovate Williston basin. The axis of the basin trends north-northwest, and the deepest part is in eastern McKenzie County, North Dakota. Maximum thickness of the sedimentary rocks of Cretaceous and Tertiary age is about 15,000 feet.

The oldest formation exposed in the area is the Cretaceous Bearpaw Shale or the equivalent Pierre Shale. The overlying marine Fox Hills Sandstone and the continental Hell Creek Formation that overlies the Fox Hills Sandstone also crop out in scattered locations in Montana. The Fox Hills Sandstone generally is considered the deepest formation that could yield freshwater; it consists of sandstone and interbedded siltstone, shale, and sandy shale. The Hell Creek Formation is composed of interbedded sandstone, claystone, and lignitic shale.

Glacial drift, primarily till and glaciofluvial deposits, covers the northeastern part of the region. Glacial till, where present, ranges in thickness from 0 to as much as 600 feet. Glaciofluvial deposits are variable in thickness but can be as much as 400 feet thick. Alluvium consisting of clay, silt, sand, and gravel is as much as 40 feet thick and occurs in channels and flood plains of present-day streams.

At present (1985), land use in the area is about 52 percent rangeland, 38 percent cropland, 1 percent woodland, and 9 percent other uses (primarily urban and developed areas). About 86 percent of the land surface is privately owned; about 9 percent is federally owned and administered primarily by the U.S. Forest Service as National Grasslands; and about 5 percent is owned by the State. About 35 to 40 percent of the coal in the region is federally owned, about 5 percent is owned by the States, and the rest is privately owned. Coal ownership is shown in detail on maps available from the U.S. Bureau of Land Management (1974, 1975, and 1977).

The population of the region is about 280,000 (U.S. Bureau of Census, 1981). Cities with populations of more than 5,000 are Bismarck, Dickinson, Mandan, Minot, and Williston, North Dakota, and Glendive and Sidney, Montana.

Thermoelectric-power generation and irrigation account for about 95 percent of the water used in the region. About 97 percent of the total water used is obtained from surface-water sources and about 3 percent is obtained from ground-water sources.

COAL RESOURCES

Coal in the study area is classified as lignite (fig. 3), and much of it is near the land surface where it can be mined economically using surface-mining techniques. Estimates of coal reserves in the region vary greatly. Strippable lignite reserves in Montana were estimated by Slagle and others (1984) to be about 7.3 billion tons, about 20 percent of previous estimates made by the U.S. National Research Council (1981a). Similarly, strippable reserves in North Dakota (fig. 33) were estimated to be about 4.2 billion tons by Pollard and others (1972), about half the estimate of the U.S. National Research Council (1981a). Pollard and others (1972) did not include in their estimate any coal beds less than 5 feet thick, even though they might overlie the principal bed to be mined. In 8 of the 16 coal deposits evaluated in North Dakota, they also did not include any coal that might occur beneath more than 50 feet of overburden. Current limits on overburden stripping in the State are about 150 feet. In attempting to correct the estimates of Pollard and others (1972) for the deficiencies noted, the North Dakota Geological Survey during 1981 estimated reserves at about 15 billion tons of strippable coal in the State (North Dakota Geological Survey, 1981), about twice the U.S. National Research Council (1981a) estimate. No strippable coal reserves occur in South Dakota.

Coal mining in the region began during the late 1800's. Early production was from small underground mines that provided fuel for local consumption. When equipment became available, strip mining began and increased until about 1940, when 2,230,000 tons were produced in the region—800,000 tons from underground mines. Total production of coal generally increased at an irregular rate to about 8.5 million tons from July 1975 through June 1976. Production from underground mines decreased and had ceased by 1966. From July 1979 through June 1980, about 17 million tons of coal was produced from 13 coal mines in North Dakota and 1 coal mine in Montana. A history of coal mining in North Dakota has been chronicled by Oihus (1983).

Most of the coal presently (1985) is being used for the production of electricity, but some is used for the manufacture of synthetic natural gas, charcoal briquettes, drilling-mud additives, and organic solvents. The largest production of coal is in Mercer, Oliver, and western McLean Counties, North Dakota, where about 10 million tons of coal is mined annually to supply nearby powerplants.

HYDROLOGY

Many data-collection changes occurred in the region as part of the cooperative U.S. Geological Survey and U.S. Bureau of Land Management coal-hydrology program. New stream-discharge and surface-water-quality sites were added, and some historical sites were expanded.

Because of funding decisions, most of the stream-discharge and surface-water-quality sites have been discontinued. The data that were collected constitute a substantial data base from which changes due to present or future coal mining may be substantiated; however, detailed studies probably will be needed to determine the rate and extent of the changes that may occur. During 1983, the U.S. Geological Survey in cooperation with the North Dakota Public Service Commission established two programs in which eight of the previously established stream-discharge and surface-water-quality sites are monitored at 6-week intervals. Monitoring at these sites is expected to continue until mining at upstream sites ends, thus providing a nearly complete record of the effects of mining activities in the basins being monitored.

Water-quality sampling began in the coal areas as early as 1945, but it was not until the mid-1970's that the need for a much larger water-quality data base was recognized. At about the same time the coal-area studies were being initiated, an expanded suite of water-quality determinations also was made at most coal-area sites. The expanded suite of constituents collected included onsite determinations of specific conductance, pH, alkalinity, dissolved oxygen, and water temperature and laboratory determinations of common ions, nutrients, and sediment. In addition, trace elements, pesticides, radioactive constituents, microbiological and biological contents, and some organic compounds were determined on an irregular basis.

SURFACE-WATER NETWORK

The surface-water data-collection network in the region started with the establishment of a few continuous-record stream-discharge sites during 1903. The number of continuous-record sites has fluctuated but generally increased with time to the present (1985) number. The first sites were established as part of a water-accounting system and were located on the Missouri and Souris River main stems and on the major tributaries to the Missouri River. Additional sites soon were established on these tributaries and other streams as the demands for water increased. The early established sites provide a long-term record from which surface-water statistical information can be obtained. The long-term records also can be used to extend incomplete or short-term records using correlation techniques. However, regulation, storage, or diversion on many streams has rendered invalid the usage of parts of long-term records to define surface-water characteristics.

Before 1970, most of the continuous-record stream-discharge sites were established on the larger perennial streams to meet some specific water-management need. During the 1970's, the continuous-record stream-discharge measurement site network was expanded to obtain data to evaluate the hydrology of the region.

Generally, sites established during the 1970's were established in response to the U.S. Bureau of Land Management's energy-related responsibilities. As a result, 10 continuous-record stream-discharge sites and 15 crest-stage stream-discharge sites were added to those in Montana. Forty-five continuous-record stream-discharge sites were added to those previously established in North Dakota. One continuous-record stream-discharge site was added in South Dakota.

Miscellaneous stream-discharge measurements (generally low flow) were made at 104 sites in the region. Many of the measurements were made as part of 13 small-area coal studies. These stream-discharge measurements were used to determine the ground-water contribution to streamflow.

Interest in low-flow characteristics has resulted in periodic measurements of low-flow discharge on many large and small streams for 1 or more years. Because of the ephemeral nature of the streams and the varied sources of low-flow discharge, correlation of low flow between sites is poor, and onsite measurements are the only dependable source of information.

A network of crest-stage stream-discharge sites was established along a number of streams during 1954–55. Most of these sites in North Dakota were discontinued during 1973. Data from these sites, in addition to data from the continuous-record stream-discharge sites, were used to develop flood-frequency and magnitude relations. Operation of the crest-stage stream-discharge sites also resulted in the collection of a large quantity of periodic stream-discharge information. Many new methods, such as those described by Crosby (1975), were developed to estimate surface-water characteristics from these limited data.

Most of the data collected at continuous-record and crest-stage stream-discharge sites are available in computer-usable form. The data collected since 1965 also are available in annually published U.S. Geological Survey reports, "Water Resources Data for Montana," "Water Resources Data for North Dakota," and "Water Resources Data for South Dakota."

Water-quality sampling by the U.S. Geological Survey began as early as 1945. The program to sample the major streams for water-quality properties and common ions was continued for 5 or 6 years at most sites. A major effort was made during the late 1970's and early 1980's to acquire a more complete water-quality data base. Water-quality data have been collected at 135 sites in the study area. The data collected at these sites are variable with regard to time and duration of collection. Also, there are data for additional miscellaneous, one-time-sample, water-quality sites in the U.S. Geological Survey files. The data are available in published form in annual reports of the U.S. Geological Survey, in the U.S. Environmental Protection Agency's STORET computer files, and, since about 1950, in the U.S. Geological Survey's WATSTORE computer files.

Water-quality determinations were made at 68 sites in the region as part of the U.S. Geological Survey and U.S. Bureau of Land Management coal-hydrology program. A complete list of the constituents that were determined for Montana can be found in Slagle and others (1984) and for North Dakota in Croft and Crosby (1987) and Crosby and Klausing (1984). Statistical evaluation of water-quality data during the program was completed by Haffield (1981).

A common practice for several years has been for U.S. Geological Survey investigators to obtain water-temperature and specific-conductance measurements whenever a discharge measurement is made. These data also are stored in the computer files.

Prior to 1976, most sediment data were collected on the main-stem Missouri River or near the mouths of the major tributaries. Since 1976, mainly in response to increased energy development, sediment data also have been collected at many other sites. The data generally are determinations of the sediment concentrations at the time of discharge measurements. In addition, some particle-size analyses were made.

SURFACE-WATER CHARACTERISTICS

Stream discharge varies greatly within the area. Flows in all unregulated streams have large seasonal variations, and the largest flows occur during spring as a result of snowmelt and rainfall. Stream discharge in the Missouri River is not as variable because of the effects of upstream storage reservoirs. Further information can be obtained by referring to Slagle and others (1984), Croft and Crosby (1987), and Crosby and Klausing (1984), and (or) by contacting the U.S. Geological Survey offices in Helena, Montana, and Bismarck, North Dakota.

Daily-flow hydrographs (fig. 34) indicate the seasonal variation in stream discharge during 1980 for the Yellowstone River (site 1) and for the Redwater River (site 2). The hydrographs indicate the effects of snowmelt and rainfall on the discharge in a large perennial stream (Yellowstone River) and a typical prairie stream (Redwater River). Increased discharge in the Yellowstone River during May and June and in the Redwater River during March and April is the result of snowmelt.

A method and equations for estimating average annual flows using basin characteristics have been

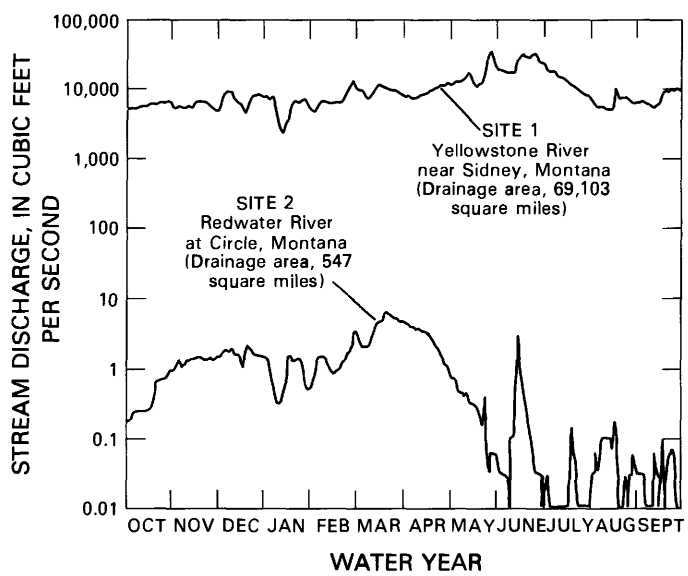


FIGURE 34.—Typical hydrographs showing variation of stream discharge for selected streams during the 1980 water year in the Fort Union region (modified from Slagle and others, 1984; see figure 33 for location of sites).

developed for ungaged sites in central and eastern Montana (Omang and Parrett, 1984). Data for calculating mean available flows for all stream-discharge sites in coal areas 46 and 47 are available in reports by Croft and Crosby (1987) and Crosby and Klausing (1984). Flood estimates can be made from available data for gaged and ungaged streams in the region. The most reliable estimators of future floods generally are the frequency analyses of stream-discharge records. Regression equations for estimating floods on ungaged streams draining less than 100 square miles are in a report by Crosby (1975), and equations for ungaged streams draining 100 square miles or more are in a report by Patterson (1966).

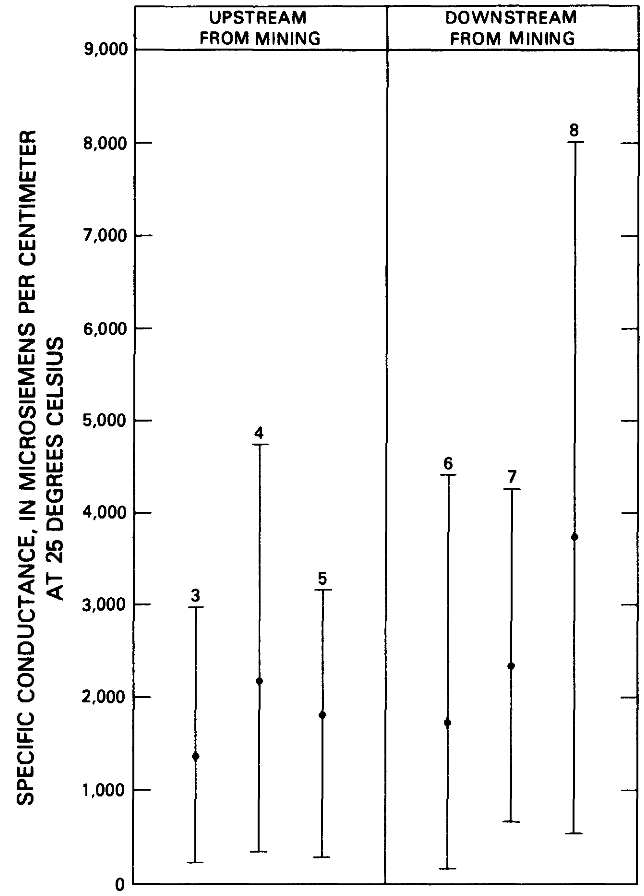
SURFACE-WATER QUALITY

Dissolved-solids concentrations vary greatly in water from all streams except the Missouri River. The most common dominant cations are calcium, magnesium, and sodium, and the dominant anions are bicarbonate, sulfate, and chloride. Large dissolved-solids concentrations can be objectionable because of possible physiological effects, mineral taste, or economic constraints associated with their removal.

Numerous standards have been established for dissolved solids. Generally, it is desirable to have concentrations of dissolved solids less than 500 milligrams per liter for public water supplies. During snowmelt runoff or high runoff from thunderstorms, most streams in the region have dissolved-solids concentrations less than 500 milligrams per liter. During periods of low flow, dissolved-solids concentrations in water from many of the streams will exceed 1,300 milligrams per liter, an approximate concentration at which the water will acquire a mineralized taste.

Water containing dissolved-solids concentrations in excess of 2,500 milligrams per liter has only limited use; however, livestock will tolerate larger concentrations of dissolved solids under most circumstances (National Academy of Sciences, National Academy of Engineering, 1973). Dissolved-solids concentrations of water in many streams will exceed 2,500 milligrams per liter during extremely low flows when ground-water discharge is the primary source of water.

Medians and ranges of specific conductance at selected surface-water-quality sites are shown in figure 35. A summary of medians and ranges of specific conductance at 26 sites for different-sized drainage areas upstream and downstream from mining is shown in figure 36. The median specific conductance of streams in small basins downstream from mining is greater than that of streams in similar unmined basins. However, the median specific conductance of streams downstream



EXPLANATION

4 SITE NUMBER
MAXIMUM
MEDIAN
MINIMUM

SITE NUMBER IN FIGURE 33	SITE NAME AND DRAINAGE AREA
3	Elm Creek near Golden Valley, North Dakota (82.0 square miles)
4	North Creek near South Heart, North Dakota (40.8 square miles)
5	Coal Creek near Stanton, North Dakota (15.8 square miles)
6	Spring Creek below Lake Ilo at Dunn Center, North Dakota (116 square miles)
7	Norwegian Creek near Belfield, North Dakota (39.8 square miles)
8	Buffalo Creek tributary near Gascoyne, North Dakota (15.7 square miles)

FIGURE 35.—Maximum, median, and minimum specific conductance at selected surface-water-quality sites in the Fort Union region. Data are from Crosby and Klausing (1984).

from mined and unmined basins greater than 50 square miles in size is essentially the same.

Unpolluted streams draining undisturbed basins in the region generally will have alkaline water. Values of pH in the streams commonly range from about 6.5 to

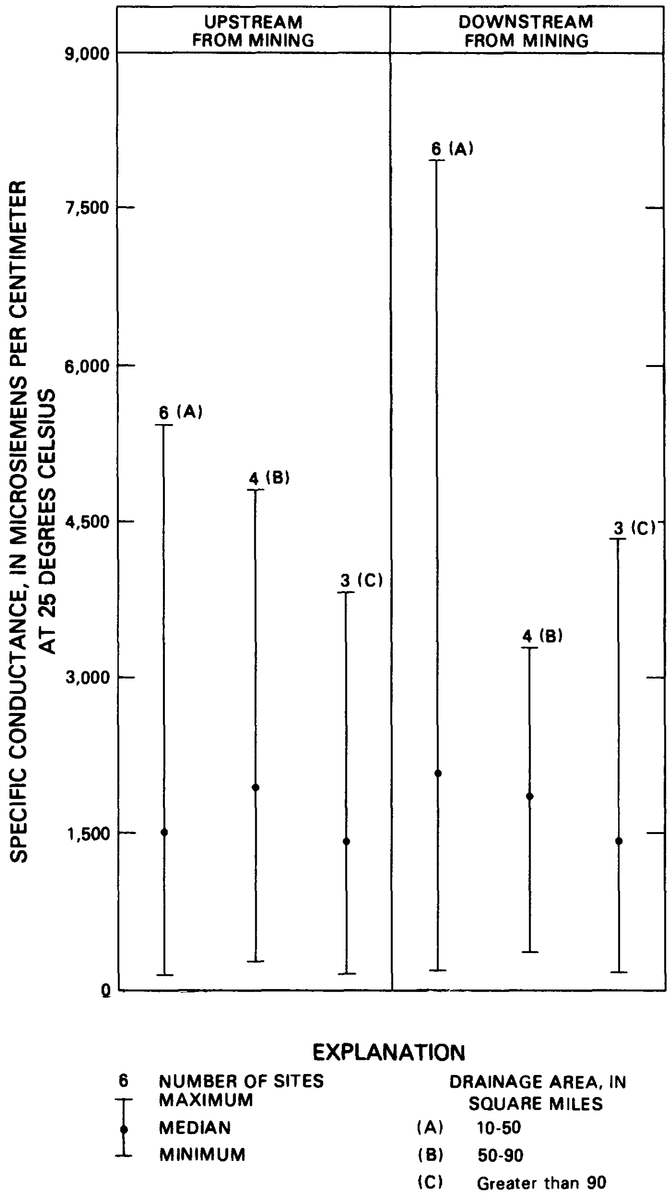


FIGURE 36.—**Summary of medians and ranges of specific conductance at 26 sites for different-sized drainage areas in the Fort Union region.**

8.5. Even though a substantial degree of basin disturbance occurs because of mining, the surface waters generally remain alkaline. The surface waters are buffered by carbonate minerals in the prairie soils, and stream pH decreases to less than 7.0 only during major precipitation or when the site is located immediately adjacent to acid sources such as lignite outcrops. Oxidation of sulfur species in the coal-mining areas generally will cause a decrease in pH. However, the prevalence of soils that have moderate buffering capacity makes acid mine drainage unlikely.

Sulfate concentrations in streams generally are discharge dependent; concentrations in most streams are less than 250 milligrams per liter during runoff from snowmelt or from intense thunderstorms, and these concentrations are more than 500 milligrams per liter at low flows when streamflow is dominated by ground-water discharge. The variation of sulfate concentrations with discharge makes detection of changes due to mining problematical without a record of concentration variations throughout a varied range of discharges. The network of surface-water sites in the region provides a substantial data base for providing this background information.

The coal-bearing formations in the area generally contain enough carbonate minerals to rapidly neutralize any acids that may form. Hence, trace elements generally are not dissolved in quantities large enough to exceed drinking-water standards (U.S. Environmental Protection Agency, 1986a, 1986c). Iron, which is not known to be toxic, is one possible exception. Many water samples contained dissolved-iron concentrations larger than 300 micrograms per liter, which is the recommended limit. Most of this excessive iron, however, is believed to be in a colloidal form that may have passed through the 0.45-micrometer filter that was used to process water samples prior to analysis of dissolved chemical species. Locally, boron concentrations may be excessive for some sensitive plants; but, generally, concentrations of boron are less than that which might damage most crops that are grown in the region. At some sites, standards for other trace-element concentrations have been exceeded for short intervals during base flow, but no deleterious effects from any of the above excessive trace-element concentrations have been reported.

A poor correlation exists between the sediment concentration and measured discharge for small basins in the area. The poor correlation is because of the great variability of factors such as soil types, soil conditions (frozen, thawed, degree of saturation, and tillage), land use, precipitation intensity, rapidity of snowmelt, and the time of sampling in relation to hydrologic events.

Almost all the available water-quality data are from areas of undeveloped energy resources. It would be extremely difficult, if not impossible, to extrapolate these data to estimate the effects of mining or other land-use changes. It is unlikely that cumulative effects of energy development will be detectable at downstream sites on major streams for many years.

GROUND-WATER NETWORK

The ground-water network provides general water-level and ground-water-quality data for most of the region. The network of ground-water observation wells being monitored is reviewed and updated periodically. The network as of September 30, 1981, comprised 395 wells. The frequency of measurement can vary from one annual measurement to a continuous record. Lithologic logs are available for all observation wells. Various geophysical logs also commonly are available. At least one chemical analysis of water is available for most wells. Chemical quality routinely is monitored at several of the wells. Many other wells have been constructed by the U.S. Geological Survey and various cooperators but are not part of the network. Information on these observation and test wells is available from the U.S. Geological Survey computer storage files and in published U.S. Geological Survey annual State reports. Some data concerning several thousand private wells scattered throughout the coal areas also are available.

GROUND-WATER OCCURRENCE

Bedrock aquifers consisting of sandstone, lignite, and clinker underlie the entire region and are the only sources of ground water throughout most of the region. Yields of wells developed in these aquifers vary depending on the thickness of the aquifer and the rate at which water moves through the aquifer.

Wells scattered throughout the region produce water from aquifers in alluvial, terrace, or glacial sand and gravel. Most stream valleys in the region contain some alluvium, but generally only the larger valleys contain sufficient alluvium to yield water.

The major glacial-drift and alluvial aquifers were deposited in river valleys formed by meltwater from glaciers. These valleys range from 0.25 to 2 miles in width and may be as much as 300 feet deep. In addition, a few preglacial river valleys contain sand and gravel aquifers. The preglacial drainages range from 0.5 to 5 miles in width and may be as much as 400 feet deep.

Ground water also is obtainable from isolated sand and gravel lenses in the glacial till. These lenses seem to be distributed randomly both laterally and vertically.

Water levels in shallow aquifers less than 200 feet deep indicate that the ground-water flow patterns follow the land surface, and flows are from the topographic high areas toward the nearby drainages. Water levels in the deeper aquifers indicate that the water is under artesian pressure, and regional flow generally is from the southwest to the northeast. Because of artesian pressure, wells flow when drilled in or near the bottom of the valleys in the Missouri, Yellowstone, or Little Missouri River basins. Flows from wells in these valleys have decreased the artesian pressure beneath these river valleys so that part of the regional flow has been diverted toward these rivers.

GROUND-WATER QUALITY

Quality of water from wells developed in alluvial and glacial-drift aquifers generally is suitable for most uses. Dissolved-solids concentrations range from 159 to 1,000 milligrams per liter. Calcium generally is the principal cation present, but magnesium or sodium may be significant locally. Bicarbonate is usually the dominant anion present, but sulfate may dominate locally when sodium is abundant.

The quality of water from shallow bedrock aquifers is quite variable. Included in this group are most lignite and sandstone aquifers that may be affected by mining. Dissolved-solids concentrations, which range from 286 to as much as 9,700 milligrams per liter, commonly increase with depth. Sodium and calcium generally are the principal cations present, but magnesium sometimes is abundant in waters dominated by calcium. Sodium dominance over calcium generally increases with depth because of cation exchange of divalent cations for sodium on sodic smectites in the siltstones and claystones of the Tertiary and Cretaceous formations. Bicarbonate and sulfate are the dominant anions present. In parts of aquifers affected by combined pyrite oxidation, gypsum dissolution, and cation exchange, local sulfate concentrations may be as much as 6,500 milligrams per liter.

Water from aquifers at depths greater than about 200 feet in the Tertiary and Cretaceous formations generally has smaller dissolved-solids concentrations than water from shallower bedrock aquifers. Furthermore, dissolved-solids concentrations generally are greater in the Tertiary aquifers in the Fort Union Formation than in the Cretaceous aquifers, but chemical compositions are similar. Sodium and bicarbonate ions dominate. Calcium and magnesium concentrations tend to be small because of cation exchange for sodium in the overlying siltstones and claystones. Sulfate usually is a minor constituent, and concentrations generally are less than 100 milligrams per liter because of sulfate reduction as the water moves downward. Dissolved-solids concentrations in the aquifers range from 610 to 10,200 milligrams per liter and increase from southwest to northeast. Wells in this group supply most of the ground water used in the region. Although the water generally is soft (less than 60 milligrams per liter calcium carbonate), large dissolved-solids concentrations in addition to large sodium-adsorption ratios make the water unsuitable for irrigation except locally near the outcrop areas. Water from bedrock aquifers generally is usable for domestic, livestock, and some industrial use, but the large concentrations of dissolved solids commonly exceed the criteria and regulations established by the U.S. Environmental Protection Agency (1986b, 1986c). Large fluoride concentrations have been detected in water from some wells, and these concentrations may restrict water used for domestic supply. Additionally, some water is unsuitable for use by people on sodium-restricted diets because of large sodium concentrations.

COAL-HYDROLOGY STUDIES

Many investigations concerning coal or water resources in the Fort Union region have been completed. Most of the studies completed prior to the mid-1970's were related to coal thickness, ash content, or some other characteristic of the coal. Hydrologic studies generally were not oriented toward coal and water relations, but much valuable data concerning well yields and the quality of water in coal beds were collected. Many of these older studies have been referenced by Slagle and others (1984), Croft and Crosby (1987), and Crosby and Klausing (1984).

Many of the investigations since about 1975 have been oriented toward coal and hydrologic relations. Many of the investigations made by the U.S. Geological Survey were initiated to aid the U.S. Bureau of Land Management in their management and leasing responsibilities (Crawley and Emerson, 1981; Armstrong, 1982; Horak, 1983a, 1983b). The studies also contributed to an expanded data base that, in turn, made it possible to determine some environmental effects and to project probable future environmental effects of coal mining. Other investigations, principally done in cooperation with the State agencies, have been oriented toward understanding the hydrologic and hydrochemical processes that may be affected by mining and documenting these effects at selected sites. Many of these investigations have been listed by Cochran and others (1983).

Extensive investigations, such as those by Moran and Cherry (1977) and Groenewold and Rehm (1980), have identified mining and reclamation practices that will maximize postmining reclamation and land use. Reports of other studies, such as those by Sandoval and others (1973) and Sandoval and Gould (1978), discuss methods of returning the landscape to maximum productivity for cropland or rangeland, which were the principal land uses prior to mining.

To develop a predictive means of simulating the effects of land-use changes such as opening a mine on previously farmed land, rainfall-runoff models were applied to typical small basins (Emerson, 1981, 1988). Because basin characteristics have not been regionalized, extension of these models to other unmined or mined sites has not been possible.

Moran and Cherry (1977) reported temporal increases in saline seeps associated with mining. The overall flow regimen probably would be altered only slightly by mining unless impoundments or other alterations are made on the main-stem streams.

Van Voast and others (1978) and Groenewold and others (1983) indicated that leachates of spoils material at several sites throughout the region are enriched two to five times in dissolved-solids concentrations relative to median dissolved-solids concentrations in unmined aquifers. Thus, runoff from spoils or reclaimed areas, or both, probably will have increased salinity.

Moran and others (1979) stated that the dissolved-solids concentration of a stream affected by mining is approximated by the mass-balance mixing of spoils water and natural ground water in proportion to the percentage of the drainage basin occupied by mine spoils. If only a small percentage of the drainage basin upstream from a monitoring site is occupied by mine spoils, no change in water quality would be observable at the site.

Attempts to assess basin-wide effects of mining have been few. To date (1985), perhaps the most successful assessment was a model developed by Woods (1981) to determine the effect of mining at multiple sites in southeastern Montana on the dissolved-solids concentration in the Tongue River. Because of the complexities and uncertainties involved, most attempts to assess the cumulative effects of mining on the hydrologic system have resembled the qualitative approach of Lumb (1983).

Typical cones of ground-water heads in the vicinity of mines in North Dakota and Montana have been described by Groenewold and others (1979, 1983), Davis (1984b), and many others. Because typical strip-mining processes produce a zone of relatively large hydraulic conductivity at the base of reclaimed spoils (Winczewski, 1977), most aquifers destroyed by mining are restored effectively during reclamation. Rehm and others (1980) have stated that the restored aquifers have hydraulic properties within the range exhibited by unmined lignite and sandstone aquifers in the area. Furthermore, because spoils and reclaimed soils have greater infiltration capacities than undisturbed over-burden, and because water-table depressions produced by mine operations induce large horizontal gradients in hydraulic head, water levels in most reclaimed aquifers approach premining levels within a few years of mine cessation. Restoration of premining water levels has been documented extensively at several North Dakota mine sites by Groenewold and others (1979, 1983).

Because increased quantities of soluble salts seem to characterize spoils relative to unmined overburden, most efforts at predicting the quality of spoils water have used ultimate column leaches (Hood and Oertel, 1984) or batch mixing solutions (Davis, 1984b). Difficulties relating experimental results to water-rock reaction ratios in disturbed and undisturbed aquifer systems have caused investigators to use empirical ratios between experimental analyses and measured spoils-water quality in one locality to predict spoils-water quality elsewhere. Resultant large uncertainties in these predictive methods need not obscure their utility as a management tool at sites having no previous history of mining.

Geochemical studies of spoil-pile samples from mines in the region indicated that leachate from spoils was more alkaline and contained considerably more soluble-salt material than did the leachate from natural topsoil from nearby locations (Sandoval and others, 1973; Groenewold and others, 1983). Sodium-adsorption ratios for spoil extracts ranged from 2 to 64; most ratios were large enough to indicate limited revegetation potential. Other analyses (Power and others, 1974) indicated that Paleocene shales from depths greater than 30 feet contained considerable exchangeable ammonium nitrogen. When these shales were exposed to the atmosphere, nitrification of exchangeable ammonium occurred that resulted in increased soil nitrate content after mining. Groenewold and others (1983) reported ground-water nitrate enrichments at several mine sites and attributed them to a combination of the above process and nitrate released by explosives used in mining operations.

Investigations of the processes affecting ground-water quality in mined and unmined shallow bedrock aquifers in the Fort Union region have been done by Moran and others (1978) and Groenewold and others (1983). These investigations documented a consistent set of interrelated chemical reactions. Mining operations accelerate these chemical reactions, which already are operative in the natural environment.

Acceleration of sulfide-mineral oxidation and dissolution of generated gypsum catalyzed by cation exchange are the principal reasons that spoils water contains sulfate and sodium. Although the quality of ground water in the vicinity of surface mines apparently has deteriorated to some extent, the mineral content of deteriorated water generally remains less than or equal to the maximum concentration that occurs in some wells prior to mining. However, Rahn (1975) and Van Voast and others (1978) indicated that median concentrations of dissolved solids in spoils water can be 60 to 73 percent greater than those in domestic and livestock wells in the vicinity of mines. Moran and others (1978) and Groenewold and others (1983) determined that median concentrations of sulfate in spoils water were two to five times greater than those in wells unaffected by mining.

From 1955 to 1967, uranium was obtained from uraniferous coal in eastern Billings, northeastern Slope, and western Stark Counties, North Dakota, by first stripping the overburden from the coal, then covering the coal with waste oil and old tires and burning the coal onsite, transporting the ash by truck to nearby kilns for further concentration of the uranium in the ash, and subsequent shipping of the ash by train to uranium-ore processing plants in Colorado and New Mexico. Once mining ceased, seepage from the lignite aquifers flooded mine pits, enabling uranium and associated trace-element constituents in residual ash and spoils to contaminate the ground water.

Because infiltration in spoils and reclaimed land is depression concentrated and fracture controlled, infiltrating water contacts a finite quantity of disturbed soils and geologic materials that are a source for soluble contaminants. Thus, available mineral salts in mined land can be removed by leaching infiltration in a relatively short period of time. Groenewold and Murphy (1983) have reported that water in spoils older than 25 years is not appreciably more concentrated in dissolved solids than water in adjacent, undisturbed aquifers. Thus, disturbance of unreclaimed spoils can produce ground-water-quality degradations from unleached salts as severe as those initially produced by mining.

Projection of hydrologic and hydrochemical consequences observed at mine sites to downgradient, offsite locations has been hindered by limited information about the hydraulic properties of spoils and coal and by the complexity of the chemical reactions involved. Available data about hydraulic properties for the aquifer materials have been collected by Rehm and others (1980), but very little is known about anisotropy and fracture control of flow. Furthermore, little is known about the potential of downgradient aquifers to cleanse themselves of mine wastes by ion exchange on coal and clay minerals and by sulfate reduction.

HYDROLOGIC ISSUES RELATED TO COAL MINING

Hydrologic issues that have occurred in the region as a result of mining have been few. Isolated issues that have been identified are associated with: (1) Modification of land-surface topography and stability; (2) increased sediment discharge; and (3) alteration of the quantity and quality of surface water and ground water available in mining areas. However, most of these issues may be ameliorated by application of appropriate mining and reclamation procedures.

Because mining changes the configuration of the land surface, postmine landscapes sometimes are not suitable for return to original land uses. For instance, if sufficient spoils are not available to restore all the landscape to elevations above the water table, it may be necessary for some of the land to be established as wetlands for use by migratory waterfowl or to construct lakes for recreational use. In the worst example of reclamation, unreclaimed spoils may be suitable only for wildlife habitat; or, in the instance of underground mining, caving may produce a pitted land surface that is of limited usefulness and that is potentially dangerous.

The effects of mining on the quantity and timing of runoff are dependent on mining practices, but these effects usually are very minor. Some realignment of small tributaries may be needed, but the overall drainage areas should remain virtually unchanged.

The watershed area subject to active mining at any one time is too small to substantially alter the flow magnitudes except possibly during periods when there is only base flow. Alteration of existing stream channels to intercept and divert surface runoff within the mining area can cause alterations in existing flow regimes downstream.

Local erosion and transportation of sediment may increase, at least initially, because of removal of vegetative cover from land contributing runoff to the streams. The sediment yield will depend on the mining practices—the development of sedimentation ponds, the stability of diversion channels, and the speed with which vegetative cover can be reestablished (Gilley, 1980). However, State and Federal laws require containment of sediment and runoff within the mine site, so offsite effects should be minimal.

Surface waters within mining areas typically are degraded by increased concentrations of sulfate, which is consistent with leachate studies. Locally, decreases in pH and increases in concentrations of hydrogen sulfide, sodium, bicarbonate, iron, and fluoride also may occur. However, the quantity of recharge of streams by runoff will be decreased by increased infiltration in spoils and reclaimed soils and containment of runoff within mined areas. Water that unavoidably flows into or precipitation that falls directly on the mined area can be pumped or otherwise routed to impoundments where excessive sediment loads and objectionable chemical concentrations may be ameliorated by settling or discharged during high-flow periods. Because runoff and surface-water flow could be readily managed by routing techniques or construction of impoundments, surface runoff should produce little change in the chemical quality of water diverted around active mining areas. If necessary, mines could chemically treat water leaving mine sites to minimize further changes in surface-water quality.

Despite control of surface factors that might affect surface-water quality at mine sites, some degradation of surface-water quality downstream from mine areas may be observed because of seepage of degraded ground water into the surface water. To accurately determine the effects of strip mining on water quality, a premining data base needs to be established in areas of proposed mining. Resampling of wells after mining has begun could indicate if there is any alteration of water chemistry because of the mining. However, most site-specific studies have had limited or no premining data; so water-quality changes attributed to mining in the studies were inferred from temporal and spatial changes as mining expanded or began in new areas.

Effects of mining on shallow ground-water systems are not nearly so manageable using design features as those on surface-water systems. Removal of the coal could disturb enormous volumes of earth, some of which may have been a local aquifer. In some instances, effects of mining excavations could extend into a regional flow system. In any event, all disturbed earth, whether it is saturated or unsaturated, is a medium for the movement of subsurface water, and removal of the coal disturbs the natural flow regime. Any aquifers within or above the coal could be destroyed at the mine site during mining and could cause decreases in hydraulic head for some distance from the mine. In most instances, local wells destroyed by mining can be replaced in deeper strata. The distance to which the drawdown extends and the rate at which it spreads depends on the magnitude of recharge and discharge fluxes, the proximity of the mine to the ground-water recharge and discharge areas, and the hydraulic characteristics of the aquifers and adjacent materials.

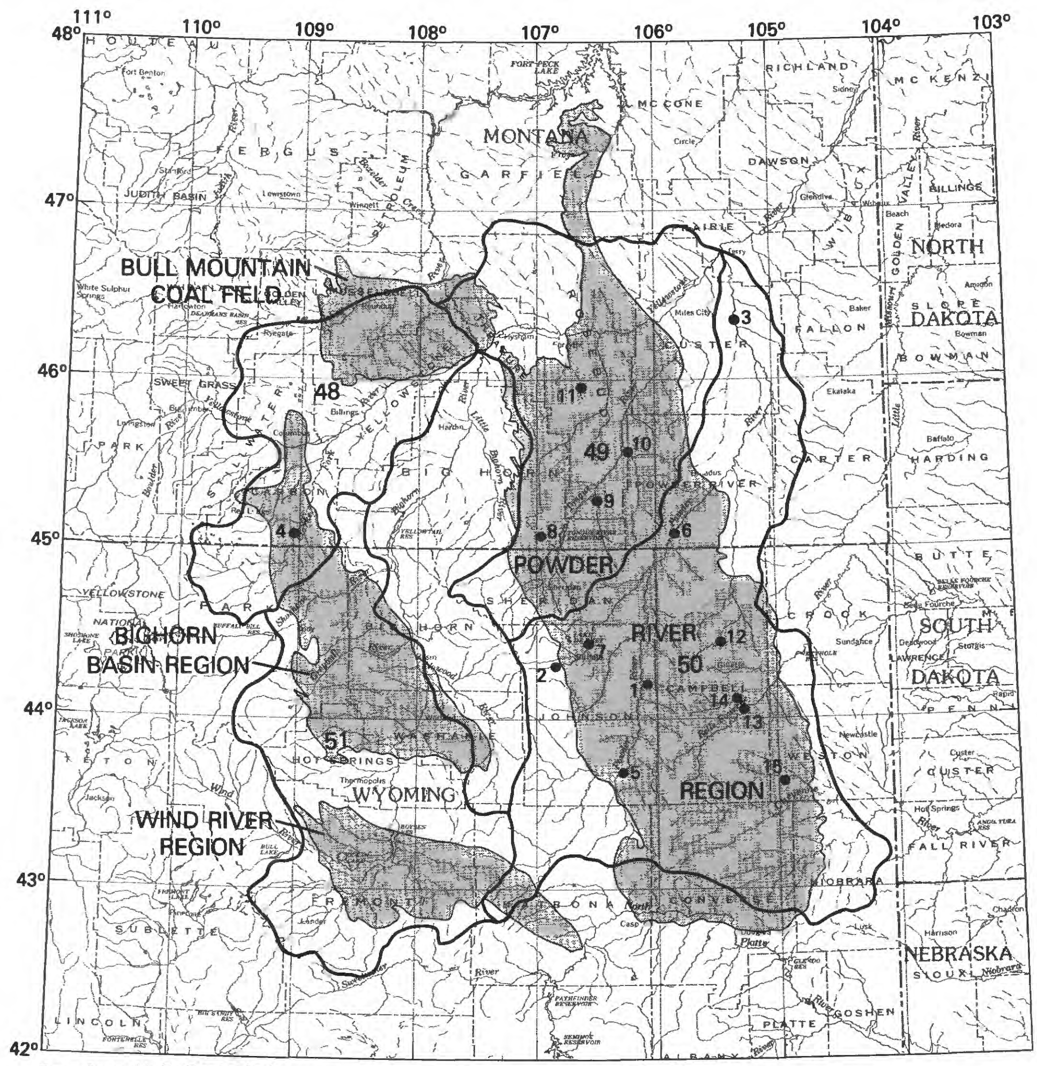
Normal dragline stripping procedures result in the replacement of materials in approximate reverse order of their original state except for the topsoil. Near-surface material is replaced at the base of the spoil piles and deeper sediments on the surface. Therefore, sediment that was deeply buried and at equilibrium with a reducing environment would be replaced in an environment of rapid oxidation and weathering; similarly, sediment that had been exposed to surface oxidation would be replaced in a reducing environment, often below the water table. Resultant oxidation, weathering, and alteration reactions could produce large quantities of soluble salts that might affect infiltrating water. Because strata exposed in mine pits are exposed to the same chemical processes that affect spoils, these strata also may be a source of soluble salts to infiltrating water.

Because sulfide minerals such as pyrite contain abundant quantities of trace-element contaminants, oxidation could release trace elements to the hydrologic system. However, the quantity and nature of the clay minerals in the Paleocene Fort Union Formation would indicate that transport of trace elements would be retarded greatly by adsorption and cation exchange. Furthermore, the large bicarbonate concentration in most ground and surface waters would produce rapid precipitation of most trace elements even though present in small concentrations. Thus, the potential for contamination of ground water by concentrations of trace elements toxic to people would seem to be small.

NORTHERN GREAT PLAINS AND ROCKY MOUNTAIN PROVINCES— POWDER RIVER, BIGHORN BASIN, AND WIND RIVER REGIONS

By JAMES F. WILSON, JR., and MICHAEL R. CANNON

The Powder River, Bighorn Basin, and Wind River regions, in addition to the Bull Mountain coal field, compose an area of about 60,000 square miles in southern Montana and northern Wyoming (fig. 37). Coal areas 48–51 (table 1) are located in this larger area, although important coal resources in the southernmost part of



Base from U. S. Geological Survey 1:2,500,000 United States base map

0 50 100 MILES

0 50 100 KILOMETERS

EXPLANATION

COAL REGION

50 COAL-AREA BOUNDARY—Number refers to local areas (Cochran and others, 1983)

•2 SAMPLING SITE AND NUMBER—See figures 38 and 39 for site descriptions

FIGURE 37.—The Powder River, Bighorn Basin, and Wind River regions, the Bull Mountain coal field, coal areas 48–51, and sampling sites.

the Powder River region are outside the boundary of coal area 50. The regions are located in three physiographic provinces. From east to west these provinces are the Great Plains, Wyoming Basin, and the Middle Rocky Mountains (pl. 1). The regions are located entirely within the Missouri River drainage basin. About 83 percent of the regions are located in the Yellowstone River basin; the remainder of the regions are located in parts of the Musselshell, Cheyenne, and North Platte River basins (fig. 37).

Climate is typified by small annual precipitation, cold winters, and hot summers. Throughout most of the plains and intermontane basins, average annual precipitation is 12 to 16 inches. Most precipitation occurs from showers and thunderstorms during April through August. Precipitation in the mountains generally averages 20 to 30 inches; much of the precipitation that sustains streamflow throughout the year occurs as snow in the mountains during November through April.

Exposed bedrock units range from crystalline rocks of Precambrian age to sedimentary rocks of late Tertiary age. Unconsolidated deposits of Quaternary age occur in many stream valleys. The bedrock units delineate the major structures of the area—mountain uplifts and large, synclinal basins. Rocks of Precambrian age are exposed in the cores of major uplifts, and progressively younger rocks through Cretaceous age outline the uplifts and basins. The centers of the basins are characterized by widespread deposits of rocks of early Tertiary age.

About 50 percent of the land is privately owned, about 10 percent is owned by Indians [Crow and Northern Cheyenne (in Yellowstone, Bighorn, and Rosebud Counties, Montana) and Wind River (in Hot Springs and Fremont Counties, Wyoming) Reservations], about 5 percent is owned by the States of Montana and Wyoming, and the remaining 35 percent is owned by the Federal Government. Federal lands are administered by the U.S. Bureau of Land Management and the U.S. Forest Service. Except for the lands of the Indian Reservations, the Federal Government owns most of the minerals beneath the surface.

Agriculture—rangeland and cropland, both irrigated and nonirrigated—is the primary use of land. Irrigated croplands are located mainly along the valleys of the largest rivers. Forests cover 10 to 15 percent of the regions. The principal industrial use of the land is development of mineral resources, chiefly coal, oil, and gas. Surface coal mines occupy only a very small percentage of the regions; lands reclaimed after the coal has been extracted generally are returned to rangeland or nonirrigated cropland.

The regions generally are sparsely populated. The principal population centers are Billings, Montana (about 84,000), and Casper, Wyoming (about 59,000) (U.S. Bureau of Census, 1981). The population of Campbell County, Wyoming, which includes Gillette, approximately doubled to 24,000 from 1975 to 1980 in response to increased mining of coal.

During 1980, about 95.5 percent of the water used was from surface-water sources and about 4.5 percent was from ground-water sources. Irrigated agriculture was by far the largest use, 98 percent of which was from surface-water sources. Most of the irrigation occurs along the Yellowstone, Clarks Fork, Wind/Bighorn, Tongue, and Powder Rivers. The flows of these rivers and their tributaries generally are fully appropriated.

COAL RESOURCES

Coal is abundant in the regions, particularly in the Powder River region. Coal deposits are contained in rocks of Late Cretaceous and early Tertiary age. Most of the coal is federally owned; however, in the northern part of the regions, there is a complex pattern of Federal, State, and private ownership. Coal on the Indian Reservations generally is held in trust for the tribes.

At least 12 formations of Late Cretaceous age have coal; however, the most economically important coals are in the Eagle Sandstone and Judith River Formation in the Bighorn Basin region in Montana and in the Meeteetse and Mesaverde Formations in the Wind River and Bighorn Basin regions in Wyoming. Most coal fields are located near the flanks of the structural basins where the deposits are steeply dipping and affected by local folding and faulting.

In Montana, the Upper Cretaceous coal beds are relatively thin, ranging from less than 1 foot to a maximum of 6 feet in thickness. In Wyoming, the coal beds generally are 4 to 6 feet thick, but a few are 15 to 30 feet thick. The coals generally are classified as high-volatile bituminous (figs. 3, 4) and have a smaller sulfur content (0.5 percent or less) and a higher heat content (about 10,000 British thermal units per pound) than the subbituminous coals of these regions.

The Upper Cretaceous coal beds generally are recoverable only by underground mining. During the early 1900's, there were underground mines in Montana and Wyoming, but production was small (10 to 200 tons per day). At the present time (1985), there is no mining of Upper Cretaceous coal beds in these regions.

The Fort Union Formation (Paleocene) and Wasatch Formation (Eocene) are the principal coal-bearing formations of early Tertiary age; the deposits underlie most of the plains areas of the Powder River region. Major coal beds within the Fort Union Formation can be traced for many miles, some for more than 50 miles. The Tongue River Member of the Fort Union Formation contains the largest reserves of all the coal-bearing rocks; most of the coal presently mined is in this unit.

Reserves of lower Tertiary coal in the regions are very large. Recent estimates of strippable coal are 33 billion tons in the Montana part of the regions (Matson and Blumer, 1973) and 24 billion tons in the Wyoming part (Lowry, Wilson, and others, 1986, p. 34). Total coal reserves in Wyoming exceed 500 billion tons. The estimated reserves for Wyoming probably will change as the result of a recently completed, extensive coal-mapping program by the U.S. Geological Survey.

Generally, the lower Tertiary coal beds are nearly flat lying, are at or near the surface, and are uninterrupted by folding or faulting. The thickness of coal beds in one coal field in the Bighorn Basin region in Montana ranges from 3 to 12 feet. In contrast, in the Powder River region, the Healy coal bed (Wasatch Formation) near Buffalo, Wyoming, is more than 200 feet thick, and the extensive Wyodak-Anderson coal bed (Fort Union Formation) near Gillette in northeastern Wyoming is 25 to 175 feet thick, averaging about 70 feet. Most of the Tertiary coals of these regions are classified as subbituminous (figs. 3, 4), although some coal in the extreme northern part of the Powder River region is lignite. Similarly to the Upper Cretaceous coal beds, the subbituminous Tertiary coals have a small sulfur content—less than 1 percent in the Wasatch and less than 3 percent in the Fort Union. Heat content of the coals generally is about 8,200 British thermal units per pound, although 10,000 British thermal units per pound is reported for coals in the Bull Mountain coal field.

Strip mining of the lower Tertiary coal beds, particularly in the Powder River region, is extensive. The coal beds first were mined during the late 1800's in many of the coal areas. Much of the early mining was underground, and production was small in comparison with that of the present (1985). As of 1984, there were no underground mines, but 26 active surface mines produced more than 140 million tons in Montana and Wyoming (table 3). All mining is from the Fort Union Formation, except in Converse County, Wyoming, where mining is from the Wasatch Formation. Nearly all the coal produced is used for thermoelectric power generation in at least 16 States. Campbell County, Wyoming, leads the Nation in coal production with 14 mines, including the Nation's two largest, Black Thunder and Belle Ayr. All 14 mines are in the Wyodak coal bed. Two additional mines are under construction in Campbell County, and several more are planned in Montana and Wyoming.

Most of the foregoing information about coal resources, unless otherwise noted, was obtained from the coal-area hydrology reports by Slagle and others (1983, 1986), Lowry, Wilson, and others (1986), and Peterson and others (1987). The original sources of the information are cited in those reports.

TABLE 3.—*Active coal mines and coal production by county, lower Tertiary coal beds, Powder River, Bighorn Basin, and Wind River regions and Bull Mountain coal field*

[Sources: Montana Department of Labor, written commun., 1984; Wyoming State Inspector of Mines, written commun., 1985]

Location of mines	Number of mines	Production (millions of tons)
Montana (1983)		
Big Horn County	4	16.32
Musselshell County	2	.02
Rosebud County	2	12.12
Subtotals	8	28.46
Wyoming (1984)		
Campbell County	14	106.80
Converse County	1	3.34
Sheridan County	2	2.52
Hot Springs County	1	.04
Subtotals	18	112.70
Totals	26	141.16

HYDROLOGY

Information about the hydrology of the Powder River, Bighorn Basin, and Wind River regions was inadequate, in view of the impending very large increase in coal strip mining in the eastern half of the region. Two generalized objectives for the coal-hydrology program in these regions have remained unchanged since 1974: (1) To increase knowledge about the availability of water; and (2) to provide information for assessing the effects of coal development on water resources on a regional basis and on a site-specific basis. The term "coal development" includes mining and transportation of coal, mine reclamation, coal conversion, and increased population.

A twofold approach was used: (1) Hydrologic-data networks were expanded or otherwise enhanced; and (2) interpretive hydrologic studies were begun. The two types of activities, which were coordinated, were confined mainly to the Powder River region. Regionally, there was a substantial base of information upon which to build, largely because of long-term interest in water supplies in the semiarid areas of the regions. Locally, the information base was sparse to nonexistent; for example, except for flood hydrology, little was known about the hydrology of small basins that have ephemeral streams typical of most of the areas underlain by strippable coal. Data bases and techniques for estimating flood discharges and hydrographs for small ephemeral streams were available from previous studies and proved invaluable to the coal-hydrology program.

SURFACE-WATER NETWORK

Collection of systematic (continuous or recurrent) records of discharge in these regions began during the 1890's at a few sites. Collection of daily or monthly water-quality and suspended-sediment samples did not begin until 1946. Most stream-discharge, water-quality, and suspended-sediment sites were located on the largest streams and their principal tributaries. The data were needed by the U.S. Geological Survey to inventory and assess the surface-water resources of the regions and by State and other Federal agencies to plan and develop surface-water resources. Over the years, the network has been expanded substantially.

Sampling frequency and types of analyses of water-quality samples vary at a site and differ among sites. Onsite determinations of temperature, pH, and specific conductance of water commonly are made. At some sites, determinations may include dissolved oxygen and turbidity. Laboratory analyses usually include common dissolved ions (salinity) but also may include trace elements, nutrients, pesticides, and radiochemical and biological constituents.

During 1974, there was considerable expansion of the surface-water network for coal hydrology and of the funding from three main sources: (1) The U.S. Geological Survey's program to describe the water resources of the coal regions; (2) the U.S. Bureau of Land Management's program to obtain information for the orderly and environmentally sound development of Federal coal resources; and (3) the U.S. Environmental Protection Agency's energy-related program for expanded water-quality monitoring at network sites. The coal-hydrology program included a 4-year (1977–81) experiment in which the U.S. Geological Survey contracted with a private engineering firm to install and operate a number of stream-discharge, water-quality, and suspended-sediment sites in the regions. The data collected by the contractor met or exceeded U.S. Geological Survey accuracy standards, but the activity was determined to be more costly than if done by U.S. Geological Survey personnel; therefore, the experiment was terminated.

Pairs of stream-discharge sites were installed during 1974 at 16 locations to measure gains or losses of discharge in streams crossing outcrops of the Madison Limestone in the Powder River region in northeastern Wyoming. This project was done in cooperation with the Wyoming State Engineer and the Old West Regional Commission. The number of pairs of sites was decreased during 1976; operation of the remaining sites continued through 1982. Many of the sites were located at remote, high-mountain locations, making access difficult. Time and funding constraints precluded construction of cableways for making high-water measurements. Therefore, dye-dilution techniques were modified for measuring discharge at the remote sites. The results were considered adequate for computing the high-water discharge at the sites.

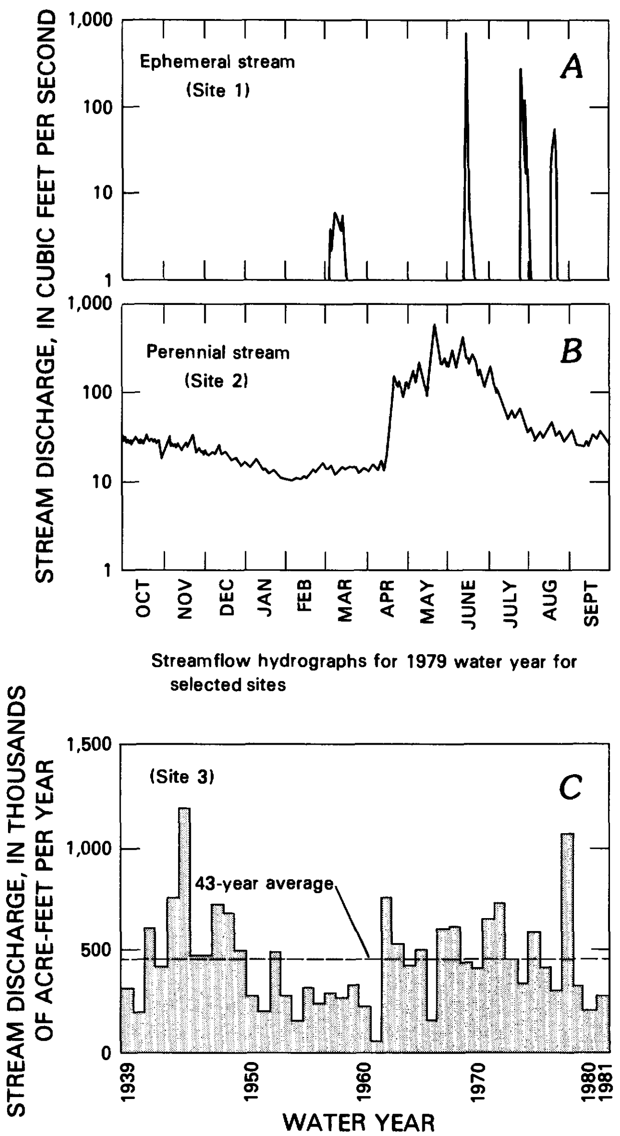
As of 1982, approximately 290 stream-discharge sites, 230 water-quality sites, and 190 sediment sites had been operated at one time or another in these regions. Most water-quality and sediment sites are located at stream-discharge sites so that dissolved-solids concentrations and suspended-sediment loads can be computed. The period of record at these sites ranges from 1 year to many decades. Since 1980, the network has decreased steadily as Federal funding for coal-hydrology investigations has decreased. However, most of the sites added after 1973 have 5 or more years of record, thus providing valuable documentation of conditions with which future conditions can be compared.

In addition to continuous-record stream-discharge sites, the network includes partial-record stream-discharge sites and miscellaneous stream-discharge sites. Partial-record stream-discharge sites are operated to obtain supplemental flood-frequency data. Funded mainly in cooperation with the Montana and Wyoming Highway Departments, most partial-record stream-discharge sites are used to record only the annual peak discharge, but a few specially instrumented sites were used to record complete hydrographs of rainfall and runoff on small ephemeral streams. A total of 117 partial-record stream-discharge sites have been operated in the regions, but most have been discontinued.

Approximately 300 documented miscellaneous stream-discharge sites are in the regions, particularly in the Powder River region. These are sites where one-time or occasional measurements of discharge have been made or chemical or biological samples collected. Commonly, data collection is done on a synoptic or areawide basis, such as reconnaissance measurements of low flow or water quality.

SURFACE-WATER CHARACTERISTICS

Although about three-fourths of the area of the regions consists of plains drained by ephemeral and interrupted streams, most of the runoff occurs in the few large perennial streams that transect the regions and in their smaller perennial tributaries that originate in the mountains. Discharges in all streams have large seasonal and year-to-year variations (fig. 38); the largest discharges occur during the spring as a result of snowmelt and rainfall. Plains streams, many of which do not flow most of the year, can have large flows of short duration because of thunderstorms. Characteristics commonly used to describe or assess surface-water



EXPLANATION

SITE NUMBER IN FIGURE 37	SITE NAME AND DRAINAGE AREA
1	Dead Horse Creek near Buffalo, Wyoming (151 square miles)
2	Clear Creek near Buffalo, Wyoming (120 square miles)
3	Powder River near Locate, Montana (13,194 square miles)

FIGURE 38.—Typical hydrographs showing variation of stream discharge for selected streams in the Powder River, Bighorn Basin, and Wind River regions. *A*, Seasonal variation in a small ephemeral stream. *B*, Seasonal variation in an intermediate-sized perennial stream draining the mountains. *C*, Year-to-year variation in a large perennial stream.

resources are low-flow statistics, average annual flow, and flood-frequency statistics.

Low-flow frequency statistics can be computed from discharge records for sites on perennial streams but not for sites on ephemeral streams. Frequency curves plotted from low-flow statistics differ greatly among streams. Low-flow statistics can be considered as indicators of the minimum sustained supply available in a stream without the use of artificial storage. Because the differences are related to factors that are difficult to quantify, such as geology, predictive equations for low-flow frequency generally are not available for this region; however, a low-flow analysis for surface-water sites in northeastern Wyoming was made by Armentrout and Wilson (1987).

Average annual discharge differs greatly among streams. Small plains streams typically have average annual discharges of less than 10 cubic feet per second, larger mountain streams have average annual discharges of 20 to 200 cubic feet per second, and the largest stream, Yellowstone River at Miles City, Montana, has an average annual discharge of 11,620 cubic feet per second (for 56 years of record). Equations are available in reports by Omang and others (1982) and Omang and Parrett (1984) for estimating average annual discharges at ungaged stream sites in the Montana part of the regions and in the report by Lowham (1976) for sites in the Wyoming part. Equations used in both States are based on two very different methods—channel geometry and basin characteristics.

Flood-frequency information is derived from the record of annual peak discharge at stream-discharge sites. The magnitude and frequency of floods at ungaged sites can be estimated using equations by Omang and others (1982) for sites in Montana and by Lowham (1976) for sites in Wyoming. For small ephemeral streams in Wyoming (drainage areas smaller than about 11 square miles), the equations of Craig and Rankl (1978) can be used to estimate the magnitude and frequency of floods. A revision of the equations for estimating peak discharges on streams in Wyoming is in Lowham (1988). Also available are procedures for estimating flood volumes and for constructing synthetic hydrographs for small ungaged basins (Craig and Rankl, 1978) and a useful compilation of rainfall and runoff hydrographs for small basins with ephemeral streams (Rankl and Barker, 1977).

During May 1978, the maximum flood of record was exceeded at about one-third of the sites in the regions (Parrett and others, 1984, p. 1). The 1978 peak discharge on the Yellowstone River at Miles City was 102,000 cubic feet per second, the largest ever recorded in this region. The 1978 flood data were used to substantiate the use of the step-backwater method of developing rating curves at sites on ephemeral streams (Druse, 1982).

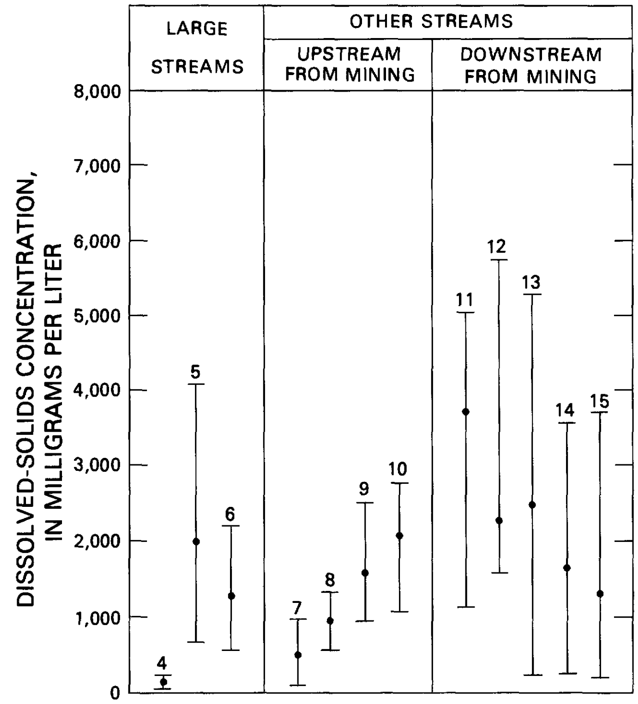
SURFACE-WATER QUALITY

Dissolved-solids concentrations, used to characterize the general quality of water in streams, generally are larger in plains streams than in mountain streams. Dissolved-solids concentrations also vary inversely with discharge at a given site but generally increase downstream. Perennial plains streams typically have large variations in dissolved-solids concentration between the time of spring runoff and the period of base flow. During times of spring runoff, the concentration of dissolved solids sometimes is less than 100 milligrams per liter, while during base flow, some of the plains streams have concentrations greater than 4,000 milligrams per liter. Dissolved-solids concentrations for selected streams in these regions are shown in figure 39.

The major cations in most streams are calcium, magnesium, and sodium; the major anions are bicarbonate and sulfate. Generally, the mountain streams have a calcium magnesium bicarbonate type water and downstream enrichment in sodium and sulfate; most plains streams have sodium sulfate type water. Concentrations of dissolved trace elements seldom exceed drinking-water standards in the regions; exceptions are iron and manganese, which occur in naturally large concentrations in many plains streams. The pH of water in nearly all streams is greater than 7, thus precluding excessive dissolution of trace elements from streambed materials. Concentrations of alkalinity are large in most streams; because of that buffering capacity, streams in the regions are not susceptible to acid drainage from mines.

Baseline water-quality data in the Powder River region generally are adequate to assess effects of future mining because of the network expansion and miscellaneous sampling that occurred during the coal-hydrology program. Also, equations for estimating dissolved-solids concentrations from measurements of specific conductance of water samples are given in Slagle and others (1983, 1986) for the Montana part of the Powder River region and in Rucker and DeLong (1987) for the Wyoming part. Dissolved-solids loads can be simulated from records of specific conductance and stream discharge.

Suspended-sediment transport is quite variable in time and space and is documented adequately because of long-term monitoring for the largest streams, such as the Bighorn and Powder Rivers, and for a few perennial tributaries. Since 1975, sediment sites also have been operated on many smaller streams in the Powder River region, thus providing baseline information about perennial streams. Generally, more than 80 percent of the suspended sediment is silt and clay. Concentrations, which vary directly with discharge, have ranged from



EXPLANATION

4	SITE NUMBER
	MAXIMUM
	MEDIAN
	MINIMUM

SITE NUMBER IN FIGURE 37	SITE NAME AND DRAINAGE AREA
4	Clarks Fork Yellowstone River near Belfry, Montana (1,154 square miles)
5	Powder River at Sussex, Wyoming (3,090 square miles)
6	Powder River at Moorhead, Montana (8,088 square miles)
7	Clear Creek below Rock Creek near Buffalo, Wyoming (322 square miles)
8	Squirrel Creek near Decker, Montana (33.6 square miles)
9	Hanging Woman Creek near Birney, Montana (470 square miles)
10	Otter Creek at Ashland, Montana (707 square miles)
11	East Fork Armells Creek near Colstrip, Montana (97.3 square miles)
12	Little Powder River below Corral Creek near Weston, Wyoming (204 square miles)
13	Belle Fourche River above Dry Creek near Piney, Wyoming (594 square miles)
14	Caballo Creek at mouth near Piney, Wyoming (260 square miles)
15	Little Thunder Creek near Hampshire, Wyoming (234 square miles)

FIGURE 39.—Maximum, median, and minimum dissolved-solids concentrations at selected surface-water-quality sites in the Powder River, Bighorn Basin, and Wind River regions.

a few milligrams per liter to more than 100,000 milligrams per liter. Annual sediment yields from basins in these regions range from less than 10 to more than 1,000 tons per square mile. Equations are available for estimating sediment yields from small ungaged watersheds in eastern Montana (Lambing, 1984). Suspended sediment in streams of the Powder River structural basin of southeastern Montana was summarized by Litke (1983).

Valuable sediment data were collected at many sites during the widespread flooding of May 1978 (Parrett and others, 1984); a maximum daily suspended-sediment load of 2.81 million tons was recorded in the Powder River at Arvada, Wyoming (Sheridan County), on May 20, 1978. The load in the Powder River at Arvada during 1978 was 16.3 million tons; the 24-year average annual load is 4.7 million tons. In contrast, the 5-year average annual load in the Yellowstone River at Billings, Montana, is only 1.7 million tons.

Sediment data for small ephemeral streams are scarce. Calibration and operation of automatic-sampling devices necessary to collect the data is expensive and time consuming. Such data are available, however, for one experimental basin (drainage area, 0.8 square mile) in Wyoming.

GROUND-WATER NETWORK

Information for about 3,200 wells in the Montana part of the regions and about 4,300 wells in the Wyoming part is stored in the computer files of the U.S. Geological Survey. The information for each well includes some or all of the following: ownership and use, completion data, geologic data, water levels, well yield, and water quality. From the 1920's to 1974, most ground-water data were collected during hydrologic studies to assess the availability of water. The information was needed mainly for agricultural, municipal, and domestic use.

In response to increased coal development beginning in 1974, large quantities of ground-water data have been collected by industry, universities, and government agencies, mostly for studies of the hydrology and possible environmental effects in relatively small areas, such as a proposed or existing mine, but also for identifying baseline conditions. Much of the data collected in Campbell County, Wyoming, consists of water levels in the Wyodak-Anderson coal bed and in the overburden. These data are centralized through the Gillette Area Groundwater Monitoring Organization (GAGMO), which is mainly composed of mining companies. Water levels were reported for more than 780 wells at 21 mine sites during 1981, resulting in a compilation of data for most of the area close to the coal outcrop in Campbell County (Gillette Area Groundwater Monitoring Organization, 1983).

The U.S. Geological Survey continues to measure water levels and collect water samples for chemical analyses from selected wells. Most samples are analyzed only for common ions; some analyses include trace elements. Samples for analysis of radiochemical constituents mainly are from areas of known uranium deposits. Recent reports for Montana include data for test wells (Levings, 1981b; Wood, 1984), for water-supply wells (Slagle and Stimson, 1979; Levings, 1981a), and for water quality (Lee, 1979). Reports for Wyoming include water-level data (Ragsdale, 1982), records of wells in alluvium (Wells, 1982), and water-quality data (Wells and others, 1979; Wells, 1982; Larson and Daddow, 1984).

GROUND-WATER OCCURRENCE

Paleozoic aquifers, such as the Mississippian Madison Limestone, Pennsylvanian Tensleep Sandstone, and the Pennsylvanian and Permian Minnelusa Formation, may yield more than 950 gallons per minute. However, the large yields are dependent on secondary permeability that is not present everywhere. Water has not been developed from these rocks in much of the area because of the great depth at which they occur and the uncertainty about the quality of the water. Where the rocks occur within 2,000 feet of the surface, which is only near the uplifts, the dissolved-solids concentration commonly is about 500 milligrams per liter.

Upper Cretaceous and lower Tertiary aquifers, such as the Fox Hills–Hell Creek (or Lance) and Fort Union–Wasatch, are the most extensively used. Aquifers within the formations primarily are sandstones but may include coal beds, particularly in the Tertiary aquifers. Most wells are drilled for stock or domestic supplies, which generally can be obtained from wells less than 500 feet deep. Because the rocks are more than 500 feet thick in some places, yields greater than 500 gallons per minute can be obtained from deep wells. The quality of the water in shallow wells generally is a sulfate type and has dissolved-solids concentrations in excess of 2,000 milligrams per liter. Water from wells more than 250 feet deep generally is a bicarbonate type and dissolved-solids concentrations are about 1,000 milligrams per liter.

Quaternary alluvial deposits that will yield adequate quantity and quality of water for even the relatively small supplies required for stock or domestic use generally occur only along streams that originate in and near the mountains. Elsewhere the alluvium may be too thin or too fine grained, or the quality of the water may be too poor for most uses. Alluvium occurs in the flood plains and as capping on terraces, but the deposits capping the terraces may not have adequate saturated thickness to yield water to wells unless irrigation is practiced on the terraces.

GROUND-WATER QUALITY

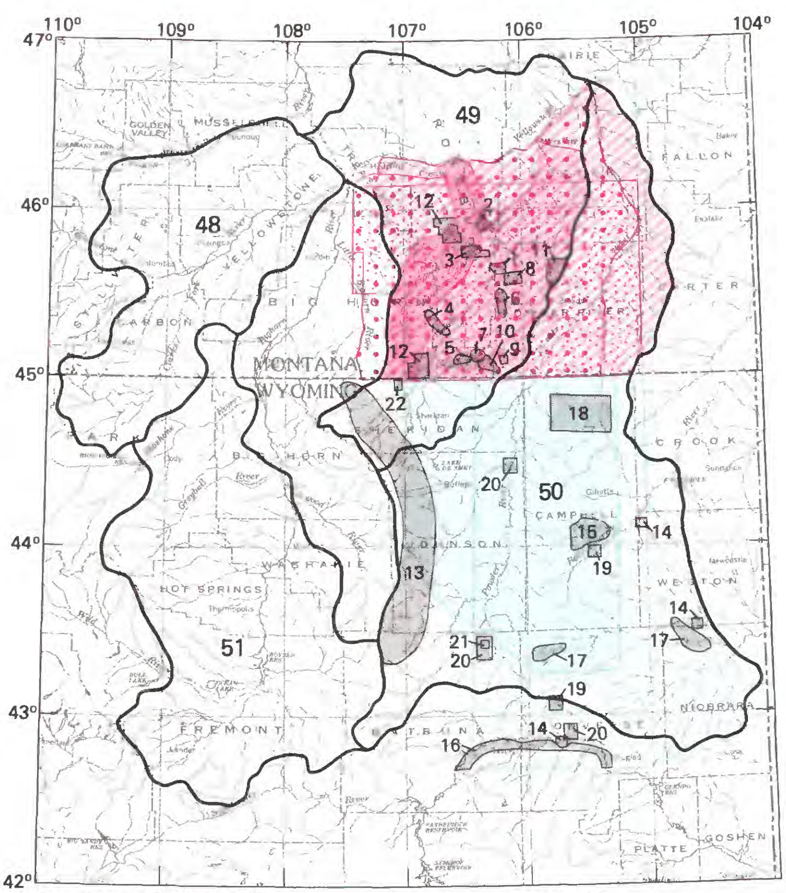
Water quality, as characterized by the quantity and type of dissolved constituents, differs greatly within and between the aquifers. Dissolved-solids concentration, the most commonly used indicator of water quality, ranged from 150 to 16,500 milligrams per liter in samples from approximately 2,000 springs and wells. Average concentrations in various aquifers ranged from about 1,500 to about 3,300 milligrams per liter; about 90 percent of all samples had concentrations exceeding 500 milligrams per liter.

Dominant ions vary throughout the regions. In northeastern Wyoming, dominant ions in aquifers in rocks of Paleozoic age are calcium and bicarbonate at or near the outcrops but are more likely to be sodium and sulfate or chloride at increasing distances from the outcrops. Water from shallow wells in the Upper Cretaceous and lower Tertiary aquifers has calcium, sodium, and sulfate; water from deeper wells has sodium and bicarbonate, similar to most wells in the western part of the region in Montana. The dominant ions in water in southeastern Montana are calcium, magnesium, sodium, and bicarbonate in shallow wells drilled at topographically high areas, sodium and sulfate in shallow wells drilled in valleys, and sodium and bicarbonate in deeper wells (Lee, 1980).

Dissolved trace-element concentrations generally are small in most aquifers; the notable exceptions are iron and manganese, which occur in large concentrations in water from many wells. In northeastern Wyoming, for example, dissolved manganese concentrations exceeded 50 micrograms per liter in 43 percent of the wells sampled, and dissolved iron concentrations exceeded 300 micrograms per liter in 35 percent of the wells. Large concentrations of boron, selenium, and strontium occur in a few wells throughout the regions.

COAL-HYDROLOGY STUDIES

Many studies and reports that characterize the water resources or that evaluate potential effects of coal mining in these regions, mostly in the Powder River region, have been completed since 1974 (fig. 40); a few remaining reports are in progress. With few exceptions, the studies were done as part of either the U.S. Geological



Base from U. S. Geological Survey 1:2,500,000 United States base map

0 50 100 MILES

0 50 100 KILOMETERS

FIGURE 40 (above and facing page).—Location of areas of coal-hydrology studies done in the Powder River, Bighorn Basin, and Wind River regions.

EXPLANATION

AREAS SHOWN ON MAP

COAL-AREA BOUNDARY

48 Slagle and others (1986)
49 Slagle and others (1983)
50 Lowry, Wilson, and others (1986)
51 Peterson and others (1987)

OTHER LARGE AREAS

MONTANA

Dockins and others (1980)

Ferreira (1984)

Knapton and Ferreira (1980); Litke (1983)

Slagle and others (1985)

Woods (1981)

WYOMING

Daddow (1986b)

Peterson (in press)

18 SMALL AREAS AND NUMBER

MONTANA

1 Cannon (1982)
2 Cannon (1983)
3 Levings (1983)
4 McClymonds (1982); Cary (1984)
5 McClymonds (1984a)
6 McClymonds (1984b)
7 McClymonds (1985)
8 U. S. Bureau of Land Management (1975b)
9 U. S. Bureau of Land Management (1977a)
10 U. S. Bureau of Land Management (1978)
11 U. S. Bureau of Land Management (1982)
12 Davis (1984b) (2 areas)

WYOMING

13 Boner and others (1976) (Numerous sites in area shown and in 3 areas outside mapped area)
14 Druse (1982) (3 areas)
15 Jordan and others (1984)
16 Larson (1985)
17 Lenfest (1987) (2 areas)
18 Lowry and Rankl (1987)
19 Naftz (1985) (2 areas)
20 Rankl (1982) (3 areas)
21 Rankl (1987)
22 Wangsness (1977); Ringen and others (1979)

AREAS NOT SHOWN ON MAP

(Study areas extend beyond mapped area)

MONTANA

Druse and others (1981)
Lambing (1984)
Lee (1979, 1980)
Lee and others (1981)
Levings (1981b)
Lewis and Hotchkiss (1981)
Lewis and Roberts (1978)
Miller (1979, 1981)
Omang and others (1982)
Slagle and Stimson (1979)
Stoner and Lewis (1980)
Wood (1984)

WYOMING

Armentrout and Wilson (1987)
Druse and others (1981)
Glover (1984)
Larson and Daddow (1984)
Lenfest (1985)
Lowry (1981)
Peterson (1988)
Rankl and Lowry (in press)
Wells (1982)

Survey's coal-hydrology program or the U.S. Bureau of Land Management's Energy Minerals Rehabilitation Inventory and Analysis (EMRIA) program. The studies were of three general types: (1) Appraisals or summaries for large areas within the region; (2) descriptions or assessments of small areas, usually of lease-tract size; and (3) studies of hydrologic processes.

Surface-water quality was assessed in several areal studies. The chemical quality and low flow of many streams in the Powder River region were documented during 1977–78 by Druse and others (1981). Statistical summaries of surface-water quality at sites in the coal areas were made for southeastern Montana by Knapton and Ferreira (1980) and for northeastern Wyoming by Peterson (1988). Larson (1985) summarized the chemical quality of the North Platte River in the vicinity of Casper, Wyoming; this stream reach is susceptible to indirect effects of coal development in northeastern Wyoming. Additional studies by Lee and others (1981) documented the chemical quality of base flow of Otter Creek, Tongue River, and Rosebud Creek in southeastern Montana. Peterson (in press) studied benthic invertebrate communities in streams in northeastern Wyoming. Invertebrate data are useful to evaluate possible changes in stream environments caused by land disturbance; for example, Peterson (in press) determined that the average density of invertebrates in the Belle Fourche River downstream from a coal mine was larger than that upstream from the mine.

Studies of large areas included determination of the areal extent and hydrogeologic properties of significant aquifers. Lewis and Hotchkiss (1981) delineated and described five hydrogeologic units in the Wasatch–Fox Hills sequence in Montana and Wyoming. Lewis and Roberts (1978) and Stoner and Lewis (1980) did similar studies in eastern and southeastern Montana. Miller (1979, 1981) mapped the thickness and configuration of the base of the Fox Hills–lower Hell Creek aquifer and described the availability of water from selected aquifers in the Powder River region. Daddow (1986b) mapped the potentiometric surface of the Wyodak-Anderson, the coal bed mined extensively in northeastern Wyoming. Ringen and Daddow (in press) demonstrated that the alluvium of the Powder River valley is not a significant aquifer. Lowry (1981) and Rankl and Lowry (in press) indicated that regional movement of ground water in shallow aquifers in northeastern Wyoming is not substantial in comparison with local movement. Discharge by evapotranspiration from alluvial aquifers was estimated by Lenfest (1985) at 12 sites in Wyoming and Montana.

Two regional studies of major aquifer systems contributed important information for assessing the availability of large supplies of ground water for coal development: the Madison Limestone Study (U.S. Geological Survey, 1975) and the Northern Great Plains Regional Aquifer-System Assessment (U.S. Geological Survey, 1979). Although not part of the coal-hydrology program, these studies were closely coordinated with that program. The areas of the two studies were nearly identical, encompassing eastern Montana, northeastern Wyoming, and western North Dakota and South Dakota. The Powder River region is within the areas of the two studies. Most of the information used in the two studies was obtained from data for municipal, industrial, and private water wells and from oil-and-gas wells; however, the U.S. Geological Survey drilled three additional test wells for the Madison study and one well for the Northern Great Plains study. The studies produced a series of reports (for example, MacCary and others, 1983; Henderson, 1984). A preliminary description of the hydrology of the Madison Limestone was prepared in cooperation with the Montana Bureau of Mines and Geology and the Wyoming State Engineer (Swenson and others, 1976). Also, an assessment of losses and gains in discharge of streams crossing outcrops of the Madison was done in cooperation with the Wyoming State Engineer and the Old West Regional Commission (Boner and others, 1976; Wyoming State Engineer's Office, 1976).

The physical features, resources, and hydrology of four large areas delineated by major drainage basins were summarized by Slagle and others (1983, 1986), Lowry, Wilson, and others (1986), and Peterson and others (1987). The reports partly fulfill the requirement of the Surface Mining Control and Reclamation Act of 1977 (Public Law 95-87) for information to be used by regulatory agencies in assessing the potential hydrologic effects of proposed mines.

The potential effects of surface mining on the hydrology of the following coal tracts were studied as part of the U.S. Bureau of Land Management's EMRIA program in Montana: Otter Creek (U.S. Bureau of Land Management, 1975b), Bear Creek (U.S. Bureau of Land Management, 1977a), Hanging Woman Creek (U.S. Bureau of Land Management, 1978), Pumpkin Creek (U.S. Bureau of Land Management, 1982), Prairie Dog Creek (McClymonds, 1982), Cook Creek (Cannon, 1982), Snider Creek (Cannon, 1983), Greenleaf-Miller (Levings, 1983), Corral Creek (McClymonds, 1984a), West Otter Creek (McClymonds, 1984b), and Horse Creek (McClymonds, 1985). The locations of these sites are shown in figure 40. Several additional site studies are scheduled for completion in the near future. Study results indicate that the effects of coal mining on ground water range from negligible effects in areas where coal beds are located above the water table to substantial problems associated with aquifer dewatering and leaching of soluble materials from mine spoils in areas where coal beds are saturated. In almost all areas, shallow aquifers removed by mining are not the only available water supply; wells drilled to deeper, unaffected aquifers could replace water supplies lost because of mining.

In a study of the White Tail Butte area in northeastern Wyoming, which included an EMRIA site, Lowry and Rankl (1987) described the effect of large areas of exposed clinker beds (coal altered by igneous intrusion) and the effect of changes in infiltration (as might be caused by reclamation, for example) on runoff from small basins. Lowry and Rankl (1987) also concluded: (1) That the area is a discharge area for part of the regional ground-water flow, although the volume of water moving regionally is small compared to that moving locally; and (2) that, based on water-quality samples, the discharging water had moved only a short distance through the bedrock. Water in aquifers below the coal is adequate for the present land use, which is livestock grazing.

Two studies were made of the hydrologic effects of an abandoned, nonrehabilitated surface mine in the Hidden Water Creek area near the Wyoming-Montana State line. The mine was operated from 1944 to 1955. Wangsness (1977) determined that, in comparison with ponds outside the mined area, ponds within the mined area had smaller concentrations of dissolved oxygen, larger concentrations of major ions, and less diverse biological communities. Ringen and others (1979) determined that the effect of mining on sediment yield was greater than the effect on chemical quality of water; sediment accumulated in a pond in the mined area at a rate more than 11 times that in a pond in a nearby unmined area.

A study of potential hydrologic effects of active surface coal mining at the Belle Ayr and Caballo Rojo mines in Campbell County, Wyoming, was done in cooperation with the Wyoming Department of Environmental Quality. Preliminary findings, based on modeling of discharge in Caballo Creek, were that there is little, if any, change in discharge caused by mining (Jordan and others, 1984). A report (Bloyd and others, 1986) provides a detailed description of the results of the surface-water modeling as well as a general description of ground-water flow in the area.

Digital-model simulations also were used in two studies in Montana. Slagle and others (1985) used models to depict maximum drawdown of shallow ground water as a result of mine dewatering. Ferreira (1984) modeled the cumulative effects of mining and agriculture on concentrations of dissolved solids in Rosebud Creek; the simulations indicate that irrigation accounts for a larger cumulative percentage of dissolved-solids concentration than present (1985) mining, but that planned, full-scale mining would account for a larger percentage than irrigation.

The objectives of several studies done in southeastern Montana and northeastern Wyoming were to describe or simulate various hydrologic processes. The general purpose of such studies, usually done at one or a few sites, is to use the knowledge gained in studies at other locations that have similar characteristics but that lack data. The studies are discussed in the following paragraphs.

Three studies of hydrologic processes were concerned with discharge. A procedure using storage analysis of discharge records to assess the long-term water supply of an ephemeral stream was developed by Glover (1984); the method overcomes deficiencies of previous methods developed for perennial streams by accounting for zero-flow periods and the large day-to-day variability of discharge of ephemeral streams. Cary (1984) tested the U.S. Geological Survey's Precipitation-Runoff Modeling System (PRMS) to develop, calibrate, and verify a watershed model for use in simulating hydrologic processes in small basins. Rankl (1982) developed an empirical infiltration model for estimating runoff from specified design storms in small basins that have ephemeral streams; the method uses incipient-ponding curves based on rainfall-runoff data and information from soils maps. In a follow-up study that estimated runoff from rainfall and infiltration, Rankl (1989) extended his previous work to other small ephemeral-stream basins that have a variety of soil types, and verified a physically based equation for defining the infiltration parameters.

The problem of predicting the source and quantity of sediment discharge from small ephemeral-stream basins was studied by Rankl (1987). Rankl collected rainfall, discharge, and sediment-concentration data from a very small basin (0.8 square mile) and used the PRMS to evaluate the physical processes that affect sediment production. For a given storm, sediment load and peak discharge were strongly correlated, a potentially useful means to evaluate the effects of surface coal mining on erosion and sedimentation.

The interrelation of discharge and shallow ground water was the subject of two studies. Rankl and Lowry (in press) determined that vertical movement of ground water was restricted and that discharge occurred at outcrops not necessarily at stream level and in insufficient quantities to reach perennial streams. Also, data indicate that base flow, present in only a few streams, is related to local conditions rather than to a regional flow system. Lenfest (1987) investigated the function of alluvium in stream channels in recharging bedrock aquifers; the use of discharge losses between stream-discharge sites to estimate recharge resulted in underestimation, in comparison with an analytic solution of a ground-water flow equation.

Geochemical processes that control or affect the quality of ground water in the Fort Union Formation were investigated by Lee (1980). Water quality was determined to be related to mineralogy, distance along a ground-water flow path, ion exchange, and anaerobic bacteria that reduce sulfate to sulfide. The process of sulfate reduction in ground water was investigated further by Dockins and others (1980).

Water quality and geochemical processes affected by mining were the subject of three studies. Woods (1981) developed a computer model for assessing the effects of various combinations of mining and agricultural development on potential increases in dissolved-solids concentrations in streams as a result of leaching of overburden materials used to backfill surface coal-mine pits. In a study of geochemical processes that affect the quality of water in mine spoils, Davis (1984b) compared the quality of water in mine spoils with that in undisturbed aquifers and developed a method of predicting future water quality in mine spoils and the effects of mine spoils on the hydrologic system. The geochemical processes in reclaimed mines in Wyoming is being studied by Naftz (1985) to determine the differences between the quality of water in undisturbed aquifers and that in spoil aquifers.

HYDROLOGIC ISSUES RELATED TO COAL MINING

At the beginning of the coal-hydrology program it was recognized that one issue was a general lack of knowledge about the hydrology of small ephemeral-stream basins. The most significant issue of all, however, was that no large, inexpensive supplies of water were readily available even though the Powder River region has abundant coal. That fact was the rationale for using air cooling, rather than less expensive water cooling, at the Wyodak steam-electric plant in Campbell County, Wyoming—the world's largest (1983) plant of that kind. In another example, a plan to use ground water (20,000 acre-feet per year) for a coal-slurry pipeline from northeastern Wyoming to Arkansas was abandoned, partly because of opposition to transporting water out of the area.

The scale of present (1985) and planned mining in the Powder River region is large; therefore, some regional consequences of mining can be expected. The largest regional effect on water resources probably will be caused by the increases in population and land use, rather than by mining activities. Increased use of ground water in the population centers may cause overwithdrawals. Generally, however, regional effects of coal development on quantity of ground-water flow are unlikely.

Erosion, sediment deposition, water-level declines, and water-quality degradation are potential local issues associated with mining. Erosion and sediment deposition, potential issues in any watershed affected by mining, generally are controlled at all active mine sites as required by State and Federal surface-mining regulations. Erosion is controlled by proper grading and revegetation of areas affected by mining, and sediment runoff is controlled through the use of settling ponds. However, channel scour can occur downstream from settling ponds if the discharged water has suspended-sediment concentrations that are substantially smaller than the natural, or premining, concentrations.

Mine pits that intersect the water table will lower water levels near the mine and have the potential to affect nearby wells and springs. Water-level declines have been measured near surface mines in Montana and Wyoming; however, such effects generally are limited to areas within 1 or 2 miles of the mine. Lowering of the water table near the Wyodak Mine in Campbell County, Wyoming, which began operations during the 1920's, had not extended westward more than 1,500 feet by 1979. Where surface mining begins at the edge of the coal mine and extends some distance beyond the point where the water table is intercepted, the water levels in adjoining aquifers may be lowered.

Although infiltration, runoff, and aquifer properties can be engineered in a variety of ways, the most likely effect of reclamation will be to insert into the existing hydrologic system a unit having completely different hydrologic properties. The changes could be either beneficial or detrimental; for example, flooding may be decreased downstream from reclaimed areas that have increased capacity for infiltration, but useful low-to-average flows also may be decreased. If recharge is increased, however, low flows could be increased by an increase in ground-water discharge to the stream.

Possibly the most important long-term issue associated with surface mining is the potential for degradation of water quality because of the leaching of soluble materials from mine spoils. Chemical analyses of spoil-derived water from mine areas in Montana have indicated that the dissolved-solids concentrations of water in spoils statistically are greater than those in undisturbed aquifers near the mines. Acid mine drainage is not an issue in these regions, however, because of the abundance of carbonate minerals and the large buffering capacity of the natural waters.

The hydrologic effects of underground mines were not studied as part of the coal-hydrology program in these regions because large-scale underground mining is not planned. In an analysis of the effects of past underground mining in the Sheridan, Wyoming, area, Dunrud and Osterwald (1980, p. 41) described environmental issues such as subsidence, diversion or pollution of surface or ground water, and a variety of adverse effects of underground mine fires. They stated (p. 43-44) that such issues are much easier to assess and control in surface mining. On the positive side, water supplies have been developed from wells bored into flooded mine workings (Lowry, Wilson, and others, 1986, p. 8).

NORTHERN GREAT PLAINS AND ROCKY MOUNTAIN PROVINCES— GREEN RIVER AND HAMS FORK REGIONS

By Neville G. Gaggiani

The Green River and Hams Fork regions (fig. 41), an area of about 46,900 square miles located primarily in southwestern Wyoming and northwestern Colorado but also in parts of Idaho and Utah, include coal areas 52–54 (table 1). Major coal fields outside the regions also are included in this discussion; these include the Hanna and Rock Creek coal fields in Wyoming and the North Park and Danforth Hills coal fields in Colorado (fig. 4). The regions are located in parts of the Middle Rocky Mountains, Southern Rocky Mountains, and Wyoming Basin physiographic provinces and the Uinta Basin section of the Colorado Plateaus physiographic province (pl. 1).

The major rivers draining the regions are the Green and North Platte Rivers (fig. 41). Major tributaries of the Green River are the Yampa and White Rivers and major tributaries of the North Platte River are the

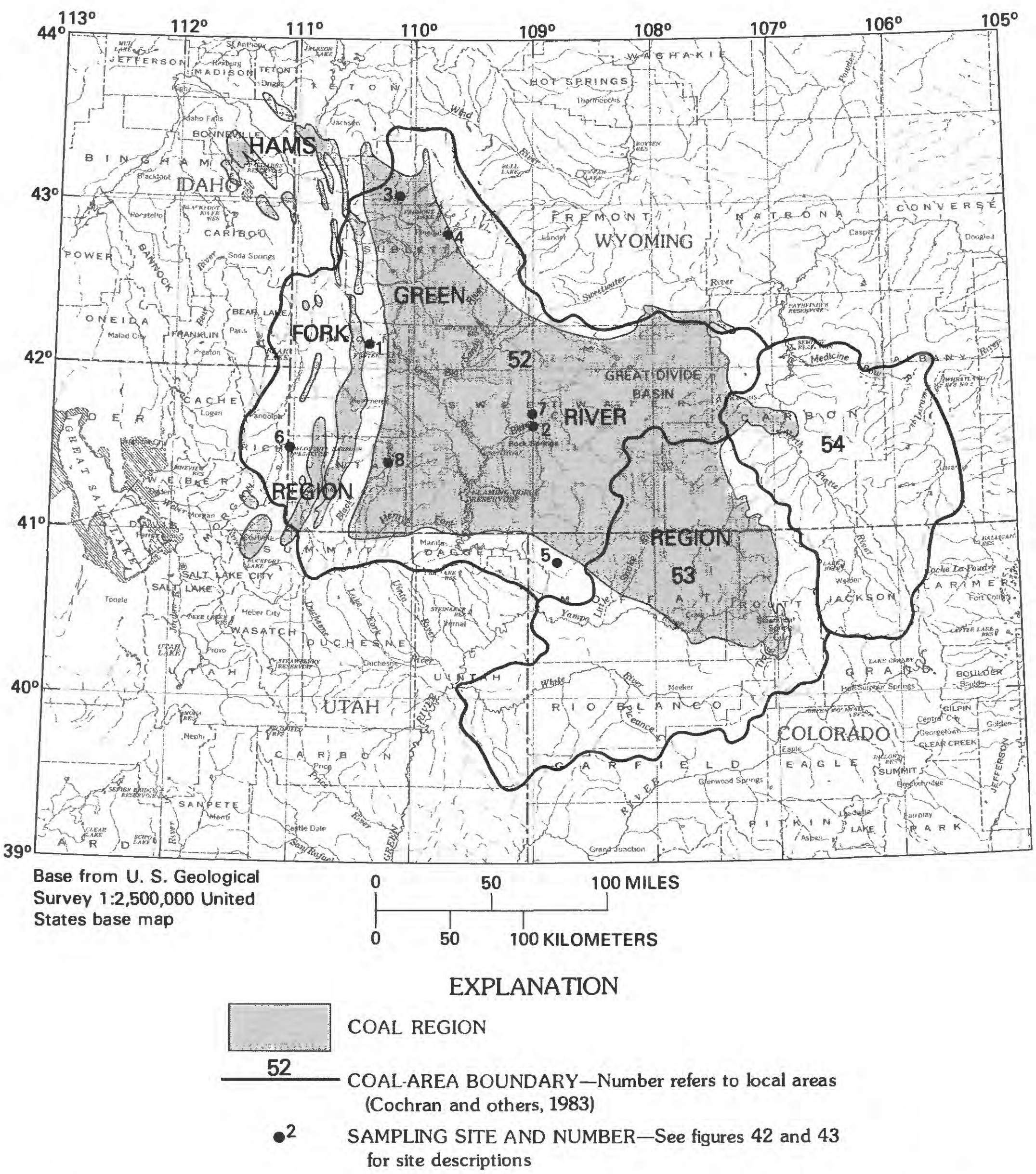


Figure 41.—The Green River and Hams Fork regions, coal areas 52–54, and sampling sites.

Laramie and Medicine Bow Rivers. Other smaller drainages in the regions include the Great Divide Basin, where there is no surface flow into or out of the basin, and the Bear River, which drains the western edge of the regions and flows into Idaho. The major rivers and many of the tributaries originate in granitic mountains and flow into and through sedimentary basins between mountain ranges.

The regions are semiarid and have warm summers and cold winters. Parts of the regions vary from alpine in the higher altitudes of the mountain ranges to arid in parts of the Green River basin in Wyoming and the White River basin in Colorado and Utah. Precipitation in the regions is quite variable. In the high mountains, average annual precipitation is as much as 60 inches and occurs mainly as snow. In the semiarid basins, average annual precipitation ranges from less than 7 to more than 16 inches and occurs mainly as rain.

Rocks of Precambrian age to Quaternary age are exposed in the Green River and Hams Fork regions. The tectonic activity of the Laramide orogeny during the Late Cretaceous Period consisted of major faulting, folding, uplift, and subsidence, which formed the basic structure of the synclinal basins and anticlinal mountains. It was the last major episode of tectonic activity in the regions. Erosion by water, wind, and glaciation further shaped the physiographic features of the regions by exposing mountain peaks composed of rocks of Precambrian age and filling in basins with alluvial and aeolian deposits of Quaternary age.

Bedrock in most areas of the regions consists of sedimentary deposits of Cretaceous and Tertiary age. Most of the coal deposits occur in these rocks. Outside of the sedimentary basins, where the mountains have been pushed up by tectonic activity, most of the bedrock is crystalline rock of Precambrian age. Economic deposits of coal occur in units of the Cretaceous Mesaverde Group, the Lance and Medicine Bow Formations, the Cretaceous and Tertiary Evanston and Ferris Formations, and the Tertiary Fort Union, Wasatch, Hanna, and Coalmont Formations.

The major land use in the regions is livestock grazing. Other land uses are timber harvesting, farming, recreation, mineral mining, and urban use. More than 60 percent of the land in the regions is rangeland that is either privately owned or owned by the Federal or State Government. The majority of cropland is used to grow hay for livestock or to improve grazing on pastureland. Where possible, cropland is in a low area near a river so that the land can be flood-irrigated by canals. Irrigated and nonirrigated cropland compose less than 10 percent of the land area. Timberland (forested land) compose less than 10 percent of the land west of the Continental Divide (in the Rocky Mountains) and about 30 percent of the land area east of the Continental Divide. Fourteen percent of the land in the regions is forested; generally these areas are located on the slopes of the mountain ranges.

The regions have a small population density, and there are few urban areas. According to the 1980 census, the regions have less than 262,000 people. The two major urban areas in the regions are Laramie in southeastern Wyoming (population 24,410) and Rock Springs (population 19,485) in southwestern Wyoming (Kuhn and others, 1983; Lowham and others, 1985).

The major water use in the regions is irrigation of crops. Both surface- and ground-water sources are used, but more surface water is used than ground water (Lowham and others, 1985). In the Green River basin, the Bear River basin, and the Great Divide Basin of Wyoming, more than 80 percent of the water is used for irrigation. Other uses include residential and industrial, public water supplies, and stock watering.

COAL RESOURCES

Coal-bearing rock formations underlie most areas of the two regions; the largest continuous area underlain by coal deposits is in the Green River region. The major coal-bearing formations in the regions are in the Mesaverde Group, which contains coal beds 3 to 20 feet thick. Most of the coal occurs in the Williams Fork and Iles Formations of the Mesaverde Group. Other economic deposits of coal occur in the Lance Formation, which contains coal beds generally 0.5 to 10 feet thick, the Fort Union Formation, which contains coal beds that are as much as 40 feet thick, and the Wasatch Formation, which contains coal beds that also are as much as 40 feet thick.

Three coal fields are located outside the boundaries of the regions. The Hanna coal field (fig. 4), in Carbon County, Wyoming, is the largest of the three. Coal deposits occur in the Hanna, Ferris, and Medicine Bow Formations and in the Almond Formation of the Mesaverde Group. The Hanna Formation has 32 coal beds that are more than 5 feet thick and 8 coal beds that are 20 to 40 feet thick. The Ferris Formation has 28 mineable coal beds that generally are 5 to 10 feet thick and 3 coal beds that are 25 to 40 feet thick. The Medicine Bow Formation has three coal beds of economic importance; the thickest of these is 9 feet. The Almond Formation has coal beds 5 to 10 feet thick that are suitable for surface mining.

Little is known about coal beds in the Rock Creek coal field (fig. 4), which is located in Albany and Carbon Counties, Wyoming. A few coal beds occur in the Pine Ridge Sandstone of the Mesaverde Group and in the Hanna Formation. The North Park coal field (fig. 4) in

Jackson County, Colorado, has coal deposits in the Coalmont Formation. Three coal beds of economic importance, ranging in thickness from 3 to 80 feet, occur in this formation.

Coal in the regions is of moderate heating value and has comparatively large moisture content but has small concentrations of sulfur. The coal ranges from subbituminous to high volatile B and C bituminous (fig. 4). The strippable coal reserves in the regions have been estimated to be about 10.5 billion tons.

Total coal production from the 14 coal fields in the Green River and Hams Fork regions is reported to be more than 660 million tons. Most of this production was low-sulfur subbituminous coal and was from surface and underground mines. During 1983 in coal area 52, there were 7 active surface mines and no active underground mines; underground mining ceased during 1982. During 1980 in coal areas 53 and 54, there were 10 active surface mines and 8 active underground mines, but by 1983 there were only 5 active surface mines and no active underground mines.

HYDROLOGY

Two general objectives for the coal-hydrology program in the regions were: (1) To increase knowledge about the availability of water; and (2) to provide information for assessing the effects of coal development on water resources on a regional basis and on a site-specific basis.

At present (1985), all the coal mined in the Green River and Hams Fork regions is from surface mines. Potential issues using this method of mining are related to the changes in the quantity and quality of surface runoff caused by changes in soil infiltration rates and vegetative cover. After surface mining ceases, revegetation is difficult in arid-to-semiarid areas. Also, changes to the natural landscape will affect the hydrology of an area in some way. The extent of that effect will vary from site to site depending on the following factors:

1. Mining and reclamation methods;
2. Slope of land being mined;
3. Types of soil and rock;
4. Quantity of precipitation;
5. Quality of ground water and surface water; and
6. Rate of water movement.

As part of the coal-hydrology program, the hydrologic-data-collection network was expanded or otherwise enhanced, and interpretive hydrologic studies were undertaken. This twofold approach was to indicate existing and potential issues discussed above and to evaluate data requirements to address the factors affecting potential hydrologic effects from coal mining.

SURFACE-WATER NETWORK

Surface-water and water-quality data are available for 951 sites, of which 195 sites are presently active (1981 for coal area 54; 1982 for coal areas 52 and 53). The earliest records for measured discharge were for the Laramie River during 1890 at Woods Landing in Laramie County near the Colorado-Wyoming State line and for the Green River during 1891 at Green River, Wyoming. The Laramie River measurement probably was related to water rights for irrigated cropland (Lowham and others, 1985).

The historical surface-water network includes 391 continuous-record stream-discharge sites, 57 water-quality sites, 130 sites where discharge and water-quality data were collected, 57 peak-discharge (crest-stage) sites, and 316 miscellaneous sites where one or more discharge measurements or water-quality samples were made as part of interpretive studies. The number of sites added since the coal-hydrology program began during 1974 are 119 continuous-record stream-discharge sites and 185 water-quality sites.

Water-quality data collected at the sites include dissolved-solids concentrations, specific conductance, alkalinity, pH, and concentrations of sulfate and selected dissolved trace elements. Collection intervals varied from only one sample at some miscellaneous sites to monthly or daily samples at some water-quality sites. Generally, the ephemeral streams in the arid and semiarid basins of the regions where coal mines usually are located do not have long periods of record.

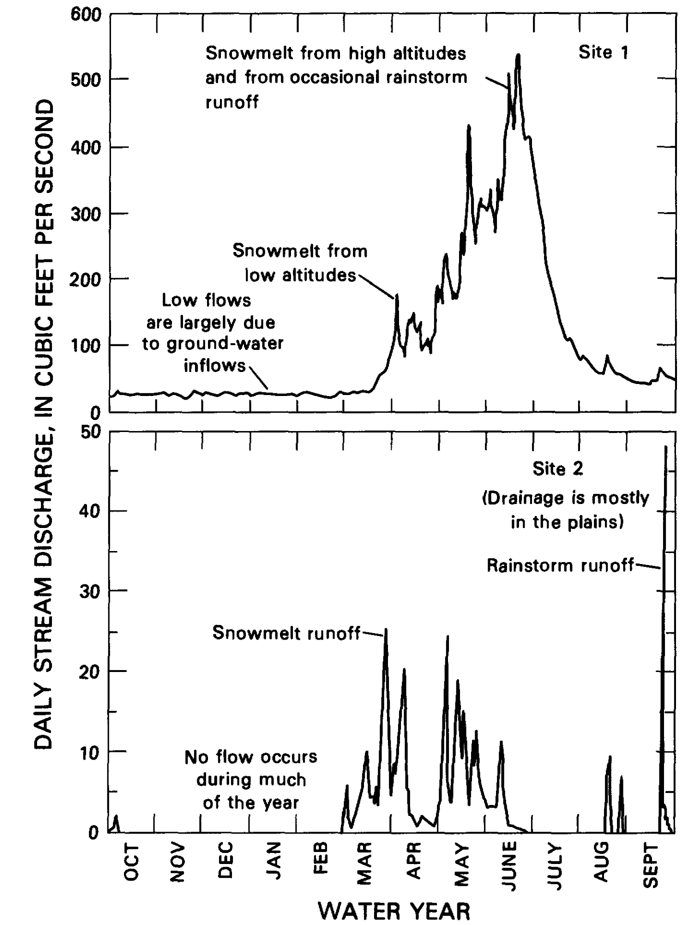
Suspended-sediment data are available for 161 sites in the Green River and Hams Fork regions, of which 83 presently are active (1981 for coal area 54; 1982 for coal areas 52 and 53). The longest period of record and earliest record of a suspended-sediment measurement are from a site located on the Green River near the town of Green River, Wyoming, that has records from 1951 to the present (1985). Many of the sites have only 1 year of record. The frequency of collection varies; most sites have weekly, monthly, or quarterly records. Some sites have daily records where samples are obtained either by using automatic pumping samplers or by having a local observer collect the samples.

SURFACE-WATER CHARACTERISTICS

Most of the discharge in the regions occurs in streams draining mountainous areas and originates from snowmelt. Most of the annual discharge occurs during spring and early summer. The exact time of the snowmelt varies within the regions and is controlled by temperature, altitude, slope, aspect (the direction the slope is facing—if the slope is facing north, the melting will be the slowest), and vegetative cover. At the White River downstream from Meeker, Colorado, 60 percent of the discharge occurs during May, June, and July, whereas at the Yampa River near Maybell, northwestern Colorado, 70 percent of the annual discharge occurs during April, May, and June. During late summer, fall, and winter, flows primarily are the result of ground-water inflows. Minimum discharges occur from January through March.

Intermittent and ephemeral streams that originate in and drain the arid to semiarid basins have extended periods of no flow. Because flow for these streams is supplied by summer rainstorms, ground-water discharge, and springs, there is not enough water to sustain flow throughout the year (fig. 42).

Estimates of average annual discharge and high flows at selected frequencies can be made at ungaged streams using relations developed at gaged streams. Average annual discharge can be estimated at ungaged streams using predictive equations developed for Colorado (Livingston, 1970) and Wyoming (Lowham, 1976). High-flow and floodflow frequencies and magnitude can be estimated using equations developed for Colorado, Wyoming, Utah, and Idaho for the respective areas in the regions. Floodflows usually are caused by summer rainstorms or rain occurring on snow in the spring. Flows in the small ephemeral streams, where the coal generally is mined, are the most difficult to estimate. Craig and Rankl (1978) developed relations especially for these types of streams in Wyoming. Similar relations also are presently being developed for streams in Colorado (Livingston and Minges, 1987). Low-flow frequencies are not predictable in the regions because perennial streams are affected by regulation and diversion and ephemeral streams are dry for most days each year.



EXPLANATION

SITE NUMBER IN FIGURE 41	SITE NAME AND DRAINAGE AREA
1	Fontenelle Creek near Herschler Ranch near Fontenelle, Wyoming (152 square miles)
2	Salt Wells Creek near Salt Wells, Wyoming (526 square miles)

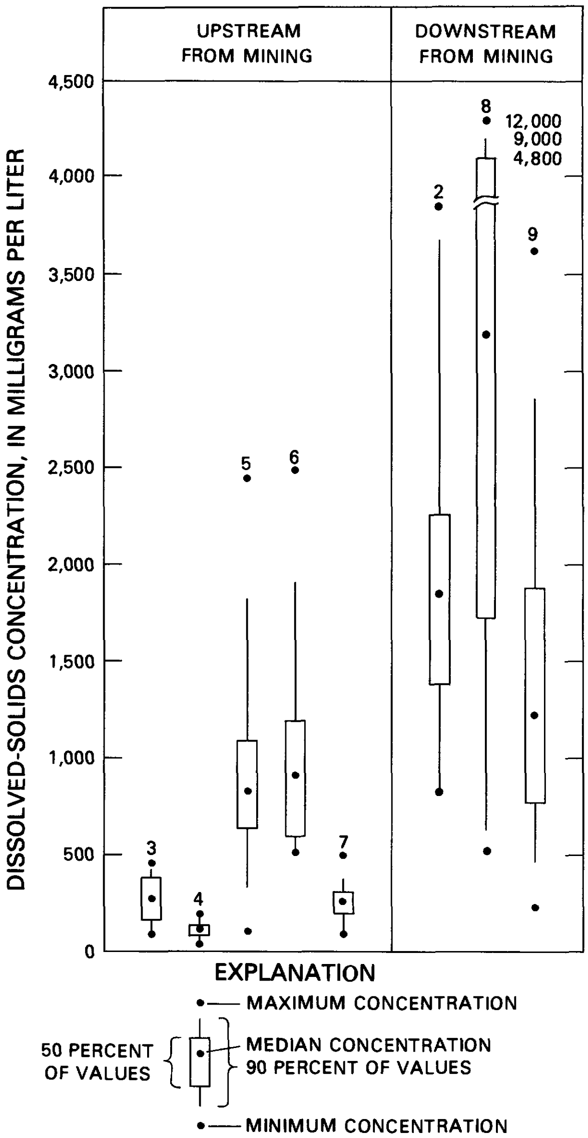
FIGURE 42.—Typical hydrographs showing variation of stream discharge for selected streams during the 1978 water year in the Green River and Hams Fork regions.

SURFACE-WATER QUALITY

Results of chemical analyses of water samples collected throughout the regions indicate that the quality of water in the mountainous streams is good but degrades to fair or poor in many of the plains streams (Lowham and others, 1985). Lakes and reservoirs in the regions have had occasional algal blooms. Data collected from streams, lakes, and reservoirs include water temperature, specific conductance, pH, alkalinity, and concentrations of dissolved solids, sulfate, phosphorus, and trace elements, such as arsenic, boron, cadmium, chromium, copper, iron, lead, manganese, mercury, selenium, and zinc. Biological and bacteria samples also were collected.

Dissolved-solids concentrations generally were small (less than 500 milligrams per liter) in streams in and near the mountains and large (1,210 to more than 15,000 milligrams per liter) in streams in the lower drainage basins (Lowham and others, 1985). As water moves downstream, human activities such as irrigation, water storage, and waste disposal increase dissolved-solids concentrations. For example, the dissolved-solids concentrations increase twofold between the Green River upstream from Fontenelle Reservoir in Wyoming and Flaming Gorge Reservoir in Wyoming (fig. 41).

The maximum, median, and minimum concentrations of dissolved solids for selected sites on streams with similar-sized drainage areas in the Green River basin in Wyoming are shown in figure 43. The sites are divided into those that are upstream from coal mining and those that are downstream from coal mining. The



SITE NUMBER IN FIGURE 41	SITE NAME AND DRAINAGE AREA
2	Salt Wells Creek near Salt Wells, Wyoming (526 square miles)
3	Green River at Warren Bridge, near Daniel, Wyoming (468 square miles)
4	New Fork River near Boulder, Wyoming (552 square miles)
5	Henry's Fork near Manila, Utah (520 square miles)
6	Vermillion Creek at Ink Springs Ranch, Colorado (816 square miles)
7	Bear River above reservoir, near Woodruff, Utah (752 square miles)
8	Bitter Creek above Salt Wells Creek, near Salt Wells, Wyoming (836 square miles)
9	Blacks Fork near Lyman, Wyoming (821 square miles)

FIGURE 43.—Maximum, median, and minimum dissolved-solids concentrations at selected surface-water-quality sites in the Green River and Hams Fork regions.

sites downstream from coal mining had larger dissolved-solids concentrations than those upstream from mining. Dissolved solids in the Yampa and White River basins range from 10 to 15,500 milligrams per liter. Mean dissolved-solids concentrations at sites in the North Platte River basin, including the Medicine Bow and Laramie Rivers, range from less than 50 to more than 1,000 milligrams per liter. Measurements of specific conductance in the regions ranged from less than 30 to more than 18,000 microsiemens per centimeter.

Alkalinity concentrations and pH values in the regions generally are not water-quality issues. The large buffering capacity of the streams in this mostly arid and semiarid area prevents acid mine drainage. In the Piceance and White River basins, alkalinity in 72 percent of the analyses was less than 400 milligrams per liter calcium carbonate (Driver and others, 1984), and in the North Platte River basin, alkalinity in about 95 percent of the analyses was less than 200 milligrams per liter calcium carbonate. The majority of pH measurements throughout the regions ranged from 6.5 to 9.0.

Sulfate concentrations are large in the plains streams but, in this instance, they are not a good indicator of mine drainage because there are many natural sources of sulfate not related to mining (Lowham and others, 1985). Sulfate concentrations ranged from 0 to 10,000 milligrams per liter in the regions.

Total phosphorus concentrations in streams in the regions frequently exceed the recommended limits above which reservoirs and streams are affected by nuisance growth of algae and other aquatic plants. The total phosphorus concentration criterion for streams entering reservoirs is 0.05 milligram per liter, and the criterion for streams elsewhere is 0.10 milligram per liter (U.S. Environmental Protection Agency, 1986b). The Green River upstream from Fontenelle Reservoir had total phosphorus concentrations at or less than the detection limit of 0.01 milligram per liter. In Bitter Creek drainage basin upstream from Flaming Gorge Reservoir, the median total phosphorus concentration for all streams is more than 0.10 milligram per liter. Most of the phosphorus is transported adsorbed to suspended sediment in streams. Reservoirs trap sediment; thus, phosphorus is concentrated, and eutrophic conditions sometimes exist.

Trace-element concentrations, except for iron and manganese, generally are not a water-quality issue in the regions. Large total-recoverable iron and total-recoverable manganese concentrations usually are associated with large suspended-sediment concentrations. In coal area 53, total-recoverable iron and total-recoverable manganese concentrations commonly exceeded water-quality criteria for domestic water supplies (U.S. Environmental Protection Agency, 1986b).

In 65 percent of the analyses, total-recoverable iron concentrations exceeded 300 micrograms per liter, and in 69 percent of the analyses, total-recoverable manganese concentrations exceeded 50 micrograms per liter. Other trace-element concentrations occasionally exceeded water-quality criteria.

In most parts of the regions, upstream reaches of streams have a healthy biotic community and a balanced taxonomic composition. However, diversity of biota decreases downstream and probably is related to deteriorating water quality. Fecal-coliform bacteria occurred only in small concentrations; this indicates little pollution from warmblooded animals.

In coal area 54, discharge-weighted, suspended-sediment discharge concentrations generally are less than 50 milligrams per liter in the mountains and as much as 2,730 milligrams per liter in the plains. In coal area 52, only a relatively small quantity of sediment is transported out of the area, primarily because large quantities of sediment are trapped by reservoirs. For example, out of 183,000 tons of sediment transported into Fontenelle Reservoir by the Green River, only about 10,800 tons are discharged from the reservoir. A combined total of 549,000 tons of sediment were transported by the Green River, Blacks Fork, and Henrys Fork into Flaming Gorge Reservoir, but only about 400 tons were measured downstream from the dam (Lowham and others, 1985). In coal area 53, values of sediment yield range from less than 0.1 acre-foot per square mile per year in the mountains to almost 3.0 acre-feet per square mile per year in the lower and drier parts of the area.

GROUND-WATER NETWORK

Ground-water data are available for more than 4,000 wells and springs in the Green River and Hams Fork regions. The types of data available include water levels, water-quality analyses, yield measurements from wells and springs, aquifer characteristics, well-construction information, and well logs. Frequency of water-level measurements vary from a single measurement to continuous measurements made by a water-level recorder. Most of the wells are used for areal ground-water studies where there is a relatively short period of data collection and then no data collection after that. Water-quality data were collected as part of areal studies of limited duration and therefore have a relatively short period of record for any given site.

Periodic water-level measurements have been made at sites throughout the regions for varying periods as part of State and (or) Federal ground-water-level networks. Records in coal area 54 date back to the early 1940's. The earliest water-level record dates back to 1936 at well (A-11-7) 9CD-1 (Lowham and others, 1985), which is located in a shallow aquifer in Rich County, Utah. Water-level measurements generally have been continued at this well until the present (1985).

GROUND-WATER OCCURRENCE

Brogden and Giles (1977) studied ground-water resources in the Yampa River basin (coal area 53) between Craig and Steamboat Springs, Colorado. They determined that ground water is obtained from the Fort Union, Lance, Williams Fork, and Iles Formations and that the wells generally yield less than 25 gallons per minute; however, in the alluvium of the Yampa River basin, wells yield as much as 900 gallons per minute.

Welder (1968) reported that the wells in the Green River basin of Wyoming (coal area 52) had yields that range from 1 to 500 gallons per minute, but yields of most wells range from about 10 to 100 gallons per minute. Yields greater than 500 gallons per minute probably could be obtained from deep wells (2,000 to 5,000 feet) penetrating thick sandstone sections in the Wasatch and Fort Union Formations.

Ground-water occurrence in the Great Divide Basin and Washakie basin, in southwestern Wyoming (coal area 52), has been reported by Welder and McGreevy (1968). In the Great Divide Basin, the principal water-bearing formations are the Wasatch and Battle Spring Formations. Water in these formations generally is under artesian pressure; however, unconfined ground water exists locally. Most wells tapping the Wasatch Formation are less than 1,000 feet in depth and have yields that range from 5 to 110 gallons per minute (Welder and McGreevy, 1968); however, maximum yields of 500 gallons per minute might be obtained from saturated sandstone. Wells tapping the Battle Spring Formation have yields that range from 1 to 71 gallons per minute. However, wells that tap the greatest thickness of the formation might have maximum yields in excess of 1,000 gallons per minute.

In the Washakie basin, sandstone is the principal water-bearing medium in the aquifers (Welder and McGreevy, 1968). The Wasatch and older aquifers in the basin generally are deep and less accessible to wells than in the Great Divide Basin. Relatively impermeable beds of claystone and shale in the Green River, Bridger, and Uinta Formations overlie the Wasatch Formation in most of the Washakie basin. The wells that tap the Wasatch have yields that are reported to range from 1 to 67 gallons per minute, and maximum yields probably would not exceed 400 gallons per minute (Welder and McGreevy, 1968). Wells that tap the Bridger and Uinta Formations can be expected to have very small yields.

Aquifers in the Hanna, Carbon, and northern Laramie basins (coal area 54) include sandstone, conglomerate, and coal beds of the Hanna, Ferris, and Medicine Bow Formations and Mesaverde Group (Kuhn and others, 1983). Generally the yields are less than 50 gallons per minute. Yields as much as 1,000 gallons per minute may be possible where the unit is very thick. Other principal water-bearing formations in coal area 54 include the Browns Park and North Park Formations, and they yield as much as 500 to 1,000 gallons per minute (Kuhn and others, 1983).

GROUND-WATER QUALITY

Chemical analyses of ground water have been made for water from wells throughout the Green River and Hams Fork regions. Only a general description of the ground-water quality of the regions can be given because of the relatively small number of wells sampled compared to the large area of the regions, the poor distribution of wells in coal areas 53 and 54, and the short period of record for the water-quality observation wells (many wells were sampled only during 1 year).

Generally, wells that yield water that have small dissolved-solids concentrations are located in or near the mountainous recharge areas where recharge water from snowmelt or mountain streams is of good quality. Wells in the lower basins, however, generally have large dissolved-solids concentrations that, in many instances, exceed the water-quality criteria for drinking water (U.S. Environmental Protection Agency, 1986b) but usually do not exceed the criteria for livestock watering. Most wells in the basins, except for the Bear River valley, are used for livestock watering. In the Bear River valley, which is located in Utah and Wyoming at the northwestern corner of the regions, the well yields are large enough and dissolved-solids concentrations are small enough that irrigation is the major use of ground water.

In the Green River basin and Great Divide Basin of Wyoming, 40 percent of the ground-water samples had dissolved-solids concentrations less than 500 milligrams per liter, 68 percent were less than 1,000 milligrams per liter, and 92 percent were less than 5,000 milligrams per liter (which generally would be suitable for livestock watering). Dissolved-solids concentrations of water in the coal-bearing Wasatch Formation ranged from 149 to 9,710 milligrams per liter, and averaged 1,030 milligrams per liter. In the White River and Yampa River basins, the dissolved-solids concentrations ranged from 46 to 109,000 milligrams per liter. In coal area 54 (the North Platte River basin), ground-water samples collected from the coal-bearing formations had dissolved-solids concentrations that exceeded 2,000 milligrams per liter only in the Ferris and Hanna Formations. The maximum dissolved-solids concentration in the Hanna basin was 8,160 milligrams per liter.

Fluoride and nitrate concentrations exceeded drinking-water regulations in some areas (U.S. Environmental Protection Agency, 1986a, 1986c). Fluoride concentrations of more than 2 milligrams per liter occurred in some wells in the Green River basin, and fluoride concentrations of more than 3 milligrams per liter occurred in wells in the coal-bearing formations of the Hanna basin in Carbon County, Wyoming. Nitrate concentrations in about 1 percent of the samples in coal area 52 exceeded 10 milligrams per liter.

Except for iron and manganese, trace-element concentrations in ground water from the regions are only an occasional water-quality issue. Iron concentrations exceeded the regulation of 300 micrograms per liter for drinking water (U.S. Environmental Protection Agency, 1986c) in about 20 percent of the chemical analyses, ranging from 0 to almost 50,000 micrograms per liter. Manganese concentrations exceeded the regulation of 50 micrograms per liter in about 30 percent of the chemical analyses, ranging from 0 to more than 3,000 micrograms per liter.

COAL-HYDROLOGY STUDIES

Studies done in the Green River and Hams Fork regions can be subdivided into three general categories: (1) Studies that encompass large areas; (2) studies that are site specific, usually coal-lease size; and (3) studies that deal with hydrologic processes.

Lowham and others (1976) developed a plan to study the effects of economic development on the surface- and ground-water availability and water quality in the Green River basin and the Great Divide Basin. Development of coal, oil, trona, and oil shale, as well as other associated development, would require a projected 490,000 acre-feet per year of water by the year 2020. An additional 270,000 acre-feet per year of water also could be needed by other parts of Wyoming because of transbasin diversion. Lowham and others (1976) presented a plan for the study and discussed particular methods of approach by: (1) Describing the existing water resources and hydrologic relations necessary to determine water supplies and to predict effects of proposed energy-related water development; and (2) designing data-collection programs to evaluate the effects of energy-related water development.

Surface water and ground water were studied in the Green River basin. Stream channel dimensions and discharge were tabulated and analyzed, and regional relations were developed that characterize hydraulic features of streams throughout the Green River basin

(Lowham, 1982). A regional model also was developed for predicting stream temperatures at ungaged sites in the Green River basin using data from 43 measured sites in the basin (Lowham, 1978). DeLong (1977, 1978, 1979) estimated dissolved-solids concentrations and loads in the streams of the Green River basin using discharge records and a regression model derived from chemical analyses of monthly samples of dissolved solids. DeLong also demonstrated methods to predict the effects of future coal development on surface-water salinity. For example, DeLong (1977) applied a simple-harmonic time function in developing a regression model for predicting dissolved-solids concentrations and salinity loads in the Green River and its tributaries. DeLong (1977) estimated an average gain of 114,000 tons of dissolved solids per year during a 6-year period in a 70-mile reach of the Green River from Fontenelle Reservoir to the town of Green River, Wyoming, including the lower 30-mile reach of the Big Sandy River. The computer program for the model was prepared by Glover (1978). The model can be used for assessing the effects of proposed or past water-development projects and for modifying long-term water-quality monitoring networks. Turk and Parker (1982) analyzed water for major-constituent and trace-element concentrations from semiarid watersheds in the Green River basin and determined that the stream chemistry is characterized by saturation with respect to common carbonate minerals and that trace-element concentrations are similar between watersheds. A comprehensive, basin-wide summary and analysis of water quality of streams and springs in the Green River basin was done by DeLong (1985). Salinity, phosphorus, and trace-element data were evaluated for 28 water-quality sites and more than 500 miscellaneous-sampling sites on streams and springs.

Two studies of fluvial sediment were done in the Green River basin. Ringen (1984) used sediment data collected at selected sites to develop regression relations for determining daily, monthly, and annual suspended-sediment discharges at existing sites using records of daily stream discharge. Kircher (1982) made a detailed investigation of sediment transport and the source areas of sediment and runoff in the Big Sandy River basin. This basin drains about 10 percent of the Green River basin in Wyoming and is a major contributor of sediment to the Green River. The suspended-sediment and bedload samples collected at stream-discharge sites were used to estimate long-term sediment-transport rates. Computerized models by DeLong (1977) and Glover (1978) were adapted for Kircher's analysis.

Rankl and Barker (1977) published rainfall and runoff data for small basins in Wyoming, and Craig and Rankl (1978) provided methods for predicting flood volumes and for preparing synthetic flood hydrographs for ephemeral streams that drain less than 11 square miles. Mining companies in Wyoming are required to apply the methods in their mine plans. The water resources of the thrust belt area in western Wyoming was studied by Lines and Glass (1975). They determined that most of the water was used for irrigation of alfalfa, grass hay, and pasture. Water-resources reconnaissance studies also have been done at several sites in the region.

An areawide ground-water report for the southwestern Wyoming basins was prepared by Zimmerman and Collier (1985). The report contains data for about 1,600 ground-water sites including lithologic logs, analyses of major chemical constituents, trace elements, and selected radiochemicals, and measurements of temperature and specific conductance. These data are an extensive compilation from files of the U.S. Geological Survey and the Wyoming State Engineer as of 1977.

The hydrology of two basins that are typical of southwestern Wyoming was studied in detail. The hydrology of the drainage basin of Salt Wells Creek was studied by Lowham and others (1982); the biology of Salt Wells Creek and its tributaries was studied by Engelke (1978). A third study was in the drainage basin of Separation Creek (Larson and Zimmerman, 1981). The drainage basins of Salt Wells and Separation Creeks contain economic deposits of coal. The results of the studies of the two drainage basins include assessments of streamflow, channel morphology, sediment transport, salinity of surface water, aquatic biology, and availability and quality of ground water.

A resource and potential reclamation evaluation of the Hanna basin was prepared by the U.S. Bureau of Land Management (1975a) as part of the EMRIA program. The main purposes of this study were to: (1) Ensure the collection of adequate baseline data for choosing optimum reclamation and rehabilitation objectives; and (2) establish appropriate data and interpretations for preparation of lease stipulations.

Water-quality data for the Hanna and Carbon basins in Wyoming were collected and published in Freudenthal (1979). Major-chemical constituent, trace-element, and radiochemical data are included for selected surface- and ground-water sites. A statistical summary of the chemical quality of surface water in the Hanna coal field and Green River coal region in Wyoming was done by Peterson (1988). In addition to statistically summarizing the water-quality data, the report evaluates the adequacy of the water-quality data and identifies needs for future water-quality data-collection activities in the coal areas of Wyoming. The ground-water resources in the Hanna and Carbon basins were assessed for 1974-80 (Daddow, 1986a). Data for well-completion records, lithologic logs, and water levels are presented for 105 wells in the study area. The data are from stock wells, coal test holes, and mining company observation wells that were completed mostly in coal-bearing formations.

Several reports were published from the studies done in the Yampa River basin. The effects of coal development on water resources in the Yampa River basin were studied by Steele (1978, 1979), Steele and Hillier (1981), Steele and others (1976, 1979), and Udis and others (1977). These studies indicated that development of coal resources in the southern Rocky Mountains will have a variety of effects on available water resources. These effects include direct effects caused by coal extraction, processing, transport, and conversion techniques used or proposed for the region and indirect effects associated with regional economic growth. Wentz and Steele (1976, 1980) studied the chemical quality of surface water in the Yampa River basin. They determined there was no significant change in water temperature since 1951 in the Little Snake or the Yampa Rivers, the two major streams in the Yampa River basin in Colorado and Wyoming. Three of the 92 sites sampled showed water-quality degradation. The sources of this degradation were proposed to be from pyritic materials associated with coal at one site, discharge from blowdown water from a powerplant cooling tower at a second site, and runoff from a small watershed containing a gas field at the third site. Andrews (1978) studied sediment yields in the basin. He estimated that the lower Little Snake River subbasin contributes about 60 percent of the total Yampa River basin sediment yield even though the subbasin represents less than 35 percent of the area and supplies less than 3 percent of the streamflow. In contrast, the eastern one-third of the basin contributes only about 14 percent of the sediment yield but 76 percent of the streamflow. An estimated 10,000 to 30,000 tons per year of additional sediment will be contributed to the main stem of the Yampa River by the projected economic development, especially the surface mining of coal in the basin. Bauer and others (1979) and Ruddy and Britton (in press) studied traveltime and reaeration characteristics of the upstream reaches of the Yampa and Little Snake Rivers and tributaries of the Yampa and North Platte Rivers. Simulations of traveltime for other stream conditions not measured were done using a mathematical model. These simulations provide a convenient means of predicting the arrival time and concentration of soluble contaminants accidentally spilled in a stream. A comparison of measured reaeration coefficients to those computed from semiempirical and empirical equations also was completed for the study reaches. A program for the synoptic collection of selected trace-element data in streams of the southern Yampa River basin was developed, and samples were collected and analyzed and results reported for about 36 streams for water years 1976–82 (Maura, 1985). A study using Landsat images and aerial photography to determine land-use and geologic and hydrologic characteristics was completed by Heimes and others (1978).

A calibration procedure was developed for the U.S. Geological Survey's Precipitation-Runoff Modeling System for small watersheds in the Yampa River basin. The calibration process is for use in those watersheds in which snowmelt is the major contributor to the annual discharge (Norris and Parker, 1985). A water-quality model was developed to assess the cumulative effects of anticipated coal mining for a selected reach of the Yampa River and an area of concentrated coal-mine development—Trout Creek and its tributaries in Routt County, Colorado. The model uses an accounting process that sums upstream surface-water discharge and associated dissolved-solids concentration through the stream network to a downstream point. Output is mean monthly discharge, dissolved-solids concentration, and dissolved-solids load.

Spoil-pile water quantity and quality were monitored using lysimeters installed in a reclaimed spoil pile in Routt County, Colorado (Williams and Hammond, 1988). Spoil piles differ from undistured soils in the manner in which water percolates through the spoil or soil matrices and the time of peak water content. Results also indicate that undisturbed soils are nearly saturated at 4.5 to 5 feet, but spoil piles are not near saturation at measured depths as much as 6 feet. There were large differences between the measured potential spoil-pile recharge and the undisturbed soil recharge, but subsequent weathering of the spoil, spoil-pile setting, vegetation development, and other factors may decrease spoil-pile recharge in the future (Williams and Hammond, 1988).

Ground-water quality in Routt County, Colorado, was studied by Covay and Tobin (1981). The effects of mine drainage on streams in Colorado was studied by Wentz (1974a, 1974b), and he concluded that coal-mine drainage does not adversely affect water quality in Colorado, apparently because of the small sulfur content of Colorado's coal. A study about thermodynamic controls on quality of water from underground mines was published by Turk (1982). He determined that seepage from 13 of the 14 coal mines studied was saturated with respect to calcite. Some samples had a calcium-to-sodium activity ratio similar to that of seawater.

The Piceance basin is the smallest of the three basins in the region that have been studied intensively because of projected energy development. Hydrologic, geophysical, and geohydrologic data for the basin are in Weeks and Welder (1974) and Welder and Saulnier (1978). Weeks (1978) developed a digital model of the ground-water flow in the Piceance basin. The model is quasi-three-dimensional in that it simulates ground-water flow in a multiaquifer system by assuming horizontal flow in the aquifers and vertical flow through the confining layers separating the aquifers. The hydrogeochemistry and solute transport in the ground water in the basin was studied by Robson and Saulnier (1981). They determined that the proposed oil-shale mining in the basin could adversely affect the ground-water quality.

There also were studies in other basins in the region. Hood and Fields (1978) studied the water resources of the northern Uinta basin in Colorado and Utah. Price and Miller (1975) made a hydrologic reconnaissance of the southern Uinta basin in Utah and Colorado. In the southeastern Uinta basin, Naten and Fuller (1981) studied selected biological characteristics of the streams.

Alley and others (1978b) did a reconnaissance of water resources for hydraulic mining at the Grand Hogback coal field, Garfield and Rio Blanco Counties, Colorado. Brogden and Giles (1977) did a reconnaissance of ground-water resources in a part of the Yampa River basin between Craig and Steamboat Springs, Colorado, where they determined that well yields generally were less than 25 gallons per minute and dissolved-solids concentrations ranged from 82 to 4,230 milligrams per liter.

Surface-water quality was studied by Kuhn (1982), who prepared statistical summaries of water-quality data for two coal areas of Jackson County, Colorado. Regression equations that relate seven water-quality constituents to specific conductance were developed at eight sites in the study area. These equations can be used to estimate selected water-quality constituents by making an onsite measurement of specific conductance.

Britton (1983) assessed the relation of stream water-quality conditions to benthic invertebrate communities in tributaries of the Yampa and North Platte River basins. Generally, sampling provided quantitative and qualitative data for density and for relative abundance of various benthic invertebrate species. Most of the variation in benthic invertebrate densities and taxa among the stream sites was associated with sampling-date differences. There also were some close correlations of mean densities with measured water-quality constituents and properties.

HYDROLOGIC ISSUES RELATED TO COAL MINING

Although the regions have minimal acid mine drainage because of the buffering quality of the natural water, there are some undesirable side effects from coal mining on the quality of the surface and ground water in the regions. Some issues already have been identified. Lowham and others (1985) refer to land subsidence in Rock Springs, Wyoming, and erosion of channels because of inflow from mine dewatering; both were caused by underground coal mining during the 1900's. Driver and others (1984) report that dissolved-solids concentrations are larger in spoil-pile aquifers in northwestern Colorado than in natural aquifers.

Because coal mining in the Green River and Hams Fork regions occurs only in the arid and semiarid basins that have water that has naturally large alkalinity concentrations, acid mine drainage generally does not occur. However, other effects caused by surface mining are as follows: (1) Difficulty in growing vegetation on reclaimed land in coal area 52; (2) increased dissolved-solids concentrations in Trout Creek in Routt County, Colorado, from mine spoils; and (3) water-level declines as much as 59 feet in wells near mines being dewatered in the Hanna coal field in Carbon County, Wyoming.

The magnitude of the effects on the hydrologic environment from coal mining vary from site to site and depend on such factors as mining and reclamation methods, slope of land, type of soil and rock, quantity of precipitation, quality of ground and surface water, and rate of water movement.

Of regional (and international) concern is the cumulative, salt-loading and salt-concentrating effect of coal mining on the Colorado River. This is a major issue that the U.S. Department of the Interior has been attempting to solve for a number of years (U.S. Department of the Interior, 1981). Increasing salinity in the Colorado River associated with increasing coal production in the basin no doubt will increase the cost of the U.S. Department of the Interior's Colorado River Salinity Control program.

NORTHERN GREAT PLAINS AND ROCKY MOUNTAIN PROVINCES— UINTA AND SOUTHWESTERN UTAH REGIONS

By Don Price

The Uinta and Southwestern Utah regions, an area of more than 50,000 square miles in eastern and southwestern Utah and western Colorado (fig. 44), include coal areas 55–58 (table 1). No reports were prepared for coal area 55 so this area is not included in the regional discussion. More than 90 percent of the area of the regions is in the Southern Rocky Mountains and Colorado Plateaus physiographic provinces (pl. 1); drainage from that part of the area is almost entirely to the Colorado River. The remaining (westernmost) part of the

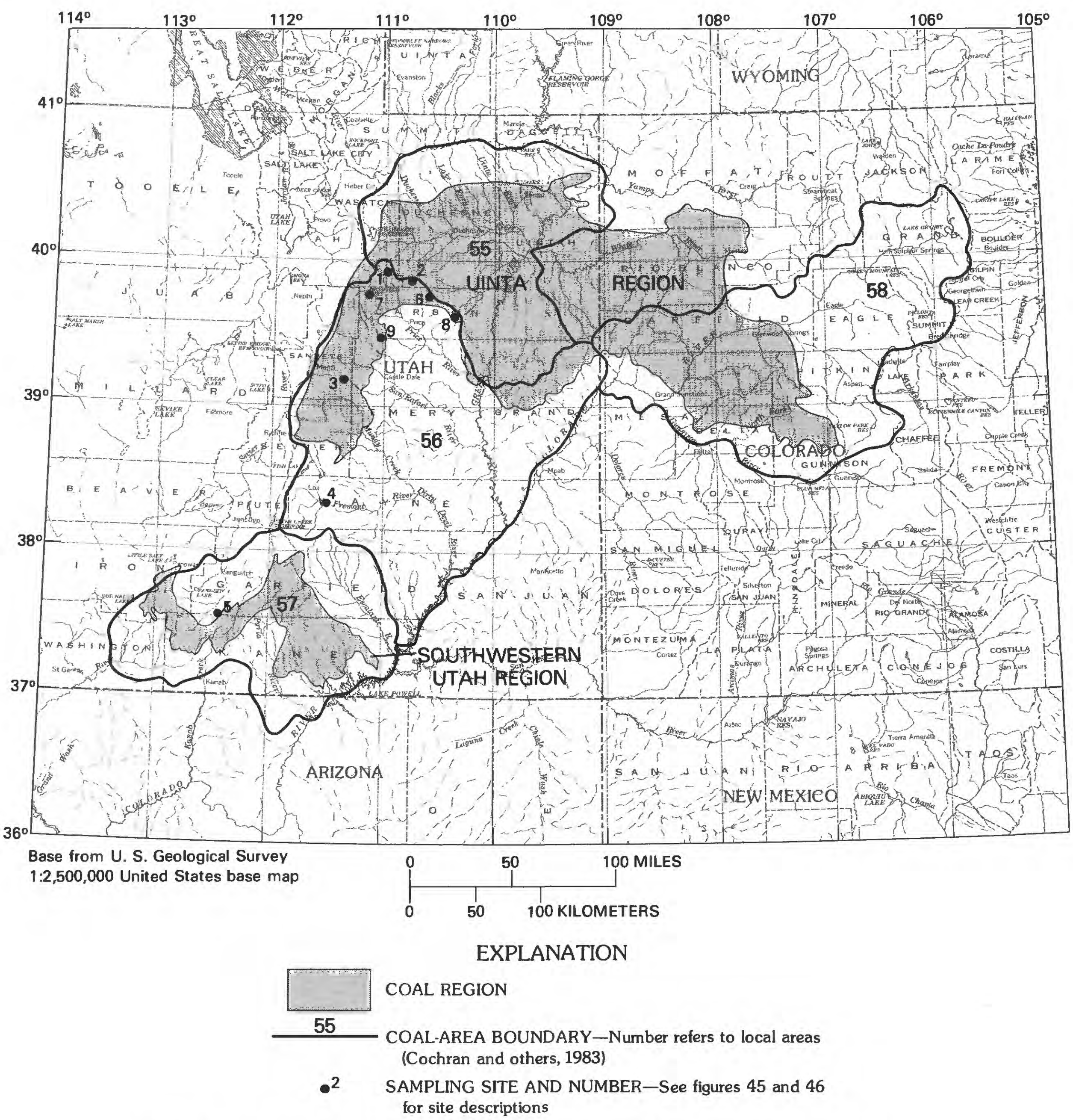


Figure 44.—The Uinta and Southwestern Utah regions, coal areas 55–58, and sampling sites.

area of the regions is in the Basin and Range physiographic province; drainage from that part of the area is to topographically closed basins in western Utah. The Uinta and Southwestern Utah regions are composed mostly of broad plateaus of varying height that are dissected by the deep, narrow canyons of the Colorado River and its larger tributaries.

Climatic conditions in the Uinta and Southwestern Utah regions range from arid and semiarid in the lower plateaus to subhumid and humid in the higher plateaus and mountains. Average annual precipitation ranges from less than 6 inches at the lower altitudes to more than 40 inches on the highest plateaus and mountains. Most of the annual precipitation occurs primarily as snow from October to April; this snow commonly accumulates to depths of more than 100 inches on the highest plateaus and mountains. These high-altitude snowpacks are the principal source of runoff from within these regions. May-to-September precipitation occurs primarily as widely scattered, local torrential rainstorms or cloudbursts. Although those storms contribute relatively little to total annual runoff from within the regions, they produce considerable local runoff, which commonly occurs as damaging flash floods. Annual evaporation rates are large; annual evaporation rates substantially exceed annual precipitation rates.

Rocks that range in age from Precambrian to Holocene are exposed in the Uinta and Southwestern Utah regions. The most widely exposed geologic formations are the Mesozoic and Cenozoic formations of continental sedimentary origin. Those formations (consisting mostly of sandstone, mudstone, and shale) are exposed throughout more than 90 percent of the area of the regions. Igneous rocks (mostly extrusive) of Tertiary and Quaternary age cap parts of the highest plateaus. Stream-valley alluvium, glacial outwash, dune sand, and other unconsolidated deposits of Quaternary age locally mantle the consolidated Tertiary and older rocks throughout the regions.

More than 80 percent of the land in the regions is owned by the Federal Government and is administered by the U.S. Bureau of Land Management, the U.S. Forest Service, and the National Park Service. This Federal land, as well as the small quantity of State-owned land in the regions, primarily is used for livestock grazing, recreation, and minerals development. The privately owned land, mostly along and near the perennial streams, primarily is used for irrigated agriculture. Most of the regions' population is concentrated in and near these irrigated agricultural areas. The largest cities and their approximate 1980 populations (U.S. Bureau of Census, 1981) are Grand Junction, Colorado (28,000), in coal area 58; Cedar City, Utah (11,000), in coal area 57; and Price, Utah (9,000), in coal area 56. Many of the other communities (about 65) that are scattered throughout the regions had 1980 populations of less than 2,000.

Irrigation is the principal consumptive use of water in the regions. Generally, more than 98 percent of the water used for irrigation is diverted from streams in the regions, but wells and springs are the principal local sources of supplemental irrigation water in some areas. Wells and springs also are the principal sources of water for most public and rural-domestic water systems throughout the regions.

COAL RESOURCES

Nearly all mineable coal in the Uinta and Southwestern Utah regions occurs in geologic formations of Cretaceous age. The principal coal-bearing formations in the central Utah coal fields (coal area 56) are the Blackhawk Formation and the Ferron Sandstone Member of the Mancos Shale; those in the southern Utah coal fields (coal area 57) are the Dakota Sandstone, the Straight Cliffs Sandstone, and the Tropic Shale; those in the west-central Colorado coal fields (coal area 58) are the Iles, Williams Fork, Mesaverde, and Mount Garfield Formations. In those areas, coal generally crops out near the bottoms of the deep canyons that dissect the higher plateaus. Thickness of the individual coal beds ranges from less than 5 feet to as much as 20 feet; thickness of the overburden varies from zero where the coal crops out to more than 2,000 feet where it extends beneath the higher plateaus.

Most of the coal is high quality bituminous (locally anthracite and subbituminous in coal area 58) (fig. 4) and has good heating values and relatively small percentages of ash and sulfur. According to data compiled by Doelling (1972) and Doelling and Graham (1972), caloric values of the coal generally range from about 8,000 to 14,000 British thermal units per pound; the coal also generally contains less than 10 percent ash and less than 1 percent sulfur.

Reserves of recoverable coal from major coal fields in the regions are estimated to exceed 50 billion tons. Probably more than 90 percent of the total is recoverable only by underground mining, and less than 10 percent is recoverable by surface mining. Most of the coal is federally owned. As of May 1983, there were 270 Federal coal leases (totaling 364,279 acres) in the regions. Forty-two of those leases were producing coal during 1983 (U.S. Bureau of Land Management, 1983b, p. 2).

Coal production in the regions began during the mid 1800's; the annual tonnage produced has fluctuated considerably primarily because of changing markets, fluctuating energy needs, and changing production costs. As of 1983, total annual production in the regions was estimated to be about 12 million tons (U.S. Bureau of Land Management, 1983b, fig. 2–1); this production was mostly from underground mines. Most of the production was from coal area 56, and principal markets for the coal were in the Midwest, California, and Nevada. Total annual coal production in the regions has been projected to increase to about 33 million tons by 1995; however, as part of the U.S. Department of the Interior's maximum leasing alternative of the Uinta-Southwestern Utah Round II coal-leasing proposal, the total annual production could be as much as 55 million tons by 1995 (U.S. Bureau of Land Management, 1983b, fig. 2–1).

HYDROLOGY

The U.S. Geological Survey and U.S. Bureau of Land Management coal-hydrology program was started in the Uinta and Southwestern Utah regions about 1974, primarily because of increasing environmental concerns related to the growing interest in further development of the regions' large coal reserves. Of particular concern in the regions were potential adverse effects of uncontrolled coal-resource development on the Colorado River system. Hydrologic data acquired during the program were needed by the regulatory agencies and coal operators to assess the local hydrologic conditions and mitigate the potential hydrologic effects.

SURFACE-WATER NETWORK

The coal-hydrology program in Utah and Colorado has substantially increased the surface-water data base in the Uinta and Southwestern Utah regions. Before the program was initiated, surface-water data routinely were being collected at fewer than 250 widely scattered sites in the regions. As part of the program, more than 50 additional, strategically located, surface-water-data sites were established in and downstream from the principal coal fields. By 1983, data had been or were being collected at 416 stream-discharge sites as shown in the following table:

Coal area number	Number of sites		
	Discharge only	Discharge and water quality	Total
56	96	31	127
57	63	12	75
58	161	53	214

Continuous stream-discharge records had been or still were being collected at virtually all the sites. Water-quality data had been or still were being collected continuously at several of the sites and at least quarterly at most of the other sites. Fluvial-sediment data had been or still were being collected periodically at most of the stream-discharge and water-quality sites.

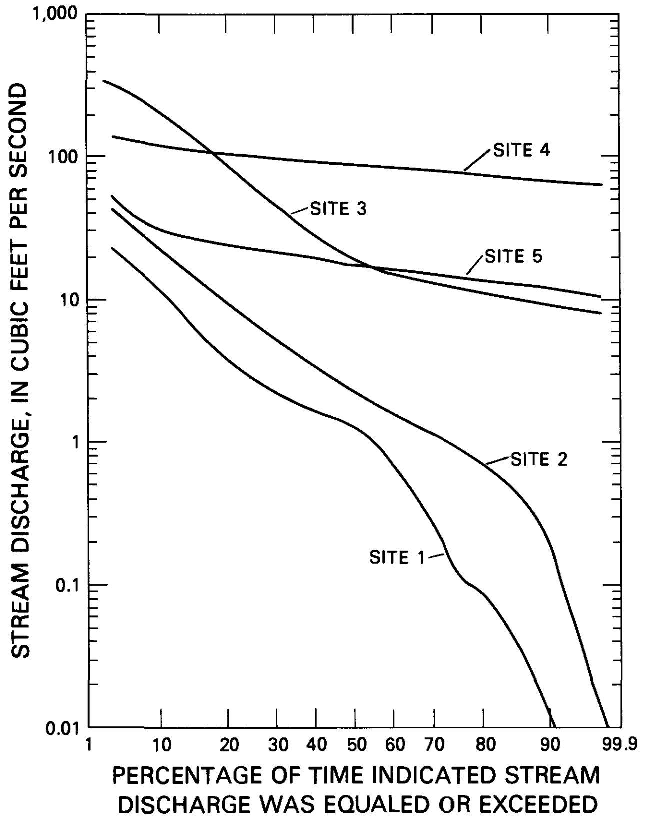
In addition to the above mentioned sites, baseline data also were collected at several hundred miscellaneous surface-water sites in coal areas 56, 57, and 58. Types of surface-water data collected included stream discharge, fluvial sediment, and chemical and biological quality of surface water. The surface-water sites are too numerous to be shown on the maps in this report; however, most of those sites are located on maps in the coal-area hydrology reports (table 1).

SURFACE-WATER CHARACTERISTICS

According to Price and Arnow (1974, pl. 1c) average annual runoff in the Uinta and Southwestern Utah regions ranges from less than 1 inch (53 acre-feet per square mile) in the lower altitudes to more than 10 inches (533 acre-feet per square mile) in the higher altitudes. Peak seasonal runoff generally occurs during May and June, primarily because of melting of the high-altitude, winter snowpacks. Flooding commonly occurs along some of the larger perennial streams during the May–June runoff period; however, the May–September cloudbursts can generate floods almost anywhere in the region. Such storms have produced floodflows of more than 5,000 cubic feet per second from drainage areas of less than 10 square miles (Price, 1984). Consequently, the bottoms of virtually all the deep, narrow canyons characteristic of this region may be regarded as flood-prone areas.

Discharges of the larger streams in the regions are regulated by reservoirs of varying size, partly for flood control. Discharges of many of the smaller perennial streams, however, are not regulated. Duration curves of the discharge of five representative, virtually unregulated streams in the regions are shown in figure 45. The curves for sites 1 and 2 probably are most typical of streams that originate on the lower plateaus of coal areas 56, 57, and 58. The curves for sites 3, 4, and 5 probably are most typical of streams that originate on the highest and wettest plateaus of the three coal areas.

In the regions, relations have been developed from which surface-water characteristics can be estimated at ungaged sites. Relations for estimating peak flows in natural-flow perennial streams in the Colorado part of the regions are presented by McCain and Jarrett (1976). Equations to estimate the peak flow and the depth of



EXPLANATION

SITE NUMBER IN FIGURE 44	SITE NAME AND DRAINAGE AREA
1	Beaver Creek near Soldier Summit, Utah (26.1 square miles)
2	Willow Creek near Castle Gate, Utah (62.8 square miles)
3	Ferron Creek (upper station) near Ferron, Utah (138 square miles)
4	Fremont River near Bicknell, Utah (751 square miles)
5	East Fork Virgin River near Glendale, Utah (69.2 square miles)

FIGURE 45.—Typical flow-duration curves for selected streams in the Uinta and Southwestern Utah regions. Data are from Lines and others (1984) and Price and others (1987).

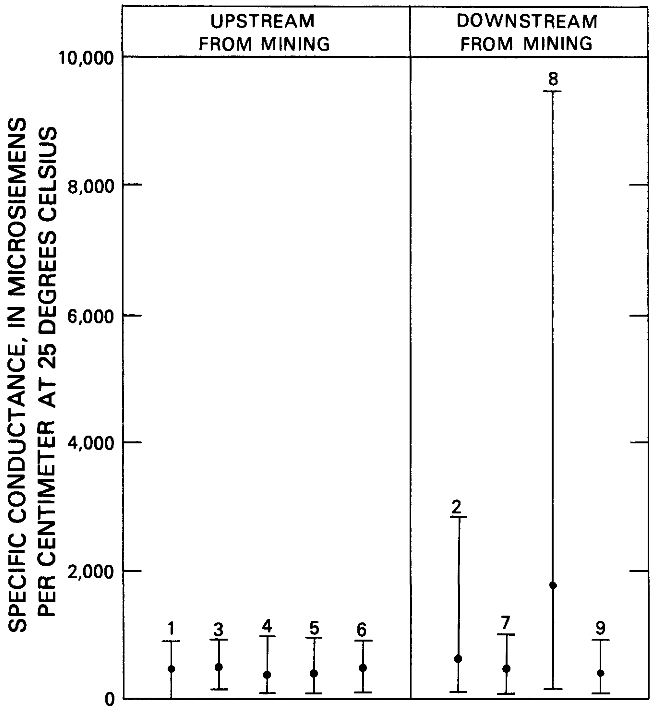
that flow for floods having recurrence intervals of 10, 50, 100, and 500 years also are presented by McCain and Jarrett (1976). Additional equations are presented by Livingston (1970) to estimate average annual, average monthly, peak, and low flows in the Colorado part of the regions (Chaney and others, 1987).

Average flow estimates for selected streams in coal area 56 that drain less than 500 square miles and have 5 years or more of record are reported in Lines and others (1984). Low-flow characteristics for selected surface-water sites in coal area 56 that have 10 years or more of record also are reported in Lines and others (1984). Updated regression relations for estimating mean annual discharge, mean monthly discharge, flow-duration series, peak discharge, and minimum and maximum 7-day discharges for natural flow streams in western Colorado are reported in Kircher and others (1985). The 7-day, 10-year low flows for coal area 56 range from 0 to 0.57 cubic foot per second per square mile. Streams in the higher altitudes have better sustained low flow than those in lower areas. Equations to estimate peak-flow values for specific recurrence intervals for ungaged sites in coal area 56 have been developed and are reported in Lines and others (1984). These regression equations were developed for streams in zone A that derive flow primarily from snowmelt and streams in zone B that derive flow primarily from thunderstorms. Similar information and regression equations for estimating surface-water characteristics in coal area 57 also are available (Price and others, 1987).

SURFACE-WATER QUALITY

Dissolved-solids concentrations of surface water in the regions generally range from less than 300 milligrams per liter in the high-altitude headwater areas during high- and low-runoff periods to more than 3,000 milligrams per liter in the lower reaches of some streams during low-runoff periods. Principal sources of the larger dissolved-solids concentrations in the lower stream reaches are: (1) Natural inflow of ground water from the salt-bearing Mancos and Tropic Shales of Cretaceous age; and (2) irrigation-return flows from soils developed on those formations. In the high-altitude headwater areas, calcium and bicarbonate generally are the dominant ions in the streamflow; in the lower stream reaches, sodium and sulfate typically become dominant ions in the streamflow. All toxic trace elements in the streamflow for which data are available generally occur in concentrations that are smaller than the maximum levels established by the U.S. Environmental Protection Agency (1986a, 1986c) for drinking water. Concentrations of arsenic, however, locally exceed the maximum level (50 micrograms per liter) in coal area 57.

Specific conductance is an indicator of the dissolved-solids concentration in the streamflow. Larger values of specific conductance in a stream generally result from larger dissolved-solids concentrations in that stream. Maximum, median, and minimum specific conductance in several streams downstream from coal mining and several streams upstream from coal mining are shown in figure 46. With the exception of the maximum specific-conductance value recorded at site 8, there seems to be no definite effect of coal mining on specific conductance of streamflow at the sites in and downstream from mined areas. The reason for the maximum value recorded at site 8 was not investigated, and it may not have been related to coal mining.



EXPLANATION

1 SITE NUMBER

MAXIMUM

MEDIAN

MINIMUM

SITE NUMBER IN FIGURE 44	SITE NAME AND DRAINAGE AREA
1	Beaver Creek near Soldier Summit, Utah (26.1 square miles)
2	Willow Creek near Castle Gate, Utah (62.8 square miles)
3	Ferron Creek (upper station) near Ferron, Utah (138 square miles)
4	Fremont River near Bicknell, Utah (751 square miles)
5	East Fork Virgin River near Glendale, Utah (69.2 square miles)
6	Dugout Creek near Sunnyside, Utah (5.8 square miles)
7	Mud Creek below Winter Quarters Canyon, at Scofield, Utah (29.1 square miles)
8	Grassy Trail Creek at Sunnyside, Utah (40.1 square miles)
9	Huntington Creek near Huntington, Utah (190 square miles)

FIGURE 46.—Maximum, median, and minimum specific conductance at selected surface-water-quality sites, water years 1979–84, in the Uinta and Southwestern Utah regions. Data are from Lines and others (1984).

Annual sediment yields exceed 3 acre-feet per square mile in many parts of the regions. Consequently, fluvial-sediment loads of many streams in the regions are relatively large, especially during periods of cloudbursts and rapid snowmelt runoff. It is not uncommon that suspended-sediment concentrations exceed 100,000 milligrams per liter in some streams during cloudburst flooding.

GROUND-WATER NETWORK

The coal-hydrology program in Utah and Colorado has increased the ground-water data base in the Uinta and Southwestern Utah regions. Before the program was begun, collection of ground-water data was limited almost entirely to the easternmost and westernmost parts of the regions, at some distance from the major coal fields. Additional ground-water-data sites subsequently were established in most of the coal fields. These ground-water-data sites include springs, observation wells, mine workings, and mine-drainage facilities. Baseline data also were collected at several hundred miscellaneous ground-water sites in coal areas 56, 57, and 58. Types of ground-water data collected included well and spring discharges, chemical quality of the water, depths of ground-water levels, and, locally, aquifer characteristics. The ground-water sites are too numerous to be shown on the maps in this report; however, most of these sites are located on maps in the coal-area hydrology reports (Lines and others, 1984; Chaney and others, 1987; Price and others, 1987).

GROUND-WATER OCCURRENCE

Water occurs at some depth in virtually all the geologic formations that underlie the Uinta and Southwestern Utah regions. Most of the formations, however, yield the water very slowly to wells and springs. For example, Price and Arnow (1974, pl. 1f) indicated that potential yields of individual wells throughout much of the regions are less than 10 gallons per minute. Geologic units in the regions that are known to yield water readily (100 to more than 1,000 gallons per minute) to wells are: (1) The widely scattered saturated sections of stream-valley alluvium and other unconsolidated deposits; and (2) the thick saturated sections of sandstone, where fractured, in areas of local folding and faulting. Stream-valley alluvium and unconsolidated basin-fill deposits contain locally important aquifers throughout the regions. Also, the Dakota Sandstone of Cretaceous age contains important aquifers in coal area 58; the Navajo Sandstone of Triassic(?) and Jurassic age contain important aquifers in coal areas 56 and 57. Limestones and extrusive igneous rocks that cap parts of some higher and wetter plateaus generally yield water readily to springs, but those rocks, except where fractured, yield water slowly to wells.

According to Price and Arnow (1974, pl. 1d), principal areas of ground-water recharge in the regions are on the higher and wetter mountains and plateaus, and the principal areas of natural ground-water discharge are along the lower reaches of larger, more deeply incised streams where the stream channels intersect the regional water table. Recharge primarily occurs as infiltration of snowmelt and seepage from upper stream reaches; discharge primarily occurs as seepage to the lower stream reaches and as evapotranspiration by phreatophytes along those lower stream reaches. However, some springs discharge from perched ground-water bodies well above canyon bottoms.

GROUND-WATER QUALITY

Dissolved-solids concentrations in ground water throughout the regions generally range from less than 500 to more than 5,000 milligrams per liter. The freshest ground water generally occurs in the rocks that cap the higher and wetter mountains and plateaus; the most saline ground water generally occurs in the Mancos and Tropic Shales of Cretaceous age that crop out near the bases of those mountains and plateaus. Water in most of the coal-bearing formations generally contains less than 1,000 milligrams per liter of dissolved solids; however, some of those formations locally contain water that has more than 4,000 milligrams per liter of dissolved solids. Available data indicate that concentrations of toxic trace elements in water from the coal-bearing formations generally are smaller than the maximum levels established by the U.S. Environmental Protection Agency (1986a, 1986c) for drinking water. Strontium is the trace element that most commonly occurs in large concentrations in water from the coal-bearing rocks. Locally, near Lake Powell in coal area 57, relatively large concentrations of arsenic occurred in water from the Navajo Sandstone. A possible source of the arsenic is the Carmel Formation of Jurassic age (Blanchard, 1984) that directly overlies the Navajo Sandstone. The Carmel Formation, however, is stratigraphically well below the coal-bearing formations and probably has little, if any, effect on the chemical quality of water in those formations.

COAL-HYDROLOGY STUDIES

The ultimate products of the U.S. Geological Survey and U.S. Bureau of Land Management coal-hydrology program in the Uinta and Southwestern Utah regions are the technical hydrologic-investigations reports. These reports are listed by author(s) in table 4 and are shown in the "References Cited" section. The principal purposes of these technical hydrologic-investigations reports are to provide hydrologic information needed by: (1) The U.S. Department of the Interior to formulate its Federal coal-leasing programs in the regions; (2) the U.S. Bureau of Land Management to lease the coal and to protect the water resources and existing water rights; (3) the coal operators in their efforts to prevent adverse hydrologic effects due to their mining operations; and (4) the U.S. Geological Survey in its mission to inventory and monitor the water resources of the Nation.

TABLE 4.—*Technical hydrologic-investigations reports compiled as part of the U.S. Geological Survey and U.S. Bureau of Land Management coal-hydrology program in the Uinta and Southwestern Utah regions*

[See "References Cited" section for report titles and publication outlet. Principal subject: BD, basic hydrologic data; GH, general hydrology; SW, surface-water hydrology; GW, ground-water hydrology; R, Reservoir. Coal-area number is coal-resource area in which study was made]

Author(s)	Publication date	Principal subject	Coal-area number
Alley and others	1978a	BD	58
Brooks	1983	GH	58
Chaney and others[1]	1987	GH	58
Christensen and Plantz	1985	BD	56, 57
Christensen and others	1986	SW	56, 57
Danielson and others	1981	GH	56
Danielson and Sylla	1982	GH	56
Kircher and others	1985	SW	58
Lines and Morrissey	1983	GW	56
Lines and others[1]	1984	GH	56
Lines	1985	GW	56
Morrissey and others	1980	GW	56
Norris	1987	SW	58
Norris and Maura	1985	BD	58
Plantz	1983	BD	57
Plantz	1985	GH	57
Price and others[1]	1987	GH	57
Richter and others	1984	SW	58
Sandberg	1979	SW	57
Sumsion	1979	BD	56
Thomas and Lindskov	1983	SW	56, 57
Waddell and others	1978	BD	56
Waddell and others	1981	GH	56
Waddell and others	1982	BD	56
Waddell and others	1985	R	56
Waddell and others	1986	GH	56

[1]Summary report compiled using U.S. Geological Survey funding only. These coal-area hydrology reports summarize substantial information given in the other reports cited in this table and include maps.

Several of the technical hydrologic-investigations reports for the Uinta and Southwestern Utah regions contain methods that have considerable transfer value for possible use in other regions. One report includes the manual by Thomas and Lindskov (1983) that describes methods for determining peak discharges and flood boundaries in the regions. A manual for estimating surface-water characteristics at ungaged sites in the regions is in the report by Christensen and others (1986). These manuals would be extremely useful in the design of roads, bridges, and other facilities associated with development of the regions' coal and other resources.

Brooks (1983) discussed the potential for mine-related subsidence and the eventual effect locally on surface water in coal area 58. Danielson and others (1981) and Danielson and Sylla (1982) described the hydrologic system in the area of several important tracts in coal area 56 and the potential effects on local ground-water flow of mining those tracts. Lines (1985) described the ground-water system, control of fracture porosity on ground-water flow, and potential effects of mining on the natural ground-water flow system of an area in coal area 56. The report by Morrissey and others (1980) is a documentation of the model developed for use in the study by Lines and Morrissey (1983) that identified several important aquifers and assessed the local effects of underground mining on ground-water flow in coal area 56. Plantz (1985) shows locations and general chemical quality of springs in relation to major coal fields in coal area 57. One of those coal fields was the focus of an Energy Minerals Rehabilitation Inventory and Analysis Program (EMRIA) study. The study by Sandberg (1979) provided useful information about the local surface-water characteristics and quality needed to assess potential effects on surface water by proposed surface mining. A regional reconnaissance hydrologic study of the two largest coal fields in coal area 56 (Waddell and others, 1978) provided useful information about regional aquifers in the coal area, general ground-water and surface-water characteristics, and mine-drainage activities. Waddell and others (1982) also provided similar types of hydrologic information for one of the most actively mined drainage basins in coal area 56, the Price River basin. Effects from coal mining, including possible eutrophication of an important multipurpose reservoir (Scofield Reservoir in the Price River basin), are described by Waddell and others (1985).

A study by Alley and others (1978a) related surface-water quantity to coal-resources development. This report provided a preliminary evaluation of the quantity and quality of water resources available for hydraulic coal mining in the Crested Butte coal field in Gunnison County, Colorado, in coal area 58. The results of a study undertaken in the drainage basin of the North Fork Gunnison River to determine the regional water-resources system in the area of the Somerset coal field in Gunnison County, Colorado, in coal area 58 is in a report by Norris (1987). A summary of water-quality data collected in streams in the North Fork Gunnison River in Colorado is reported by Norris and Maura (1985).

A new study relating many streamflow characteristics to basin characteristics of western Colorado (including coal area 58) has been completed by Richter and others (1984) and Kircher and others (1985). Compared to most of the previous studies, this study uses 13 additional years of gaged-flow measurements, a recently revised areal-precipitation map, and improved statistical techniques for model selection. Separate regression relations were developed for each of four regions in western Colorado.

The summary reports of the hydrology of coal area 56 (Lines and others, 1984), coal area 57 (Price and others, 1987), and coal area 58 (Chaney and others, 1987) were compiled largely from information given in the other reports cited in table 4. Those three summary reports are in a generally standard format. They contain sections that provide the following information about the respective coal areas: (1) Surface-water hydrology, including surface-water characteristics and quality; (2) ground-water hydrology, including springflow, potential well yields, and ground-water quality; (3) coal reserves and coal production; and (4) possible effects of coal mining on water resources, including mine-caused subsidence and its associated rock fracturing and eventual effect on ground-water flow. Those three summary reports also include bibliographic listings of all U.S. Geological Survey hydrologic-study reports for the respective coal areas and guidelines for obtaining site-specific data from the U.S. Geological Survey's computer files.

HYDROLOGIC ISSUES RELATED TO COAL MINING

Lines and others (1984), Price and others (1987), and Chaney and others (1987) discuss some of the more significant existing and potential hydrologic issues related to coal mining in the three major coal-resource areas of the Uinta and Southwestern Utah regions. The local issues primarily are the effects of: (1) Underground mine workings and related land subsidences on ground-water flow systems; (2) mine dewatering on springflow, streamflow, and water quality in the receiving streams; and (3) mine-related land disturbance on peak stream discharges and fluvial-sediment loads. Of regional (and international) concern is the cumulative, salt-loading and salt-concentrating effect of coal mining on the Colorado River. This is a major issue that the U.S. Department of the Interior has been attempting to solve for a number of years (U.S. Department of the Interior, 1981). Increasing salinity in the Colorado River associated with increasing coal production in the basin no doubt will increase the cost of the U.S. Department of the Interior's Colorado River Salinity Control program.

Acid mine drainage is not expected to become a serious issue in the regions because the coal typically contains relatively small quantities of sulfur. The most serious water-quality issues (without adequate control) can be expected with large-scale mining in the Emery coal field (part of the central Utah coal fields of coal area

56) and the Alton coal field (part of the southern Utah coal fields of coal area 57). Surface mining is feasible in both coal fields, and uncontrolled land disturbance by the surface mining no doubt would increase substantially the fluvial-sediment loads in the affected streams. Also, the coal-bearing formations in both coal fields contain very saline water, and release of that water to streams could substantially degrade the chemical quality of the streamflow and eventually compound the Colorado River salinity issue.

NORTHERN GREAT PLAINS AND ROCKY MOUNTAIN PROVINCES—DENVER AND RATON MESA REGIONS

By LINDA J. BRITTON and NEVILLE G. GAGGIANI

The Denver and Raton Mesa regions (fig. 47), an area of about 22,000 square miles in parts of Colorado and New Mexico, include coal areas 59 and 61 (table 1). Coal area 59 extends into southeastern Wyoming. The Denver region (coal area 59) is located within the South Platte River basin, while the Raton Mesa region (coal area 61) is within the Arkansas River basin. The coal areas within the regions are not connected geographically, and thus, much of the description and hydrology will be discussed individually for the two regions, rather than as a combined unit.

The major topographic features in the Denver region are the hogback ridges, mesas, and forested highlands of the Great Plains physiographic province (pl. 1), and the mountain ranges and peaks in the Southern Rocky Mountains physiographic province. The most prominent feature in the Denver region is the Continental Divide in the Rocky Mountains, which forms the boundary between the Mississippi River drainage on the east, of which the South Platte River is a part, and the Colorado River drainage on the west.

Approximately two-thirds of the Denver region is located in the Great Plains physiographic province (subdivided into the High Plains and the Colorado Piedmont sections). The Front Range is almost entirely in the Southern Rocky Mountains physiographic province. The Raton Mesa region is located primarily on the western edge of the Great Plains physiographic province at the base of the Rocky Mountains; part of the region is in the Southern Rocky Mountains physiographic province.

The South Platte River, the major stream in the Denver region, and most of its tributaries originate in granitic mountains and flow into and through the sedimentary rocks of the Great Plains. The Raton Mesa region includes the headwaters of the Huerfano, Apishapa, Purgatoire, and Canadian Rivers and their tributaries, which are all tributary to the Arkansas River; these streams originate in granitic mountains and flow into and through the sedimentary and volcanic rocks of the Great Plains.

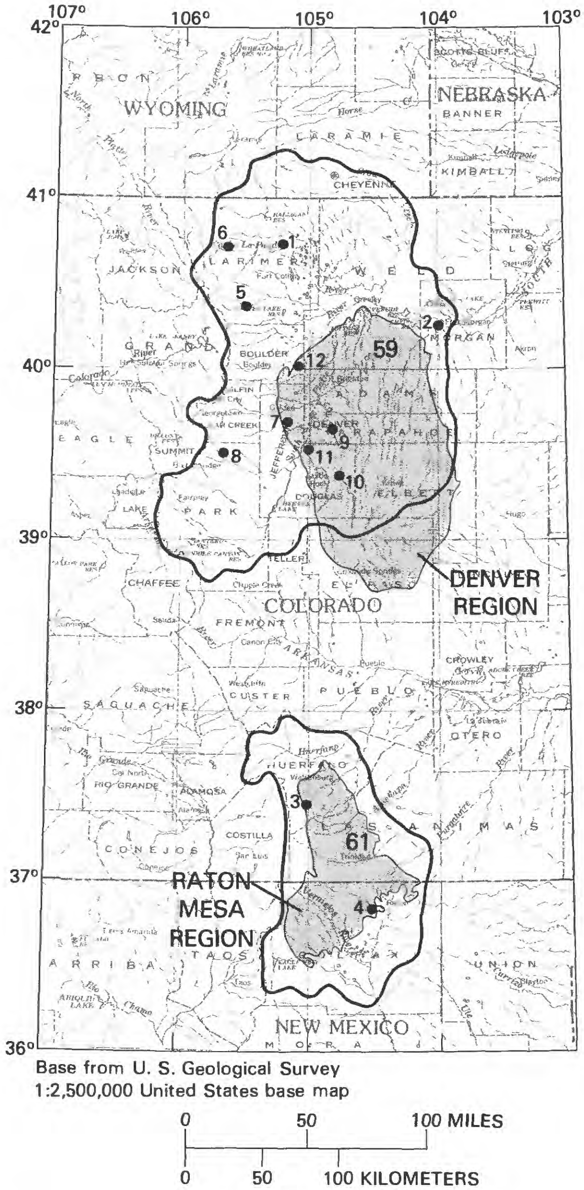
Precipitation in the Denver and Raton Mesa regions generally increases from east to west and may exceed 39 inches annually in the mountains; most of this precipitation occurs during the winter and produces deep snowpacks. The least quantity of precipitation (as little as 10 inches annually) occurs in the plains and valleys of the major drainages. Rainfall is greatest during late spring and summer, but snowmelt runoff during this same period produces most of the streamflow. Another source of streamflow is return flows from ground water. Ground water has become a major source of streamflow for some streams in the plains because leaking irrigation canals have recharged nearby alluvial deposits.

Most of the bedrock in the Denver region is sedimentary rock of Cretaceous age or younger. Bedrock in the plains generally was formed from material that was eroded from the ancestral and present Rocky Mountains. The remainder of the bedrock, located in the mountains, consists of crystalline rock of Precambrian age and a few small areas of more recent volcanic extrusive and intrusive rock.

In the Raton Mesa region, the oldest rocks in the region are Precambrian granite, pegmatite, gneiss, schist, and quartzite (Johnson, 1961). These crystalline rocks form the core of the Sangre de Cristo Range and the Wet Mountains (fig. 47). Paleozoic and Mesozoic formations flank the mountains and extend beneath the rest of the region (Griggs and Northrop, 1956; Oriel and Mudge, 1956; Shaw, 1956). The principal structure in the Raton Mesa region is an asymmetrical trough centered north of the Spanish Peaks (Gabelman, 1956; Amuedo and Ivey, 1974). The rocks of the trough dip gently on the eastern limb and steeply on the western limb; the trough is modified locally by anticlines, synclines, and faults. About 1,600 feet of sedimentary rocks overlie Precambrian basement in the center of the trough.

Most of the population of the Denver and Raton Mesa regions is in the Denver region and is concentrated in the Front Range Urban Corridor that extends north and south of the city of Denver, Colorado. The less populated eastern and western parts of the Denver region are quite different from each other; agriculture is the major industry to the east and recreation the major industry to the west. The Raton Mesa region is sparsely populated and is predominantly forest and rangeland that is used for grazing livestock. Dryland and irrigated crops are grown in the eastern parts of the Denver and Raton Mesa regions. Irrigated acreages are in the flood plains and at locations where major streams flow out of the foothills onto the plains. Uses involving smaller areas of land are industrial development, transportation, and water-resources development. Most of the land and associated minerals are privately owned.

In the eastern part of the Denver region, natural gas and petroleum reserves and small quantities of uranium and coal are being developed; in the western part, mineral deposits presently (1985) are mined at more



EXPLANATION

COAL REGION

59 COAL-AREA BOUNDARY—Number refers to local areas (Cochran and others, 1983)

•2 SAMPLING SITE AND NUMBER—See figures 48 and 49 for site descriptions

FIGURE 47.—The Denver and Raton Mesa regions, coal areas 59 and 61, and sampling sites.

moderate production levels than the extensive production during the 1800's and early 1900's. There is only one active coal mine in the Denver region. In contrast, there are four licensed surface coal mines and three underground coal mines in the Raton Mesa region.

The largest percentage of water use in each region is for irrigation, about 74 percent in part of the Raton Mesa region and 88 percent in part of the Denver region. Ground water provides only a small percentage of total water used in the regions.

COAL RESOURCES

The Denver and Laramie Formations (the sedimentary bedrock units of Tertiary and Cretaceous age that crop out in the Denver region) contain the coal and lignite deposits in the Denver region. The coal deposits are suitable for underground and surface mining, and lignite deposits are suitable for surface mining. Coal and lignite beds in the Laramie Formation generally are less than 5 feet thick; lignite beds in the Denver Formation range from 10 to 30 feet thick. Coal and lignite generally occur in the lower 50 to 275 feet of the Laramie Formation in the southern part of the region and in the lower 200 to 300 feet in the northern part of the region; these deposits are not as predictable in the western part of the region. Approximately 7,500 square miles of the Denver region are underlain by the Laramie Formation; however, coal and lignite are very thin or nonexistent in 15 to 20 percent of the region. The lignite zone in the Denver Formation occurs in the top 300 to 500 feet of the formation. The Denver Formation occurs only in the southern part of the region and encompasses a much smaller area than the Laramie Formation. The lignite beds in the Denver Formation normally are about 10 to 15 feet thick and decrease in thickness to the west.

Sedimentary bedrock units in the Raton Mesa region include the Vermejo and Raton Formations (the Upper Cretaceous and Paleocene Raton Formation overlies the Upper Cretaceous Vermejo Formation), which contain the coal deposits in the region. These formations contain commercial deposits of bituminous coal (fig. 4) that underlie approximately 1,700 square miles of the region. These deposits are at or near the surface on the edges of the Park Plateau and in the major drainage areas but are more than 2,900 feet deep near the Spanish Peaks. Coal beds in the Vermejo Formation generally are thicker, more persistent, more regular in thickness, and less widely spaced than those in the Raton Formation. Individual beds in the Vermejo Formation obtain a maximum thickness of more than 15 feet, whereas those in the Raton Formation are no more than 10 feet thick.

More than 130 million tons of coal and lignite were mined from the Denver region from 1883 to 1979, mostly in the Boulder-Weld coal field, near Boulder, Colorado (fig. 47). More than 99 percent of the coal came from underground mines. During 1982, a little more than 100,000 tons of subbituminous coal was produced from one mine in a coal seam, 5 to 8 feet thick, in the Laramie

Formation. This is the only mine now (1985) operating in the Denver region.

In the Raton Mesa region, the Walsenburg coal field near Walsenburg, Colorado, produces highly volatile B and C bituminous coal of noncoking quality; the Trinidad coal field near Trinidad, Colorado, and the Raton coal field near Raton, New Mexico, generally produce highly volatile A and B bituminous coal of coking quality. Production in the Raton Mesa region through 1975 was 325.5 million tons, of which 247.5 million tons were produced in Colorado and 78 million tons in New Mexico.

In all the coal formations of these two regions, impurities such as sulfur and pyrite are sparse. Recoverable reserves in the Boulder-Weld coal field (at 65 percent recovery factor) total more than 268 million tons; recoverable reserves in other parts of the Denver region total more than 142 million tons. In the Raton Mesa region, recoverable reserves have been estimated at about 3.3 billion tons in New Mexico and about 8 billion tons in the Walsenburg and Trinidad coal fields in Colorado.

HYDROLOGY

In the Denver and Raton Mesa regions, active coal mining has decreased to a great extent, compared to previous decades. Presently (1985), there is one active coal mine in the Denver region and seven in the Raton Mesa region. Thus, intensive coal-hydrology investigations were not as intensive in these regions as in other regions in Colorado and adjoining States. Principally, the effort in these regions was to summarize the existing data base for preparation of coal-area hydrology reports (Abbott and others, 1983; Gaggiani and others, 1987). The objectives were to summarize existing knowledge of the water resources, to identify potential issues associated with coal mining in these regions, and to document further data-collection needs to increase the capability to predict hydrologic effects from coal mining. The information needed to address these objectives was obtained through a combination of data-collection networks and interpretive studies.

SURFACE-WATER NETWORK

In the Denver region, stream-discharge information is available from 213 sites and currently is being recorded at 91 sites, 9 of which also are water-quality sites. Since the first site was installed during 1881, the network has expanded considerably to meet the demands for irrigation and for municipal and industrial uses. In more recent years, numerous partial-record stream-discharge sites have been established primarily for flood information. Continuous or seasonal records of discharge are obtained from 58 of the active sites, partial records are obtained from 23 sites, and records of transmountain diversions from the Arkansas and Colorado River basins to the South Platte River are obtained from the remaining 10 sites. There also are numerous miscellaneous sites where stream-discharge measurements generally are made during times of drought or flood. Surface-water-quality information is available from approximately 400 sites, of which results from 92 sites are included in Gaggiani and others (1987). Presently (1985), there are 18 permanent-record, water-quality sites, but a total of 51 sites have been used for permanent recording. At 80 percent of these sites, major anions and cations are analyzed on a monthly basis, and at 40 percent of these sites, trace elements are analyzed on a monthly basis.

In the Raton Mesa region, stream-discharge information is available from 52 sites, 27 of which are active sites. Forty-four of the 52 sites recorded continuous discharges, and 8 sites were crest-stage gages that only recorded high stages of runoff associated with rainstorms or snowmelt. In the region, water-quality data are available from 22 sites, 11 of which are active sites. Much of the available water-quality data includes major anions and cations, but several sites also have data available for nutrients, trace elements, and suspended sediment. In addition, monthly measurements of specific conductance and water temperature are made at many of the continuous-record, stream-discharge sites in both regions.

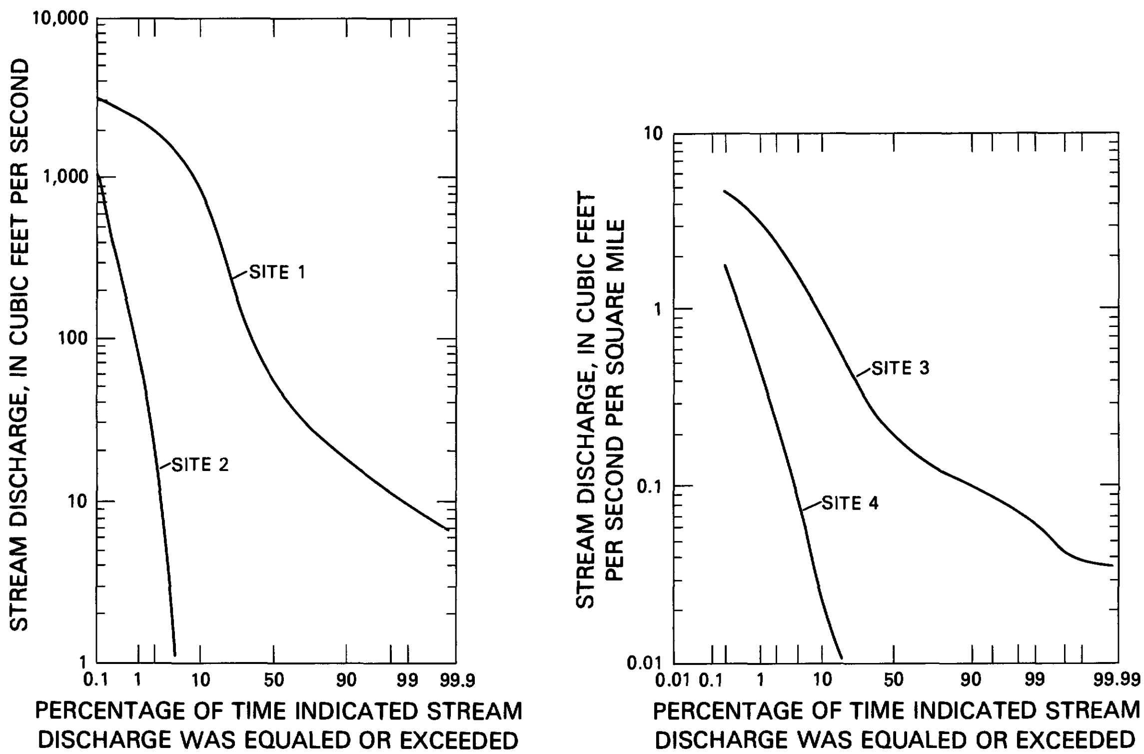
Although sediment data have been collected at 28 surface-water sites in the Denver and Raton Mesa regions, sufficient data do not exist for correlation with land use. Mining has occurred at several locations in the Denver and Raton Mesa regions, but sediment data are available only from sites where there was not much mining activity upstream.

SURFACE-WATER CHARACTERISTICS

Predictive equations are available to estimate mean annual discharge for ungaged sites for areas in Colorado (Livingston, 1970), Wyoming (Lowham, 1976), and New Mexico (Borland, 1970). Variations of these equations have been developed for ephemeral and perennial streams in the Denver and Raton Mesa regions (Abbott and others, 1983; Gaggiani and others, 1987). Because these relations were developed from a very limited quantity of data, the estimates of the mean annual discharge need to be considered approximate. In applying the relations for mountain areas in the Denver region, especially for a drainage basin that crosses the Colorado-Wyoming border, a weighting procedure needs to be used.

The time distribution of and diversity of flow characteristics for selected streams in the regions are shown in the flow-duration curves (fig. 48). The steep curves that illustrate the discharges at sites 2 and 4 indicate variable discharge that results from direct surface runoff or upstream diversions (Abbott and others, 1983; Gaggiani and others, 1987). Streams at these two sites are dry more than 50 percent of the time. The curves that have a flatter slope (sites 1 and 3), especially at the lower end, indicate discharge from delayed surface runoff and ground-water storage. At sites 1 and 3, discharge is maintained because the sites are located in the headwater areas where precipitation is greatest, and they are less affected by instream diversions (Abbott and others, 1983; Gaggiani and others, 1987); streams at these two sites never go dry.

Estimates of the magnitude and frequency of flood peaks can be made for streams in the Denver and Raton Mesa regions. McCain and Jarrett (1976) present relations for estimating 10-, 50-, 100-, and 500-year floods at sites on natural streams in Colorado. Relations are defined for four regions in Colorado, two of which—plains and mountains—are in the Denver region. A separate Colorado study (Livingston and Minges, 1987) presents relations for estimating 2-, 5-, 10-, 25-, 50-, and 100-year floods for small rural basins that do not receive substantial snowmelt flood discharges. These relations are helpful when estimating flood characteristics on small ungaged basins in the eastern plains region of the Denver region. In Wyoming, studies that define the magnitude and frequency of floods have been done by Lowham (1976) for drainage basins larger than 10 square miles, and by Craig and Rankl (1978) for drainage basins smaller than 10 square miles (generally ephemeral streams in plains and valleys). When applying these relations to the Denver region, especially to a drainage basin that crosses the Colorado-Wyoming border, a weighting procedure needs to be used.



EXPLANATION

SITE NUMBER IN FIGURE 47	SITE NAME AND DRAINAGE AREA
1	Cache La Poudre River at mouth of canyon near Fort Collins, Colorado (1,056 square miles)
2	Bijou Creek near Wiggins, Colorado (1,319 squere miles)
3	Cucharas River at Boyd Rench near La Veta, Colorado (56.0 square miles)
4	Canadian River near Hebron, New Mexico (229 square miles)

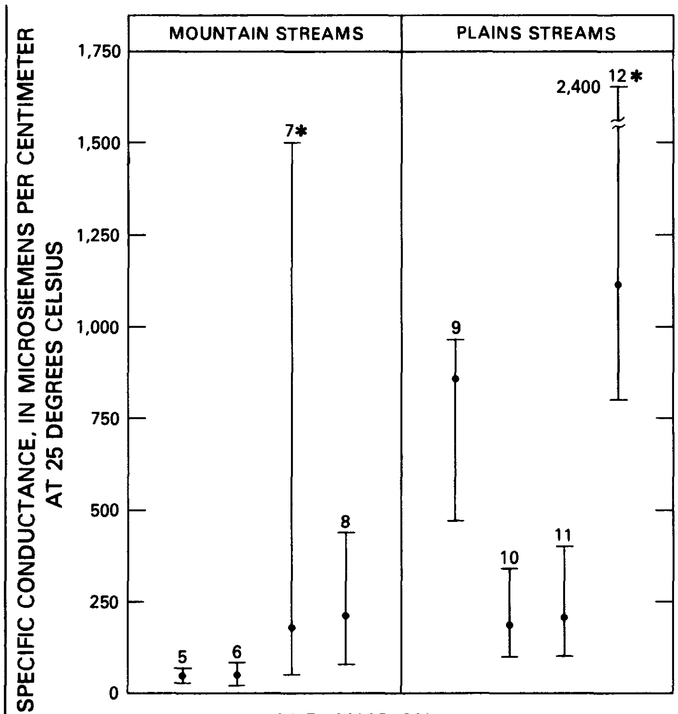
FIGURE 48.—Typical flow-duration curves for selected streams in the Denver and Raton Mesa regions.

For estimating flood frequency in the Raton Mesa region, Abbott and others (1983) determined that an average of the results of the equations developed for Colorado (McCain and Jarrett, 1976; Livingston, 1981), and an average developed for New Mexico (Thomas and Gold, 1982) give reasonable peak-discharge values for the region. For areas that are 15 square miles and less, an average of the Livingston (1981) and Thomas and Gold (1982) equation results needs to be used. For areas larger than 15 square miles, the average of the values computed by the McCain and Jarrett (1976) equation and by the Thomas and Gold (1982) equation needs to be used. The standard error of estimate probably is between the values given for each set of equations for a specified recurrence interval. Topographic maps of flood-prone locations in the Denver and Raton Mesa regions are available from the U.S. Geological Survey and other sources.

SURFACE-WATER QUALITY

In the Denver region, surface-water quality is best in the mountains where dissolved-solids concentrations, indicated by specific-conductance values, generally is small (fig. 49). Concentrations increase in the plains as streams flow through urbanized and irrigated sedimentary basins. In the Denver and Raton Mesa regions, downstream increases in dissolved-solids concentration result from variations in precipitation, land and water use, and geology. Much of the increase is related to man's use of the water for agriculture and, to a lesser extent, municipal purposes. Relations between specific conductance and discharge have been developed for several sites in the Denver and Raton Mesa regions. The position and slope of the line are substantially affected by local bedrock geology. In general, tributaries in reaches draining the coal-bearing Raton Formation in the Raton Mesa region contribute water that has larger dissolved-solids concentration than other streams in the region. In addition, as streams flow eastward across the Raton Formation, the relative concentrations of sodium and, to a lesser extent, sulfate increase.

Some mountainous stream sites indicate effects of drainage from inactive metal-mining areas, and some sites have larger trace-element concentrations and smaller pH values. Water in the coal-bearing Laramie and Denver Formations is affected locally by coal deposits, which cause dissolved-solids concentrations to be larger. No water-quality information has been recorded at sites along a stream that drains the single, active surface coal mine in the Denver region. Streams draining abandoned underground coal-mining areas generally have pH values greater than the overall mean for the region, possibly because of the use of crushed limestone during past mining activities. Although data are limited, the pH of water from sources related to coal mining in the Raton Mesa region is neutral to alkaline, but it is within the range of pH values measured at surface-water sites. Also in the Raton Mesa region, large concentrations of total-recoverable metals are associated with large concentrations of suspended sediment. Iron and aluminum are the dominant metals that occur with suspended sediment. The drainage basins where data are available are underlain by the Raton and Poison Canyon Formations.



EXPLANATION

5 SITE NUMBER

MAXIMUM

MEAN

MINIMUM

* DOWNSTREAM FROM ABANDONED COAL MINES (Data from Gaggiani and others, 1987)

SITE NUMBER IN FIGURE 47	SITE NAME AND DRAINAGE AREA
5	Big Thompson River naar Estes Park, Colorado (155 square miles)
6	Cache La Poudre River near Rustic, Colorado (199 square miles)
7	Bear Creek at Morrison, Colorado (164 square miles)
8	Tarryall Creak near Jefferson, Colorado (183 square miles)
9	Cherry Creek above Cherry Creek Lake, Colorado (360 square miles)
10	Cherry Creek near Franktown, Colorado (169 square miles)
11	Plum Creek near Louviers, Colorado (302 square miles)
12	Coal Creek at U. S. Highway 287 at Lafayette, Colorado (unknown)

FIGURE 49.—Maximum, mean, and minimum specific conductance at selected surface-water-quality sites in the Denver and Raton Mesa regions.

Generally, sediment yields are small in the foothills and increase in an easterly direction because of increased thunderstorm activity, more easily eroded soils, and sparse vegetation. Relations between suspended-sediment discharge and stream discharge were developed at eight sites in the Denver region to depict spatial variability (Gaggiani and others, 1987). Suspended-sediment discharge increases rapidly with increasing stream discharge. The percentage of suspended sediment that is finer than sand (less than about 0.002 inch) decreases with distance downstream from the source waters, indicating that more sand is transported by the river as it flows through the eastern part of the Denver region.

Suspended-sediment concentrations increase substantially during periods of peak discharge; concentrations of 50,000 to 200,000 milligrams per liter occurred during peak discharges in areas underlain by the Raton or Poison Canyon Formations in the Raton Mesa region. Computed annual suspended-sediment yields ranged from 300 to 2,480 tons per square mile per year. Relations between stream discharge and suspended-sediment discharge can be used to estimate sediment loads for stream discharges of magnitudes within the range of the relations (Abbott and others, 1983). These relations are a result of the increasing annual production of sediment with decreasing size of drainage area and the more efficient transport of this sediment to the stream channel by overland flow in the smaller drainage basins.

GROUND-WATER NETWORK

The ground-water network in the Denver and Raton Mesa regions includes information about water levels for more than 7,000 wells in the Denver region and about 500 wells in the Raton Mesa region. The U.S. Geological Survey currently (1985) measures and records water levels on a periodic basis at many of these sites. In addition, many wells, springs, and mines were inventoried and sampled in Colorado (mostly north of the Purgatoire River) and in New Mexico (mostly east and south of the Park Plateau) in the Raton Mesa region. CF&I Steel Corporation monitors water levels in mine observation wells and the volume and quality of mine discharge at its Allen and Maxwell Mines (Water, Waste, and Land, Ltd., 1980). Kaiser Steel Corporation monitors water levels and quality in 16 observation wells and the volume and quality of mine discharge at its York Canyon Mine, west of Raton, New Mexico, in the Raton Mesa region (Dames and Moore Engineering Consultants, 1978).

GROUND-WATER OCCURRENCE

In the Denver region, ground water is available in alluvial aquifers of stream valleys, in sedimentary bedrock aquifers of the plains and South Park, and in fracture systems of the metamorphic and granitic rocks of the Front Range. The Laramie–Fox Hills and Arapahoe (in the Cretaceous Arapahoe Formation) aquifers stratigraphically are the lowest of the four major bedrock aquifers in the region. Ground water in these aquifers south of the South Platte River generally flows from the main recharge areas on the west and south to the main discharge areas on the north and east. North of the South Platte River, flow generally is to the southeast. The Denver and Dawson aquifers stratigraphically are the uppermost of the bedrock aquifers in the region. They are a major source of ground water in and southeast of the Denver metropolitan area. Generally, the Dawson aquifer (in the Tertiary Dawson Arkose), encompassing a smaller area than the Denver aquifer, has water of better quality and larger well yields (Gaggiani and others, 1987). The direction of ground-water flow in these aquifers exhibits some local variations but generally is to the northeast.

Well yields in the Denver region range from less than 15 gallons per minute in the mountains to more than 1,000 gallons per minute in the stream valleys of the plains. Well yields exceed 2,000 gallons per minute in the alluvial valley-fill aquifer, an area dominated by irrigated agriculture in the northeastern part of the region.

In the Raton Mesa region, virtually all formations store and transmit water. Talus and alluvium yield small (0.5 to 20 gallons per minute) to large (100 to 500 gallons per minute) quantities of water to wells and springs but are limited in areal extent. Bedrock formations generally yield small (0.5 to 20 gallons per minute) to moderate (20 to 100 gallons per minute) quantities of ground water to wells and springs and are widespread. Within the bedrock aquifers, sandstone and conglomerate layers and basalt flows transmit most of the water, and shale and coal layers retard flow (Abbott and others, 1983).

Depth to ground water in the regions depends mostly on the topographic position of the well. In stream valleys, ground water is less than 100 feet deep because the valleys intercept ground water flowing through the bedrock. On stream divides, permeable formations are drained by seeps and springs that discharge into the valleys, and wells may have to be drilled as deep as 500 feet to obtain water.

GROUND-WATER QUALITY

Ground water in the south-central part of the Laramie Formation and Fox Hills Sandstone in the Denver region generally is of good quality, but in many other places in the aquifer, methane and hydrogen sulfide gases make the water unsuitable for many uses

(Robson and others, 1981). Kirkham and Ladwig (1980) report that ground-water quality in the Laramie and Fox Hills Formations is quite variable in the Denver region north of the South Platte River and is contaminated by coal and other mineral deposits in some localized parts of the region. In the Arapahoe and Denver Formations, mineral concentrations in the ground water range from small to large; the least mineralized water is near the centers of the aquifers where there is recharge from the Dawson aquifer. Lignite deposits in the Denver aquifer contribute to the mineralization of ground water near the edge of the aquifer through chemical action of dissolved oxygen that results from recharge from surface sources.

In the Raton Mesa region, ground-water quality deteriorates as water flows from sandstone, conglomerate, and basalt in plateaus and mesas to shale in stream valleys and plains. From west to east across the region, concentrations of dissolved solids increase, and the ground water changes from bicarbonate to sulfate and chloride in composition (Abbott and others, 1983). In addition, the pH of ground water in wells and springs ranges from 6.6 to 9.3. Variations in pH cannot be correlated with ratios of sulfate to bicarbonate or chloride to bicarbonate. In addition, local concentrations of several minor dissolved constituents, such as iron, manganese, and selenium, exceed water-quality standards (U.S. Environmental Protection Agency, 1986a, 1986b, 1986c).

COAL-HYDROLOGY STUDIES

Economic interest in coal resources and potential hydrologic issues associated with coal mining have stimulated several hydrologic investigations in the Denver and Raton Mesa regions. In the Denver region, a study was begun during 1982 in cooperation with the U.S. Bureau of Land Management to evaluate the hydrologic system associated with areas that may be mined for coal in the Denver Formation in the east-central Colorado plains (Driver and Williams, 1986). The objectives were: (1) To provide interpretive information about the hydraulic and chemical characteristics of ground water in the Denver Formation in and adjacent to areas of possible coal (lignite) mining; (2) to identify the water quality in aquifers affected by lignite mining; and (3) to evaluate possible changes in water quality due to lignite mining. This study included compilation and interpretation of historical hydrologic data as well as data from 15 water-quality samples collected from selected wells in the study area.

The study (Driver and Williams, 1986) concluded that the effects of surface mining on the hydrology of the area may be minimal, depending on location of the mine, depth of the lignite, and number of sandstone and siltstone lenses that occur above the lignite. To accurately assess these effects, extensive data about premining conditions need to be collected at each mine site. At present (1985), little information is available about the hydraulic properties of the sandstone and siltstone units above the coal or about the quantity and quality of water in the lignite aquifers.

In the Raton Mesa region, the U.S. Geological Survey and the U.S. Bureau of Land Management did a ground-water hydrology study in the part of the basin that contains most of the public land likely to be mined. The reports by Geldon and Abbott (1985) and Geldon (in press) include information compiled and collected during this investigation. From 1978 to 1982, the U.S. Geological Survey inventoried 231 wells, 38 springs, and 6 mines and collected ground-water samples from 71 sites. In addition, some stream-discharge sites were installed, aquifer tests were completed, and historical and current data were compiled from climate stations and ground- and surface-water sites. Most of the data were collected from observation networks operated by Federal and State agencies and private mining companies.

Most of the results of the study in the Raton Mesa region indicated that the principal aquifers produce either small, nonsustainable yields from wells or small, nonsustainable yields from beds that may not have been penetrated by wells. In addition, plumes of sulfate-enriched water extend from coal mines into the bedrock and alluvium. The investigation indicated that water quality in streams is affected by inflowing tributaries, mine discharge and tailings, ground-water seepage, diversions, and changes in stage. It also was determined that ground-water supplies probably are insufficient for expanded settlement and coal mining.

HYDROLOGIC ISSUES RELATED TO COAL MINING

Current coal-mining activities have a relatively small effect on surface-water flow in the Denver and Raton Mesa regions. Little surface water is diverted to the few currently (1985) operating mines, and because all perennial stream water is allocated, diversion for additional mines is unlikely unless water rights are purchased. Discharge from mines into surface drainages presently is small but probably will increase if mining activity expands. However, the abandoned Frederick Mine near Trinidad in the Raton Mesa region discharges 30 to 40 gallons per minute directly into the Purgatoire River. The eastern portal of the Allen Mine discharges from two to several hundred gallons per minute each day into the Purgatoire River. Most of the water pumped from operating mines discharges into sump ponds that drain into the Purgatoire and Vermejo Rivers.

Because the semiarid mine areas have minimal runoff and the major streams have large buffer and dilution capacities, the effects of coal mining on surface-water quality in the Denver and Raton Mesa regions are minimal. Because of these factors, acid mine drainage is largely unknown in western coal-mine areas. Presently (1985), there are no known water-quality issues associated with coal mining in the Denver region. In the Raton Mesa region, water discharging from mines is more mineralized than in nearby bedrock (Abbott and others, 1983). For example, water discharging from the Maxwell and Jacks Mines contains larger dissolved-solids concentrations than ground water from nearby wells completed in the Raton Formation. In the Raton Mesa region, the pH of water from mines and tailings is 7.0 to 9.2, generally in the same range as water in bedrock, although the sulfate concentration is notably greater in water associated with coal-mining activities. However, Wentz (1974a) indicated that sulfate seems to be an inaccurate indicator of coal-mine drainage in areas such as the plains and plateau regions of Colorado where large background concentrations of sulfate occur. In addition, discharges from the Maxwell and Allen Mines in the Raton Mesa region consistently add small quantities (less than 10 percent) of calcium, bicarbonate, and sulfate and variable quantities of sodium (0 to 25 percent) to water in the Purgatoire River.

Overall, some increases in dissolved-solids and total-recoverable, trace-element concentrations are likely because of increased mining in the Denver and Raton Mesa regions. The source of soluble mineral salts and trace elements is the unweathered rock material exposed by mining. However, because the pH of the water is neutral to basic and because bicarbonate is abundant, trace elements largely remain in the suspended phase, sorbed to sediment. Increases in total-recoverable, trace-element concentrations usually are associated with increases in suspended sediment.

Ephemeral streams in the Denver and Raton Mesa regions often have larger concentrations of suspended sediment than do perennial streams. These areas are especially susceptible to increased erosion during intense thunderstorms and from loss of vegetative cover and formation of unconsolidated spoil material from mining activities. However, because of the overall lack of water in ephemeral streams, the potential for increased sediment yield usually can be controlled by careful management and use of settling ponds. Open pit mines near perennial streams also may increase sediment yields to streams. In the Denver and Raton Mesa regions, data are inadequate to quantify this effect. Onsite measurements in the Purgatoire River in the Raton Mesa region during 1981 indicated no increased turbidity of the river near mines and tailing dumps. Tailing dumps are erodible; however, such erosion can be minimized by locating the dumps away from the flood plains of the streams. Sump ponds, such as those at currently operating mines, also prevent sediment in mine discharge from reaching nearby streams.

The effects of coal mining on ground water in the Denver and Raton Mesa regions probably will be more severe and have a longer duration than the effects on surface water. However, in some parts of the regions, ground-water and surface-water systems may be connected. The effects of mining on the aquifers in the Denver region have not been studied extensively. The area northeast of Boulder in the Denver region is the location of the abandoned Boulder-Weld coal field, where underground mines were dug into the coal deposits of the Laramie Formation. Larger dissolved-solids concentrations in ground water there (72,000 milligrams per liter) probably are the result of soluble minerals transported into the aquifer from surface sources or from the upper parts of the Laramie Formation (Gaggiani and others, 1987). In addition, studies in other areas indicate that increases in dissolved-solids concentrations may occur in water in mine-spoil aquifers (Van Voast, 1974; Van Voast and others, 1977; McWhorter and others, 1979). For example, in the Raton Mesa region, the data base indicates that human activities, such as coal mining and agricultural activities, have added dissolved solids to the ground water in stream valleys and plains (Abbott and others, 1983). The pH of ground water in the coal-bearing Raton and Vermejo Formations in the Raton Mesa region ranges from 7.5 to 8.0 but exceeds 8.0 in the vicinity of some active or abandoned coal mines. However, it has not been proven that coal mining increases the pH of ground water in the Raton Mesa region because the pH of mine discharge ranges from 7.3 to 9.2 in the region and, thus, is in the same range as that of ground water from undisturbed bedrock. In addition, large concentrations of iron and manganese occur principally in water from the Raton and Vermejo Formations, probably from the dissolution of coal, pyrite, and siderite (Howard, 1982).

Also in the Raton Mesa region, prolonged pumping of substantial quantities of water tends to lower ground-water levels (Abbott and others, 1983). For example, the ground-water level during 1980 was 240 feet lower at the Maxwell Mine than in an observation well 3,000 feet away. Because the water table tends to parallel the topographic surface, the water level at the Maxwell Mine probably was at least 240 feet higher prior to the start of mining. The drawdown of the water table in this mine is expected by the mine owners to extend outward about 3 miles when the mine reaches full production (Water, Waste, and Land, Ltd., 1980). Shallow wells near other operating mines in the Raton Mesa region may go dry as the water table declines. After mining ceases, recovery of the water table will take many years and probably will not reach premining levels because the sloping mine shafts will be permanent conduits for the ground water.

NORTHERN GREAT PLAINS AND ROCKY MOUNTAIN PROVINCES— SAN JUAN RIVER REGION

By F. Eileen Roybal

The San Juan River region, an area of about 30,000 square miles in New Mexico and southwestern Colorado (fig. 50), includes coal areas 60 and 62 (table 1). The majority of the region is within the Canyon Lands and Navajo and Datil sections of the Colorado Plateaus physiographic province (Fenneman, 1931). There are four major drainages in the San Juan River region: the San Juan, Dolores, and Little Colorado Rivers, and the Rio Grande (fig. 50). Most of the perennial streams are located in the Dolores River basin and the San Juan River basin in Colorado. Streams draining areas south of the San Juan River are ephemeral and flow in response to summer thunderstorms. Surface runoff in the perennial streams is mostly from the melting of winter snows in the mountain ranges.

The region generally is semiarid to arid; average annual precipitation ranges from less than 8 inches in the desert valleys to about 50 inches in the mountains. In

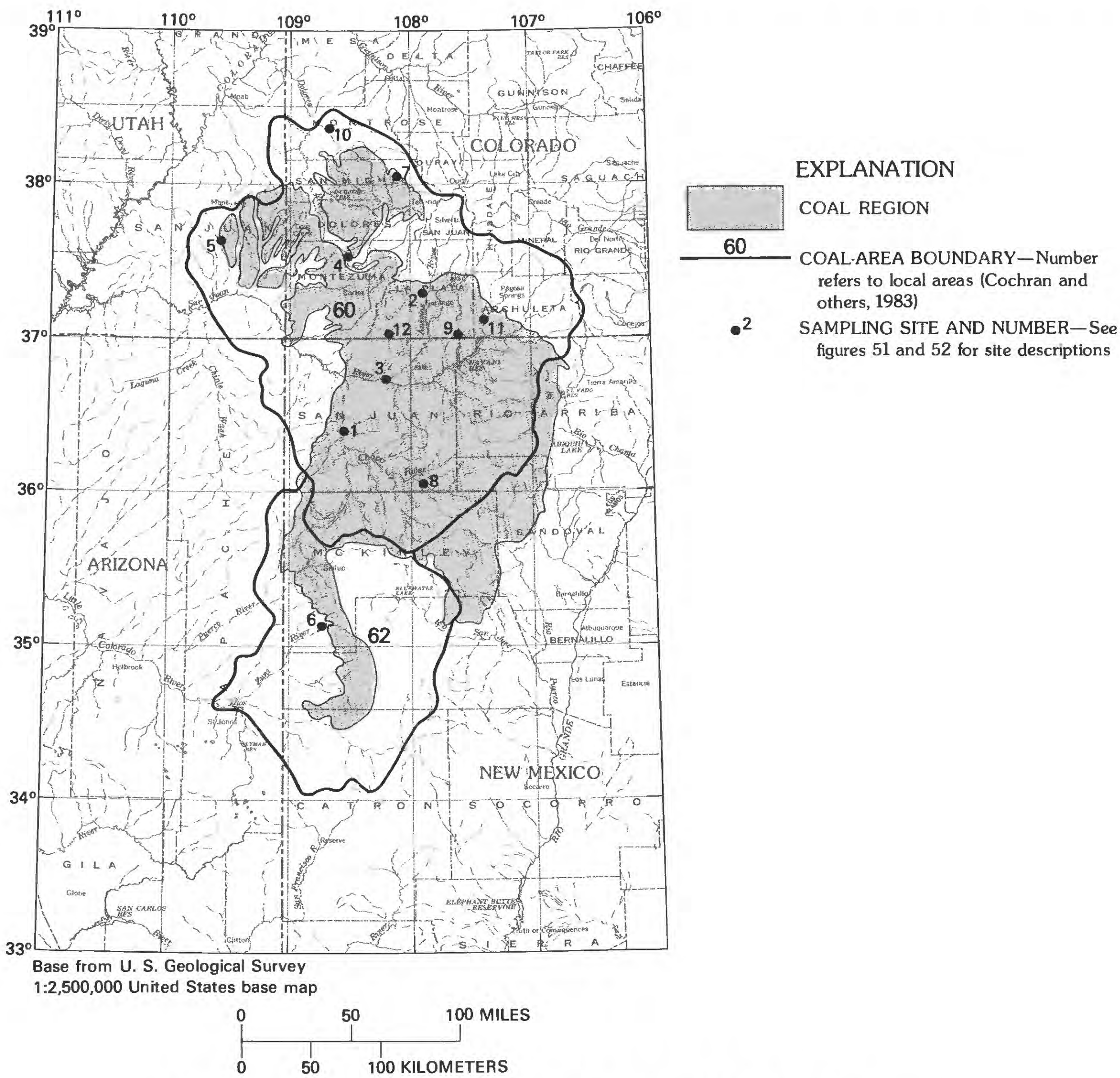


FIGURE 50.—The San Juan River region, coal areas 60 and 62, and sampling sites.

the New Mexico part of the region, annual precipitation ranges from 8 to 12 inches. Most of the precipitation occurs during late summer as intense thunderstorms. Areas of high altitude, as in most of the Colorado part of the region, have greater precipitation and lower temperatures in comparison with the areas of lower altitude in most of the New Mexico part.

Exposed rocks range in age from Precambrian to Quaternary, but rocks of Cretaceous age form the most extensive outcrops in the San Juan River region. The rocks that crop out mostly consist of igneous and metamorphic rocks of Precambrian age, sedimentary rocks of Paleozoic and Mesozoic age, and volcanic rocks of Tertiary and Quaternary age. Most recent Quaternary rocks consist of fluvial and eolian sediments and landslide, rock glacier, and talus deposits. The older rocks generally are exposed in the regionally uplifted areas where the younger rocks have been removed by erosion. The younger rocks generally are exposed in the relatively lower synclinal areas.

Major geologic structures in the San Juan River region are the San Juan and Paradox basins, the Four Corners platform, the San Juan uplift, and the Mogollon slope. The San Juan basin, an asymmetrical structural and topographic depression, occupies a large part of the central section of the San Juan River region. The San Juan structural basin is about 200 miles long (north to south) and 130 miles wide, and includes an area of about 26,000 square miles (Shomaker and others, 1971).

The region is sparsely populated; most of the population is concentrated along the San Juan River and its tributaries, the Puerco River, and Rio San Jose. The populations (U.S. Bureau of Census, 1981) of major towns in the region are as follows: Farmington, New Mexico, 31,222; Gallup, New Mexico, 18,161; Grants, New Mexico, 11,451; Durango, Colorado, 11,426; and Cortez, Colorado, 7,095.

Major land use in the region is agriculture. Approximately 90 percent of the region is used for some form of agricultural production including timber, irrigated cropland, and dry cropland. The most substantial agricultural use of land is for livestock grazing. In the San Juan River basin, approximately 83 percent of the basin is used for grazing. Much of the remainder of the land is used for towns, roads, streams, and other miscellaneous use. Only a very small percentage of the region actually is used for mining of coal. Coal-producing areas generally are on rangelands.

Major use of water in the region is for irrigated agriculture, which is supplied mostly from surface-water sources. In the Dolores River basin, about 79 percent of the water is used for irrigated agriculture. About 5 percent of the water consumption is for riparian vegetation, nonbeneficial phreatophytes, and other related use. About 16 percent of the water consumption is for municipal, industrial, domestic, and livestock use and reservoir evaporation (U.S. Soil Conservation Service, 1972, p. III-47).

In the San Juan River basin, about 71 percent of the water is used for irrigated agriculture. About 19 percent of the water is used in reservoir evaporation and incidental use (incidental use of irrigation water by phreatophytes and other miscellaneous vegetation). About 8 percent of the water is used for municipal, industrial (including thermal electric power generation), domestic, manufacturing, livestock, governmental, and commercial use. About 2 percent of the water is used for minerals, recreation, fish and wildlife, and export (U.S. Soil Conservation Service, 1974, p. III-66).

In the New Mexico part of the Little Colorado River basin, about 63 percent of the water is used for irrigated agriculture. This water is mostly from surface-water sources, and about 29 percent of the water is used for municipal, industrial, rural domestic, and livestock use. Most of the rural domestic water is obtained from ground-water sources (U.S. Soil Conservation Service, 1981a, 1981b). About 8 percent of the water is used for fish and wildlife and recreation.

COAL RESOURCES

Coal occurs in the Dakota Sandstone, the Mesaverde Group, and the Fruitland Formation of Cretaceous age. The largest coal-mining activity presently is in the Mesaverde Group and the Fruitland Formation.

Coal produced by strip mining is of subbituminous and bituminous rank (fig. 4). Much of this coal production comes from the San Juan basin. A total of about 6,000 million tons of original strippable reserves is estimated to exist below 250 feet or less of overburden in the San Juan River region (Shomaker and others, 1971, p. 125). Of the total coal reserves, about 2,000 million tons or 40 percent are within the Navajo coal field, the largest and best known coal field in the San Juan River region, which is underlain by the Fruitland Formation and is located on the Navajo Indian Reservation (Shomaker and others, 1971, p. 108). The sulfur in strippable coal within the Navajo coal field ranges from 0.3 to 3.3 percent and has an average of about 0.8 percent. The coal is subbituminous and has an average ash content ranging from 17.4 to 21.6 percent on an as-received basis. Average heating value ranges from 9,000 to 9,400 British thermal units per pound (Shomaker and others, 1971, p. 108). A total of 300 million tons of surface mineable reserves (overburden is 250 feet or less and includes measured and inferred quantities) is estimated for the Salt Lake coal field by Roybal and Campbell (1982, p. 18).

There are 12 active coal mines in the San Juan River region. During 1980, 63 percent, or about 12 million tons, of New Mexico's total coal production came from San Juan County, and 29 percent, or about 5.5 million tons, came from McKinley County. Most of the coal produced in New Mexico is used for electric power generation or for individual boilers (Arnold and Hill, 1981, p. 42).

The New Mexico Bureau of Geology has made coal-production projections for New Mexico of about 39 million tons in 1985 and about 67 million tons in 1990. The combined production projection for San Juan and McKinley Counties is as much as 37 million tons in 1985 and about 64 million tons in 1990 (Arnold and Hill, 1981, p. 48).

HYDROLOGY

Expansion of coal mining to help meet the Nation's energy needs resulted in the need for more detailed hydrologic investigations. During 1974, hydrologic studies began as a U.S. Geological Survey and U.S. Bureau of Land Management cooperative program. Prior to 1974, the U.S. Geological Survey's hydrologic-data sites were concentrated along the San Juan River and its major perennial tributaries in the northern part of coal area 60. Very limited data were available within the coal-lease areas to assess the effects of coal mining on the water resources. Thus, hydrologic-data-collection sites were established during 1974. Objectives were to monitor surface and ground water in the coal area, to detect and document changes in water quantity or quality that may result from coal mining, and to develop methods to predict the effects of surface mining.

Although more surface-water sites and wells were added to the number of existing sites since 1974, some of these sites have been discontinued. More detailed information about currently operating surface-water sites and observation wells is discussed in the "Surface-Water Network" and "Ground-Water Network" sections of this report.

SURFACE-WATER NETWORK

Prior to 1974, stream-discharge records were obtained from a total of 49 continuous-record stream-discharge sites within coal areas 60 and 62. Since 1974, discharge information was obtained from 31 additional continuous-record stream-discharge sites. Water-quality records are available for 33 surface-water sites prior to 1974. Since 1974, water-quality information has been obtained at 43 additional surface-water sites.

In coal area 60, surface-water information is available for 385 sites that include continuous-, partial-, or miscellaneous-record stream-discharge sites. Currently (1985), there are 57 continuous-, 23 partial-, and 23 miscellaneous-record stream-discharge sites that are being operated. Information available for most of the continuous-record stream-discharge sites are daily mean discharges, peak flows, base flows, and instantaneous measurements for the complete year. At partial-record stream-discharge sites, limited discharge data are collected on a systematic basis. Most of the data at miscellaneous sites consist of instantaneous discharge measurements in addition to collection of miscellaneous water-quality data. Water-quality data are available for 385 surface-water sites. Currently (1985), water-quality samples are collected at 20 continuous-record stream-discharge sites, 8 partial-record stream-discharge sites, and 23 miscellaneous sites. Suspended-sediment data are available at 46 surface-water sites.

In coal area 62, surface-water information is available for 25 sites. Currently (1985), there are seven continuous-, eight partial-, and one miscellaneous-record stream-discharge sites that are being operated. Water-quality data are available for nine surface-water sites, two of which currently are being operated. Suspended-sediment data are available at five surface-water sites.

In addition to general hydrologic characteristics presented in coal-area hydrology reports, the network of hydrologic data-collection sites was augmented in the strippable coal areas of the Fruitland Formation to meet the needs of detailed investigations, including site-specific studies. Hydrologic data-collection sites established specifically for these studies included 23 stream-discharge and water-quality sites, 15 miscellaneous stream-discharge and water-quality sites, 7 annual peak-discharge sites, and 51 observation wells.

SURFACE-WATER CHARACTERISTICS

Many of the continuous stream-discharge sites are located along the San Juan River and its major northern tributaries, which are the only perennial streams in the region. Most of the streams draining the area south of the San Juan River are ephemeral. Discharges in the San Juan River at Shiprock, in the northwestern corner of New Mexico, average 2,172 cubic feet per second (period of record was 1927–82) and discharges in the Chaco River near Burnham, in the northwestern part of New Mexico, average 26 cubic feet per second (period of record was 1977–82) (U.S. Geological Survey, 1983b, p. 496 and 505).

The flow-duration curve for site 1, Chaco River near Burnham, New Mexico, displays the characteristics of a stream that usually is dry and flows only during localized, short-duration, high-intensity summer thunderstorms (fig. 51). The flow-duration curve for site 2,

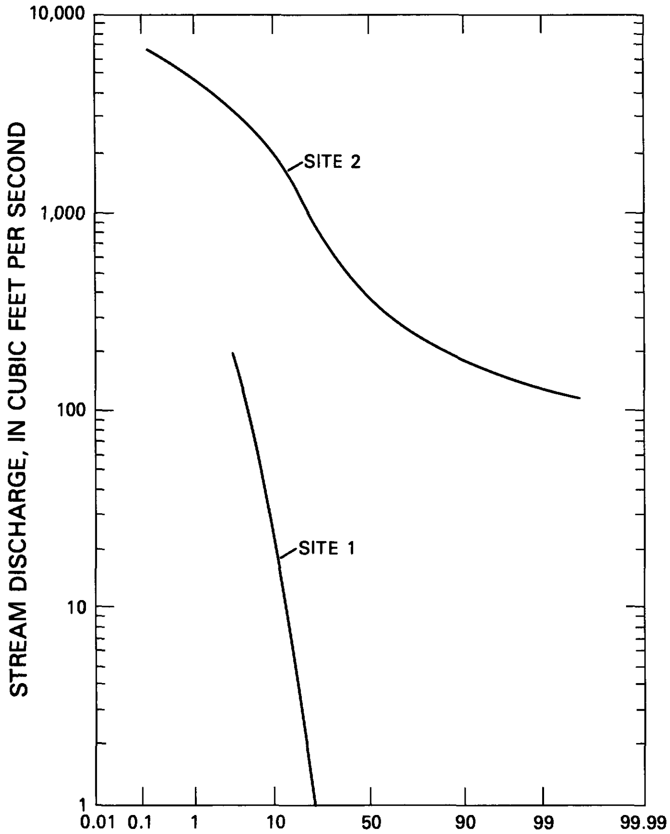


FIGURE 51.—Typical flow-duration curves for selected streams in the San Juan River region (modified from Roybal and others, 1983).

Animas River at Durango, Colorado (fig. 51), shows a flat slope in the upper and lower parts of the curve, indicating that surface- and ground-water storage in the Animas River basin is sufficient to provide a sustained flow.

Base flow is defined as streamflow that is composed only of ground-water discharge. In the Dolores River basin and in the San Juan River basin, the base flows are small. In the southern part of the San Juan River basin, base flow for most ephemeral streams is zero, indicating no substantial ground-water discharge.

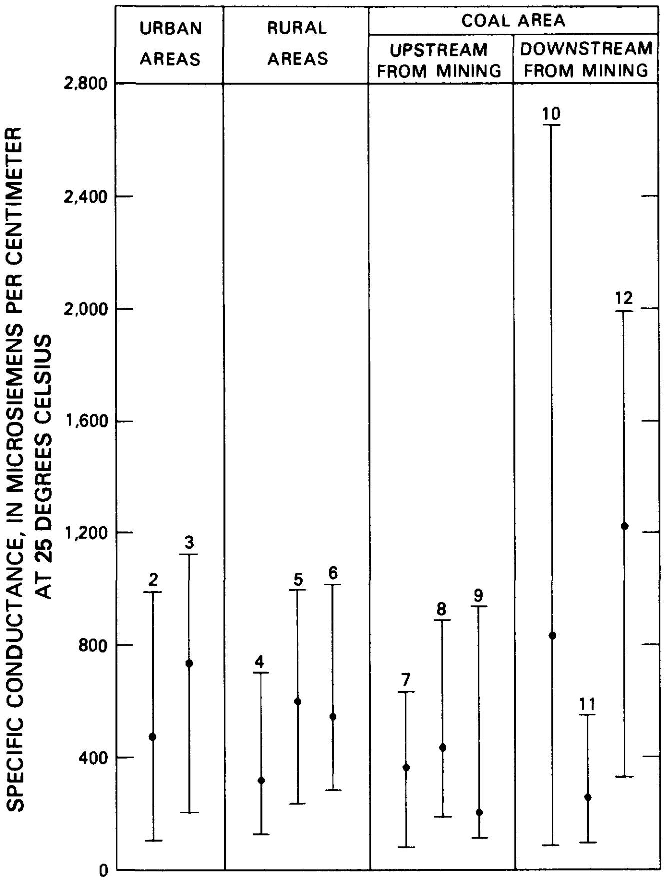
Methods have been developed for estimating magnitude and frequency of floods at sites where no flood data have been collected. Thomas and Gold (1982) prepared flood-estimating equations using basin characteristics developed from data collected in New Mexico. These estimating equations can be used for the San Juan River and its tributaries in coal area 60 and all of coal area 62. McCain and Jarrett (1976) prepared estimating equations for Colorado streams based on basin characteristics. These estimating equations can be used for the Dolores River basin in coal area 60.

SURFACE-WATER QUALITY

Water that has a dissolved-solids concentration greater than 1,000 milligrams per liter is considered saline, but concentrations as large as 5,000 milligrams per liter may be used for salt-tolerant crops. The recommended maximum dissolved-solids concentration in drinking water supplies is 500 milligrams per liter (U.S. Environmental Protection Agency, 1986c). In coal area 60, the average dissolved-solids concentration ranges from 44 to 6,450 milligrams per liter; however, at a majority of the surface-water sites, the concentration is less than 500 milligrams per liter. The predominant ions in headwater flows are calcium and bicarbonate, whereas the concentration of sodium and sulfate increases in the downstream direction. Changes in concentration generally are caused by dilution from snowmelt runoff, increases in salt content from watershed flushing during the initial stages of thunderstorm runoff, concentration of solutes by evaporation during low flows that mix with ground-water seepage, and contamination from wastewater discharge. Flows in perennial streams such as the San Juan River commonly contain less than 500 milligrams per liter of dissolved solids and generally are more suitable for irrigation and reclamation use than ephemeral flows such as the Chaco River that contain concentrations of 2,000 milligrams per liter or more. Medians and ranges of specific conductance at selected surface-water-quality sites are shown in figure 52. The surface-water-quality sites (except site 11) downstream from the active coal-mining areas indicate a varied range of specific conductance. Data used for figure 52 are for October 1973 through September 1983 and are from the U.S. Geological Survey WATSTORE file and from two reports by Roybal and others (1983, 1984).

Natural surface water in the area is alkaline because of the presence of bicarbonate, which is a buffering agent that reacts with alkalinity or acidity in a water solution while causing little change in pH. Naturally occurring acidic surface water does not occur in the region; however, water with pH values of 2.5 have been measured occasionally at sites that are located downstream from coal mines and coal-fired powerplants. Concentrations of trace elements generally are less than limits established in mining regulations or drinking-water standards (U.S. Environmental Protection Agency, 1986a, 1986b, 1986c).

In coal area 62 there are only nine surface-water sites at which water has been collected for chemical analysis.



EXPLANATION

5 SITE NUMBER
MAXIMUM
MEDIAN
MINIMUM

SITE NUMBER IN FIGURE 50	SITE NAME AND DRAINAGE AREA
2	Animas River at Durango, Colorado (692 square miles)
3	Animas River at Farmington, New Mexico (1,360 square miles)
4	Dolores River at Dolores, Colorado (504 square miles)
5	Cottonwood Wash near Blanding, Utah (205 square miles)
6	Zuni River above Black Rock Reservoir, New Mexico (810 square miles)
7	San Miguel River near Placerville, Colorado (308 square miles)
8	Chaco Wash at Chaco Canyon National Monument, New Mexico (578 square miles)
9	Los Pinos River at La Boca, Colorado (510 square miles)
10	San Miguel River at Uravan, Colorado (1,499 square miles)
11	Piedra River near Arboles, Colorado (629 square miles)
12	La Plata River at Colorado-New Mexico State line (331 square miles)

FIGURE 52.—Maximum, median, and minimum specific conductance at selected surface-water-quality sites in the San Juan River region.

These data are not sufficient to characterize surface-water quality. The locations and available surface-water data for this area are presented in Roybal and others (1984).

Surface coal mining may increase erosion and sedimentation because of removal of vegetation. This may be minimized by effective reclamation practices. In the San Juan River region, evidence of extreme natural erosion is present throughout the area. In coal area 60, badland escarpment areas that have 80 to 90 percent bare soil have the largest annual sediment yield of 1.2 to 3.2 acre-feet per square mile. In coal area 62, annual sediment yield generally is less than 1 acre-foot per square mile. The rates of erosion by water and wind depend on climate, surface geology, relief, vegetative cover, and land use. Most of the precipitation that occurs during intense summer rainstorms readily erodes bare land surfaces. Most of coal area 62 consists of exposures of weathered shales and sandstones or deposits of loose sand or soil. Areas at higher altitudes that are covered densely with vegetation are much less susceptible to erosion than areas that are covered sparsely with vegetation. Concentrations of suspended sediments generally greater than 10,000 milligrams per liter are present in ephemeral streams south of the San Juan River.

GROUND-WATER NETWORK

Prior to 1974, water-level information was obtained from 50 wells in the San Juan River region. Since 1974, water-level information has been obtained from 31 additional wells. Water-quality records for ground water were available at 33 wells prior to 1974. Since 1974, water-quality information has been obtained from 22 additional wells.

In this region, there are 81 wells in a ground-water monitoring network, and records are available for more than 3,700 wells and springs. There are 453 wells and springs that each have 10 water-quality records and more than 1,900 wells and springs that have less than 10 water-quality records in the WATSTORE files. However, only 49 wells in coal area 60 have complete chemical analyses.

GROUND-WATER OCCURRENCE

Major aquifers in the region include Quaternary valley fill and sandstones of Tertiary, Cretaceous, Triassic, and Jurassic age. Aquifer transmissivity values generally range from 100 to 200 feet squared per day (Stone and others, 1983, p. 11). Most wells and springs are used for stock or domestic uses, but many also are used for municipal and industrial supplies. Yields to individual wells generally range from 5 to 100 gallons per minute throughout much of the region. Depth to water generally ranges from a few feet along the major stream channels to about 500 feet beneath some plateaus.

GROUND-WATER QUALITY

For the 49 wells that have complete chemical analyses in coal area 60, dissolved-solids concentrations range from less than 500 milligrams per liter to more than 3,000 milligrams per liter. The larger dissolved-solids concentrations occur in water in shale. Sulfate concentrations are small in the ground water associated with coal deposits.

For coal area 62, median concentrations of dissolved solids range from 262 to 889 milligrams per liter. Ground-water quality in coal area 62 is variable within each aquifer and between aquifers. Water quality generally is best near recharge areas, which generally coincide with areas of greater precipitation in the mountains.

COAL-HYDROLOGY STUDIES

To facilitate determination of appropriate water-quality standards for mining and reclamation operations and to minimize adverse effects on water resources, coal-related, hydrologic-data collection and detailed hydrologic investigations were begun in the San Juan River region. The need for these data became even more critical after enactment of the Surface Mining Control and Reclamation Act of 1977. This need was fulfilled partly by reports about coal areas 60 and 62, which summarized available hydrologic data in these areas. In addition to hydrology of the general area of a proposed mine, as in the reports on coal areas 60 and 62 (Roybal and others, 1983, 1984), detailed site-specific data were collected and analyzed to predict hydrologic effects from coal mining.

A number of coal-hydrology studies have been done to characterize the water resources and to address potential effects on the hydrologic environment caused by surface coal mining in the San Juan River region. A brief summary of some of these reports is given below.

A report by Hejl (1982) provided summaries of the hydrologic investigations and hydrologic data collection done by the U.S. Geological Survey in the strippable coal areas in the San Juan River basin. The data provide information about baseline or prevailing hydrologic conditions for use by the regulatory agencies to write stipulations to minimize adverse effects on water resources and to determine appropriate water-quality standards for mining and reclamation operations.

The studies by the U.S. Bureau of Land Management (1976, 1981a, 1981b) that provided detailed data about hydrologic conditions in potential Federal coal-development areas were done as part of the U.S. Bureau of Land Management's Energy Mineral Rehabilitation Inventory and Analysis (EMRIA) program. This program began during 1975 to provide baseline soil, hydrology, and overburden information for the assessment of the rehabilitation potential of potential surface-mining coal-lease tracts within the Federal coal-development areas.

Two studies developed techniques to estimate the water-resources characteristics in ungaged areas by obtaining a knowledge of the principles and processes that affect the local and regional flow system. Hejl (1980) developed equations that can be used to estimate surface-water characteristics of ephemeral streams in the San Juan River basin. Hejl (1984) developed equations for estimating the mean annual runoff and peak discharges for the 2-, 5-, 10-, 25-, and 100-year recurrence intervals for ungaged streams in the drainage basins that contained strippable coal resources in northwestern New Mexico. The reports should be useful to Federal and State agencies in defining surface-water characteristics so that reasonable stipulations can be developed for lease-permit mining applications by agencies that enforce the Surface Mining Control and Reclamation Act of 1977. The reports were prepared in cooperation with the U.S. Bureau of Land Management.

Goetz (1981) investigated various data-analysis techniques to develop methods to predict the effects of surface mining and associated development of water resources on the local and regional flow systems. These techniques can be used to determine and separate the effects of cultural-use patterns on streamflow and water-quality variability by the use of historical streamflow and water-quality records for the San Juan River basin. Goetz and others (1987) reported about techniques for separation and quantification of individual coal-mining effects from cumulative natural and cultural effects. A report by Frenzel (1983) used a transient model analysis to provide simulated effects of coal-related ground-water withdrawals on potentiometric surfaces of aquifers in the San Juan River basin. Preliminary results indicated 2,000 feet of drawdown for a minimum quantity of coal development combined with other kinds of development. As much as 2,300 feet of drawdown was simulated for the maximum quantity of coal development. Reports of several other studies (Myers and Villanueva, 1986; Goetz and others, 1987; Hejl, in press) could be useful in predicting hydrologic effects of surface-coal mining. The report by Hejl (in press) involves use of the precipitation-runoff modeling system (Leavesley and others, 1983), which could be helpful for predicting surface-runoff characteristics and sediment yield for various reclamation practices.

HYDROLOGIC ISSUES RELATED TO COAL MINING

As a result of the increasing demand for energy, the strippable coal reserves in the San Juan River region are being considered for surface mining. Surface mining drastically alters, at least temporarily, the hydrology of previously undisturbed lands. If the areas are not reclaimed, there can be long-term, detrimental hydrologic consequences. For example, in the arid part of the San Juan River region where annual precipitation is less than 10 inches, revegetation as a part of reclamation could be difficult to maintain, hence erosion and sedimentation could be a major issue. Other potential hydrologic issues related to surface coal mining are destruction of stream channels, decline in ground-water levels, and degradation of water quality. However, hydrologic issues that result from current surface coal mining in the San Juan River region have not been documented at the present time (1985). Results of a recent study indicate no detectable effects on streamflow because of surface coal mining (Goetz and others, 1987). However, prolonged surface coal mining that alters large surface areas may cause hydrologic issues in the future.

At Shumway Arroyo, west of Farmington, New Mexico, pH values of 2.5 have been measured occasionally in water samples collected downstream from coal mines and coal-fired powerplants. Large alkalinity concentrations are present throughout the Chaco River system where extensive surface mining of coal is planned. In the ephemeral flows of arroyos, including the Chaco River, large sodium and salinity concentrations generally are present.

Most of the water-bearing formations in the region contain water that varies in quality. Generally, most of the values for concentrations of water-quality constituents increase with distance away from the areas of ground-water recharge. Ground water may supply water needs for coal development, but a limiting factor may be large salinity concentrations, particularly in parts of the San Juan River basin in New Mexico.

Of regional (and international) concern is the cumulative, salt-loading and salt-concentrating effect of coal mining on the Colorado River. This is a major issue that the U.S. Department of the Interior has been attempting to resolve for a number of years (U.S. Department of the Interior, 1981). Increasing salinity in the Colorado River that is associated with increasing coal production in the basin no doubt will increase the cost of the U.S. Department of the Interior's Colorado River Salinity Control program.

SUMMARY OF SELECTED RESEARCH ABOUT THE HYDROLOGIC EFFECTS OF COAL MINING

As part of the coal-hydrology program, substantial effort and funds were expended on topical research studies that generally were designed to further our understanding of hydrologic principles and processes related to coal mining. The studies were done nationwide but focused upon a few major topics in settings that differed not only in hydrogeology but also in hydrologic responses to coal mining.

The following discussions summarize briefly the information derived from studies concerned with watershed modeling, salinity modeling, ground-water flow systems, geochemistry of mine spoils, mine drainage, sedimentation, and aquatic biology. As a practical necessity, most of the summaries focus on studies done in a few specific areas, but a comprehensive list of references is provided to document the nationwide effort for each area of research.

Throughout the following discussions, equations are presented that document hydrologic relations or those used in model simulations. In some instances, different symbols are used to represent the same parameters. Because the symbols were used in specific, published studies, they are represented and defined here exactly as they appeared in the original referenced report.

WATERSHED MODELING

By LINDA G. STANNARD and GERHARD KUHN

An assessment of the hydrologic effects of surface mining is an integral part of the information needed to determine the suitability of an area for mining operations. However, the data necessary to make the assessments often are not available; furthermore, the time required to obtain sufficient data may be several years, thus impeding the timeliness of the coal-mine permitting process. The development of hydrologic models has been an attempt to provide both a time- and cost-effective method of estimating the hydrologic characteristics of an area, which then can be used to determine the hydrologic effects of coal mining.

The U.S. Geological Survey in cooperation with the U.S. Bureau of Land Management began a study during 1976 to develop, test, and verify a watershed model. The goals of the model development study were to provide: (1) A method for estimation of the hydrologic characteristics and processes of areas where basic hydrologic data are lacking; and (2) the capability of predicting hydrologic effects of potential coal-lease areas (Van Haveren and Leavesley, 1979).

The result of that cooperative study is the Precipitation-Runoff Modeling System (PRMS), described in detail by Leavesley and others (1983). The purpose of this section of this report is to briefly describe PRMS and some hydrologic studies in coal areas to which this modeling system has been applied.

PRECIPITATION-RUNOFF MODELING SYSYTEM (PRMS) DESCRIPTION

PRMS is a deterministic, physical-process, computer model capable of simulating the response (such as streamflow) of a hydrologic system (a watershed) to the model inputs (such as precipitation and land use). Changes in the response due to changes in the hydrologic system, whether real or hypothetical, can be represented by appropriate changes in the model input parameters.

CONCEPTUAL WATERSHED SYSTEM

The development and the operation of PRMS are based on a conceptual watershed system and its inputs (fig. 53). The conceptual watershed system consists of four reservoirs: the upper-soil-zone, subsurface, ground-water, and impervious-zone reservoirs. The outputs of the reservoirs combine to produce the total system response.

The upper-soil-zone reservoir is two layered and represents that part of the soil mantle that can lose water through the processes of evaporation and transpiration. Water storage in this reservoir is increased by infiltration of rainfall or snowmelt. The quantity of water in this reservoir and its maximum capacity are used in the computation of surface runoff (Q1, fig. 53).

Infiltration in excess of the capacity of the soil zone can be routed to the subsurface reservoir. Flow from this reservoir (Q2, fig. 53) is derived from water in shallow ground-water zones that is available for relatively rapid movement to a channel system. The ground-water reservoir, which is the source of all base flow (Q3, fig. 53), can be recharged from either the upper-soil-zone or subsurface reservoirs or both. Movement of water from the ground-water reservoir to points beyond the area of measurement is represented using a ground-water sink. The impervious-zone reservoir represents an area with no infiltration capacity and also contributes to surface runoff (Q1). Streamflow (Q4, fig. 53) is the sum of Q1, Q2, and Q3.

Inputs to the conceptual watershed system are precipitation, air temperature, and solar radiation. Precipitation, in the form of rain or snow or a mixture of the two, is delivered to the watershed. The energy inputs of air temperature and solar radiation drive the processes of evaporation, transpiration, sublimation, and snowmelt.

MODEL PARAMETERS

In PRMS, each component of the hydrologic cycle is represented by mathematical equations that are based on physical laws or empirical relations. The coefficients in these equations are the model parameters; selected model parameters are listed in table 5.

Parameter values are based on the physical, climatic, or hydrologic properties of a basin and may be distributed. Spatial distribution of most basin characteristics is accomplished by dividing a watershed into areas called Hydrologic Response Units (HRU's) on the basis of slope, aspect, altitude, soil and vegetation properties, or other factors that make a part of a basin hydrologically different from the rest of the basin. Input values for the parameters distributed by HRU can be determined from topographic maps, soils and vegetation surveys, onsite reconnaissance and measurements, and literature. Most of the values are specific to individual areas. However, after a basin has been modeled, some of the parameter values determined may be useful for other basins that have similar characteristics.

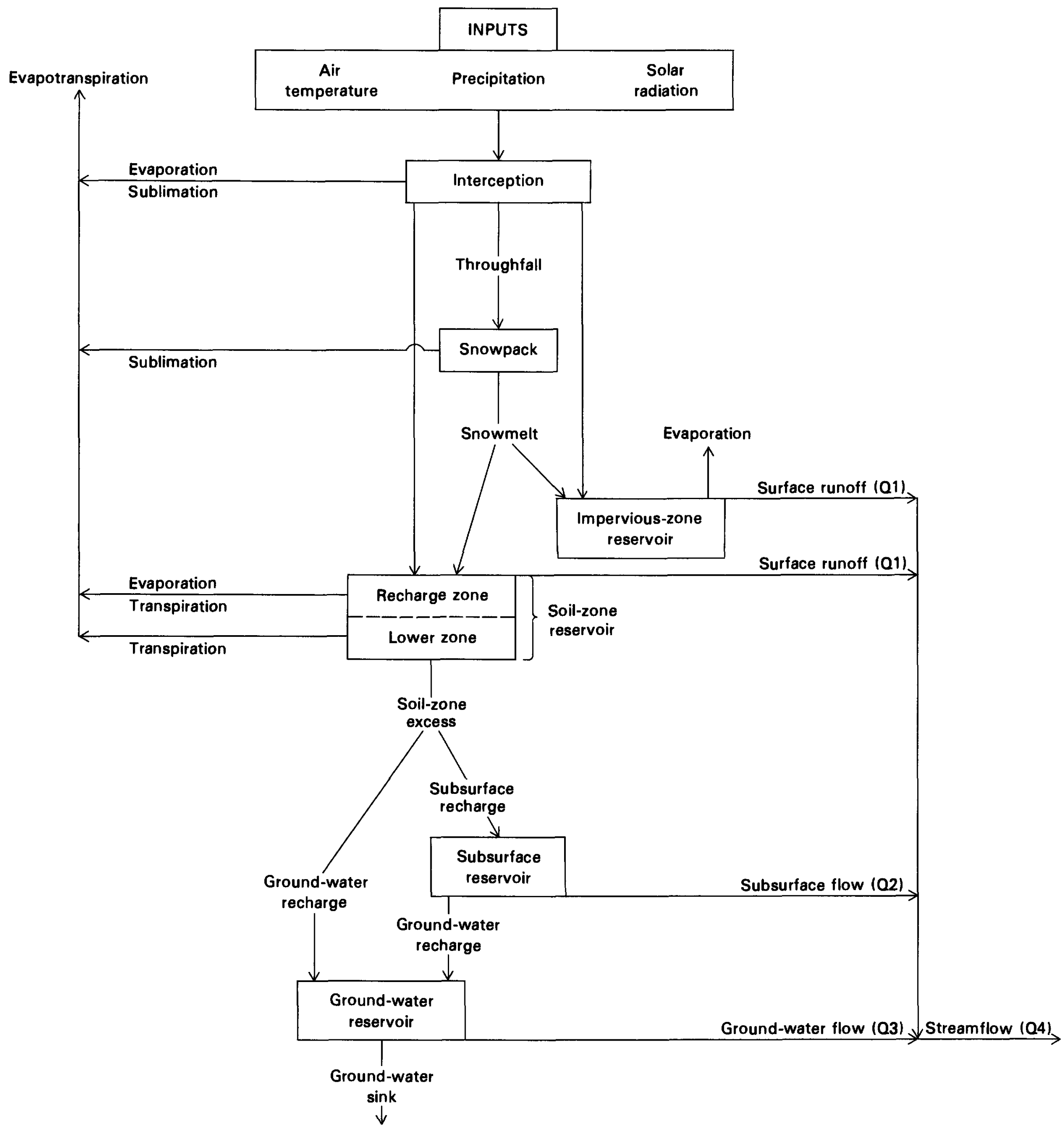


FIGURE 53.—Schematic diagram of the conceptual watershed system and its inputs (modified from Leavesley and others, 1983).

Parameters that describe the subsurface and ground-water reservoirs (table 5) and their contribution to streamflow also may be distributed when enough information is available about the basin to determine distributed values. Preliminary values for some of these parameters may be obtained by analyzing the daily-streamflow-recession hydrograph for a basin.

Several parameters are distributed by month to account for seasonal changes in their values. These and the nondistributed parameter values (table 5) are determined mainly from regional climatic characteristics and data and apply to the entire basin.

SIMULATION PROCESS

During a daily simulation run, PRMS computes: (1) The daily maximum and minimum air temperature, net precipitation, interception, solar radiation, potential and actual evapotranspiration, soil-moisture content, surface runoff, snowpack water equivalent, and snowmelt

TABLE 5.—*Selected Precipitation-Runoff Modeling System (PRMS) parameter definitions*

Parameter	Definition
Distributed by Hydrologic Response Units (HRU):	
COVDNS/CONDNW	Summer/winter vegetation cover density.
SCN, SCX, SC1	Coefficients used to determine area contributing to surface runoff as a proportion of HRU area.
SEP	Maximum daily seepage from soil-moisture excess to ground-water reservoir for an HRU.
SMAX	Maximum available water-holding capacity of soil profile.
SRX	Maximum daily snowmelt infiltration capacity of soil profile.
TRNCF	Transmission coefficient for short-wave radiation through the vegetation canopy.
Distributed by subsurface and ground-water reservoirs:	
RCB	Ground-water routing coefficient.
RCF, RCP	Subsurface routing coefficients.
RESMX, REXP	Coefficients for routing from each subsurface reservoir to a ground-water reservoir.
RSEP	Coefficient for computing seepage from subsurface to ground-water reservoirs.
Distributed by month:	
CTS	Air-temperature evapotranspiration coefficient.
TLX/TLN	Lapse rates for maximum/minimum daily temperature with altitude.
Not distributed:	
BST	Temperature above which precipitation is considered rain and below which it is considered snow.
DENI	Initial density of new-fallen snow.
DENMX	Average maximum snowpack density.
EAIR	Emissivity of dry air.
FWCAP	Free water-holding capacity of snowpack.
SETCON	Snowpack-settlement time constant.

for each HRU; (2) the storage, inflow, and outflow for each subsurface and ground-water reservoir; and (3) the basin streamflow. These values may be output on a daily, monthly, or annual basis for each HRU or as basin averages and totals.

For each day, PRMS first distributes the input air temperature, precipitation, and solar-radiation data throughout the basin based on slope, aspect, altitude, and correction factors for each HRU. Potential evapotranspiration then is computed. If precipitation occurs on that day, the form is determined and the quantity of rain and (or) snow intercepted is computed. If there is new or existing snow, the snowpack energy balance and water equivalent are updated, and snowmelt is computed.

Soil-moisture accounting is done next, and the quantity of surface runoff is determined. Soil-moisture accretions are computed from rainfall and snowmelt infiltration; depletions are computed from evapotranspiration and seepage to subsurface and ground-water reservoirs. Subsurface and ground-water flow are determined by applying the routing coefficients to the updated reservoir-storage values. Streamflow then is computed as the sum of the surface, subsurface, and ground-water flows.

The capability to estimate individual storm hydrographs from rainfall events also is available using PRMS. Precipitation data measured at 1- to 60-minute intervals may be used as input on storm days. On these days, a modified infiltration and surface-runoff method is used and streamflow routing is done. To use this option, a network of flow planes and channel segments needs to be determined for the basin and included in the input.

Sensitivity analysis and optimization routines also are available in PRMS for use with most of the model parameters. Output from the sensitivity analysis indicates the change in runoff prediction error caused by an incremental change in a parameter value. The larger the change in prediction error, the more sensitive a parameter is considered to be, and the more important it is to determine appropriate values for that parameter.

There are several optimization options that enable the user to refine parameter values to obtain the best calibration fit of predicted to observed streamflow values. Parameter values are adjusted automatically within user-defined limits during optimization to minimize the prediction error.

PRECIPITATION-RUNOFF MODELING SYSTEM (PRMS) APPLICATIONS

Because PRMS has the capability of simulating the effect of land-use changes on an area's hydrologic characteristics, it has been used in a considerable number of hydrologic studies that are related to coal-resources development; locations of selected basins studied are shown in figure 54. Sizes of the study basins range from less than 0.01 to about 44 square miles. Hydrologic characteristics of the study areas vary considerably, not only between, but also within the regions. Because of these variations and the sometimes specific nature of the application of PRMS to a watershed, generalizations regarding the use of PRMS are not easily stated. Brief descriptions of the use of PRMS in some current and completed studies are presented here.

FIGURE 54.—Location of selected U.S. Geological Survey coal-basin modeling studies, 1984. Numbered coal-basin modeling areas are described in the text.

EASTERN AND INTERIOR PROVINCES

Calibration of PRMS on five watersheds (area 1, fig. 54) in the Warrior coal field in Alabama began during 1979. The basins studied (Bear, Blue, Trinity, Turkey, and Yellow Creeks) range in size from 0.76 to about 15 square miles. The topography is mostly rolling uplands covered with deciduous and coniferous forest and has incised stream valleys. Three of the basins had been partially strip mined; the most extensive mining, 21 percent of the basin, occurred in the Trinity Creek watershed.

The length of streamflow record available for calibration of the basins ranged from 1 to 6 years. After calibration, the errors in total simulated-streamflow volume ranged from -25 to +2.9 percent. Storm hydrographs were simulated for Bear, Blue, and Turkey Creeks, and the resulting average errors in storm volumes ranged from -14 to +19 percent. Some of the parameters determined to be sensitive in this area were SMAX, SC1, SCN, SCX, and RCF (see table 5). These parameters affect the distribution of rainfall between surface runoff and subsurface flow.

Calibration results from the Bear, Blue, and Turkey Creek basins were used to define six regional HRU's. These 6 HRU's were delineated in 34 small basins (0.29 to 44.16 square miles) in the Warrior coal field. Five-year simulations were done for the basins representing: (1) Existing conditions; and (2) mined conditions corresponding to proposed leasing alternatives. The major difference in the results of the simulations was increased base flow in mined areas directly proportional to the extent that the Pottsville Formation was disturbed by the simulated mining (U.S. Bureau of Land Management, 1983a). Other reports available for this area are Puente and Newton (1982) and Kidd and Bossong (1986).

In the Beaver Creek basin of southeastern Kentucky (area 2, fig. 54), a modeling study was done for two small watersheds, Cane Branch (0.67 square mile) and Helton Branch (0.85 square mile). Approximately 10 percent of the Cane Branch basin had been strip mined (Bower, 1985).

PRMS was calibrated for Helton Branch for the 1956-58 period of record and then was run for the 1956-66 period of record. The total volume error for this period was -1.4 percent, and the total storm volume error was -11 percent. The calibrated parameter values determined for Helton Branch then were used to operate PRMS for Cane Branch for the same 10-year period. The resulting total volume error for Cane Branch was -2.6 percent, and the total storm volume error was -34 percent. The most sensitive parameters for these basins were (see table 5) SMAX, RESMX, SC1, REXP, RCP, and RCF (Bower, 1985).

Five small watersheds in West Virginia (area 3, fig. 54) were calibrated with PRMS as part of a modeling study in the coal areas of the Appalachian region. Three of the watersheds are unmined and two are mined (surface and underground) extensively for coal. Topography of the basins is mountainous and is characterized by deep, steep-sided valleys and narrow, winding ridges. The Collison Creek basin (2.78 square miles) is unmined, whereas the Drawdy Creek basin (7.75 square miles) is 9 percent surface mined and 26 percent underground mined. A 1-year calibration period was used for both basins followed by a 4-year verification period. Total volume error for the 5-year period was +2 percent for Collison Creek and 0 percent for Drawdy Creek. The sensitive parameters for both basins were SMAX, RCP, RCF, SC1, SCN, and RCB (Puente and Atkins, 1986).

Simulations of streamflow in Drawdy Creek basin during various hypothetical mining conditions indicate that total annual runoff is decreased because of surface and subsurface flow losses to ground water in underground mine workings and in overlying rocks; these losses would decrease medium to moderately high flows, negligibly affect extremely high flows, and substantially increase the quantity and duration of low flows in the basin during dry seasons. The increase in ground water would be depleted by increased losses to a ground-water sink and to base flow in the stream (Puente and Atkins, 1986).

A modeling study of 19 watersheds (area 4, fig. 54) in 11 States in the Eastern and Interior Provinces began during 1982. The basins are monitored extensively, and selection was based on the varieties of geologic and climatic settings and the areal extent of mining. The areas of the basins range from 0.17 to 5.08 square miles and average elevations range from 480 to 2,265 feet (Kilpatrick and others, in press).

The modeling part of this study has been designed to enable correlations of model parameters with physiographic, climatic, and land-use characteristics by imposing specific guidelines for determining input values for many parameters and restricting the use of model options (A.M. Lumb, U.S. Geological Survey, written commun., 1983). A series of three reports is planned as a product of the study. The first, Kilpatrick and others (in press), describes the general hydrology, geology, and data-collection methods for all the basins. The other two reports will address model calibration and verification and the potential for regionalization of model parameters.

PRMS also was calibrated for eight mined and two unmined (area 5, fig. 54) watersheds in the Tug Fork basin of Kentucky, Virginia, and West Virginia. The calibrated models were used with long-term (68 years) climate records to simulate daily streamflow and annual peaks for each watershed. The simulated records were used to compute flow characteristics (such as annual peak flow for selected recurrence intervals, mean annual discharge, and flow duration), which then were analyzed to investigate the relation between mining and runoff. Results indicated that "disturbed area" was a very significant predictor for all flow characteristics except low flow. SMAX and SEP, followed by RCF, SCN, and RCB, were determined to be the most sensitive parameters for this study (Scott, 1984). Doyle and others (1983) describe an application of PRMS to the entire Tug Fork basin.

NORTHERN GREAT PLAINS AND ROCKY MOUNTAIN PROVINCES

Prairie Dog Creek (area 6, fig. 54) in southeastern Montana was calibrated for the 1979 water year. This 25-square-mile basin is characterized by moderately steep topography and wide, flat stream valleys. Vegetation is mostly sagebrush and grass, and riparian woods occur in the stream valleys. The annual volume error for the calibration year was -1.3 percent, and for the verification water years, 1980 and 1981, the annual volume errors were +55 percent and +983 percent. These errors were attributed, in part, to inadequate representation of basin infiltration characteristics and to precipitation variability (Cary, 1984). Sensitive parameters in this area were determined to be RCB, TRNCF, SMAX, BST, and SEP; TRNCF and BST relate to snowpack accumulation and depletion. Details of this study, which included testing several different HRU configurations, are presented in Cary (1984).

The results of the Prairie Dog Creek study were used to estimate input parameters for the Squirrel Creek basin (area 6, fig. 54), also in southeastern Montana.

PRMS was calibrated for the 1979 water year, then run for the 1977–82 water years. The total volume error for the 5-year period was +29 percent, and sensitive parameters were SMAX, RCB, and SEP. Results of this parameter-regionalization study are presented in Cary (1984).

Two snowmelt-runoff basins (area 7, fig. 54), Hay Creek in east-central Montana and West Branch Antelope Creek in west-central North Dakota, were studied using PRMS. The most sensitive parameters for these areas were BST, DENMX, EAIR, FWCAP, SMAX, and SRX, most of which relate to snowpack computations in the model. Total volume error for Hay Creek for water years 1978–81 was -31 percent. Four HRU configurations were calibrated for West Branch Antelope Creek for water years 1978–82. Total volume errors varied significantly for the four calibrations. For 1 HRU, the error was -58 percent; for 9 HRU's, the error was +8.7 percent; for 18 HRU's, the error was -6.3 percent; and for 36 HRU's, the error was +0.3 percent. Details of this study were presented by Emerson (1988).

A modeling study of nine, primarily snowmelt-runoff basins (area 8, fig. 54) in northwestern Colorado has been completed by Parker and Norris (1989). The sizes of the basins range from 2.65 to 27.4 square miles, and the altitudes range from 6,300 to 9,000 feet. Vegetation types include aspen, sagebrush, and scrub oak. The basins were analyzed in groups of three; two basins in each group were calibrated and verified, and their parameters were transferred to the third basin. The calibration procedure is described in Norris and Parker (1985).

The range in errors in simulated streamflow for the transferred-parameter basins was similar to that computed for the calibrated basins. The sensitive parameters for this area were SMAX, BST, CTS, TRNCF, and TLX, which affect snowpack accumulation and snowmelt (Parker and Norris, 1989).

Rankl (1987) used PRMS in Wyoming basins that are less than 0.8 square mile in size to simulate sediment discharge. This study is discussed in the section entitled "Sedimentation."

DISCUSSION

Several deficiencies in the PRMS representation of some of the hydrologic processes were noted in the previously mentioned studies; the most commonly noted deficiencies were the inability to handle discontinuous or shallow snowpacks and runoff on frozen soils and the lack of transpiration from ground water.

SMAX, the maximum available water-holding capacity of the soil profile, was a sensitive parameter in virtually all areas studied. In the Eastern Province, SMAX generally was the most sensitive parameter followed by the surface-runoff parameters, SC1 and SCN, and the subsurface- and ground-water-routing parameters, RCF, RCP, and RCB. In areas where snowmelt was substantial, BST, the base temperature used to determine whether precipitation is rain or snow, also was a sensitive parameter. The other parameters relating to snowpack accumulation and depletion indicated varying degrees of sensitivity among basins.

PRMS has been used for a variety of hydrologic conditions, and the results of studies indicate a considerable degree of accuracy in the simulated streamflow. Much of the development of PRMS and many of the modifications that have been made were directly attributable to the hydrologic modeling studies done in coal-resource areas. Modifications will continue to be made as new methods are developed, and the potential for successful application of PRMS should continue to improve.

SALINITY MODELING

By Rodger F. Ferreira

Studies of the environmental effects of coal mining indicate an increase in the concentration of dissolved constituents in water because of the disruption of coal beds and associated overburden and the resultant dissolution of minerals in resaturated mine spoils. Although quality of ground water may be affected more immediately than surface water, there is concern about the degree to which the quality of surface water will change at locations downgradient from mined areas. Methods for predicting changes in the quality of surface water would provide information needed by resource-management agencies in directing lease options for coal development.

The U.S. Geological Survey in cooperation with the U.S. Bureau of Land Management and various State agencies has maintained several surface-water sampling networks in coal areas of the United States. Depending on the location of each site, the data provide either a characterization of water quality in streams already affected by coal mining or a characterization of water quality in streams unaffected by mining from which possible future changes can be measured. Data from these sites generally have been published in the U.S. Geological Survey's State Data Reports (published annually) or in reports describing the water resources of specific coal areas.

In addition, the U.S. Geological Survey has published various reports that have data in a form more useful for evaluating alternative coal-development plans. With reference to salinity, these reports have emphasized development of simple and multiple linear-regression models for estimating annual loads of dissolved solids, curvilinear-regression models that account for seasonal effects in estimating monthly mean dissolved-solids loads, mathematical accounting models that sum water quantity and quality at given nodes in a network of surface-water sampling sites, and mathematical routing models that mass-balance stream discharge and dissolved-solids concentrations between upstream and downstream ends of any selected number of reaches on a main-stem stream. The following general discussion of each model approach summarizes their usefulness as tools for evaluating effects of coal mining in the United States.

DESCRIPTION AND APPLICATION OF SIMPLE AND MULTIPLE LINEAR-REGRESSION MODELS

Early reports describing surface-water quality in coal areas mainly consisted of descriptive statistics (mean, standard deviation, minimum, and so forth) for several water-quality constituents measured at a site. Knapton and Ferreira (1980) summarized and evaluated water-quality data for streams in southeastern Montana from October 1974 to September 1978. The network of sites consisted of 43 water-quality sites at which routine sampling was done for about 60 different water-quality constituents. To increase the usefulness of these data, two sets of simple linear regressions were developed. For most of the constituents sampled, specific conductance and stream discharge were used separately as independent variables. The following general form of regression equation was used for each independent variable:

$$y = B_0 + B_1X, \qquad (1)$$

where y = dependent water-quality variable;
B_0 = regression constant (y intercept);
B_1 = regression coefficient of the independent variable; and
X = independent water-quality variable (either specific conductance or stream discharge).

As an improvement to the above regressions, specific conductance and stream discharge were used concurrently to produce equations of the following general form:

$$y = B_0 + B_1X_1 + B_2X_2, \qquad (2)$$

where y = dependent water-quality variable;
B_0 = regression constant (y intercept);
B_1 = partial regression coefficient for the first independent variable;
X_1 = first independent water-quality variable (discharge);
B_2 = partial regression coefficient for the second independent variable; and
X_2 = second independent water-quality variable (specific conductance).

The regression equations presented by Knapton and Ferreira (1980) were intended to indicate potentially strong water-quality relations for streams in the coal areas of southeastern Montana. The large number of sites and variables precluded determining the need for any transformation of the data to ensure that all assumptions for use of parametric regression analysis were met. Including both specific conductance and stream discharge in the regression equations generally did not greatly improve the simple regressions (Knapton and Ferreira, 1980). The best and most consistent correlations occurred with dissolved-solids concentration and specific conductance. However, better correlations for several constituents sometimes occurred using stream discharge rather than specific conductance. Generally, throughout the study area, cations and anions had the best correlation with specific conductance, whereas physical measurements, such as suspended-sediment concentrations and turbidity, had the best correlations with stream discharge.

The regression equations presented in Knapton and Ferreira (1980) can be used to simulate dissolved-solids loads on a daily, monthly, or annual basis. The following equation is an example using daily stream-discharge values to calculate load:

$$C_G = Q \cdot C_i \cdot K, \qquad (3)$$

where C_G = dissolved-solids load, in tons per day;
Q = daily mean stream discharge, in cubic feet per second;
C_i = daily mean dissolved-solids concentration, in milligrams per liter, calculated from equations 1 or 2; and

$$K = \frac{86{,}400 \text{ seconds per day} \times 62.4 \text{ pounds per cubic foot}}{2{,}000 \text{ pounds per ton} \times 1{,}000{,}000 \text{ milligrams per liter}} = 0.0027$$

The resultant loadings calculated from these equations can be used to graphically compare the relative contributions of dissolved-solids loads from selected sources (fig. 55).

At sites having adequate data, the regression equations can be used to assess land-use changes by describing baseline relations (Knapton and Ferreira, 1980). Deviation from established regression equations might be due to alteration of water quality as a result of man's activities.

DESCRIPTION AND APPLICATION OF CURVILINEAR-REGRESSION MODELS

There are many instances where a simple linear-regression model does not fully explain the variability of independent variables. The most often used equation that relates stream discharge to dissolved-solids concentration is:

$$C = A \cdot Q^B, \qquad (4)$$

where C = concentration, in milligrams per liter;
Q = stream discharge, in cubic feet per second; and
A and B = regression coefficients.

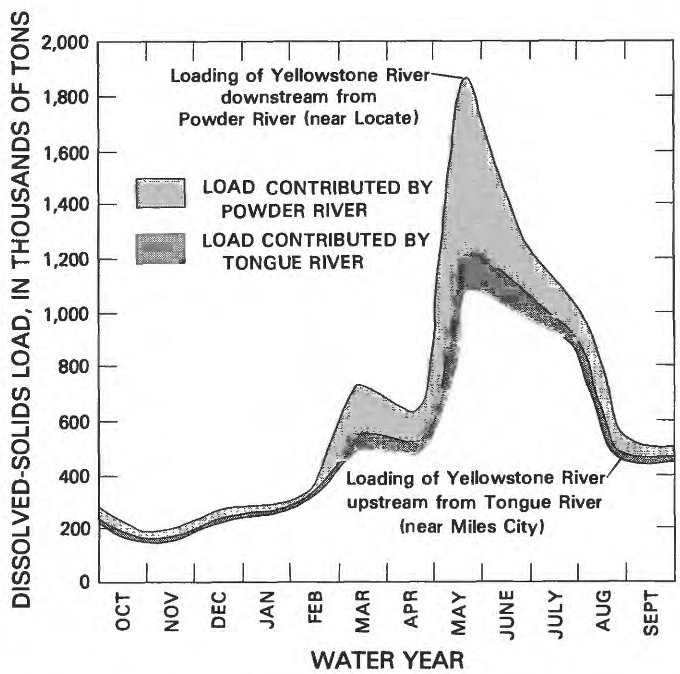


FIGURE 55.—Simulated dissolved-solids loading to the Yellowstone River from the Tongue and Powder Rivers, Montana, 1978 water year (modified from Knapton and Ferreira, 1980).

Equation 4 becomes linear (as in eq. 1) when log transformations are made on variables C and Q.

Equation 4 assumes a constant year-round relation; however, there are many sites that do not follow this assumption. Seasonal shifts in the relation between estimated and measured dissolved-solids concentration are exemplified by dissolved-solids residuals from a site in the Green River basin of Wyoming, as shown in figure 56 (DeLong, 1977). In this example, the positive residuals during one period are balanced against negative residuals during another period. To account for their seasonal effects, DeLong (1977) incorporated a time variable into coefficients A and B in equation 4 using the following functions:

$$\text{Log}_{10} A = B_0 + B_1 \sin(\alpha t) + B_2 \cos(\alpha t), \text{ and} \qquad (5)$$

$$B = B_3 + B_4 \sin(\alpha t) + B_5 \cos(\alpha t), \qquad (6)$$

where α = 0.987 degree per day or 0.0172 radian per day;
t = day of the water year; and
B_0 through B_5 = regression coefficients.

Regression coefficients B_0 through B_5 are determined by a multiple-variable-regression technique referenced by DeLong (1977). The improved residual plot for the Green River at Warren Bridge near Daniel, Wyoming, is shown in figure 57.

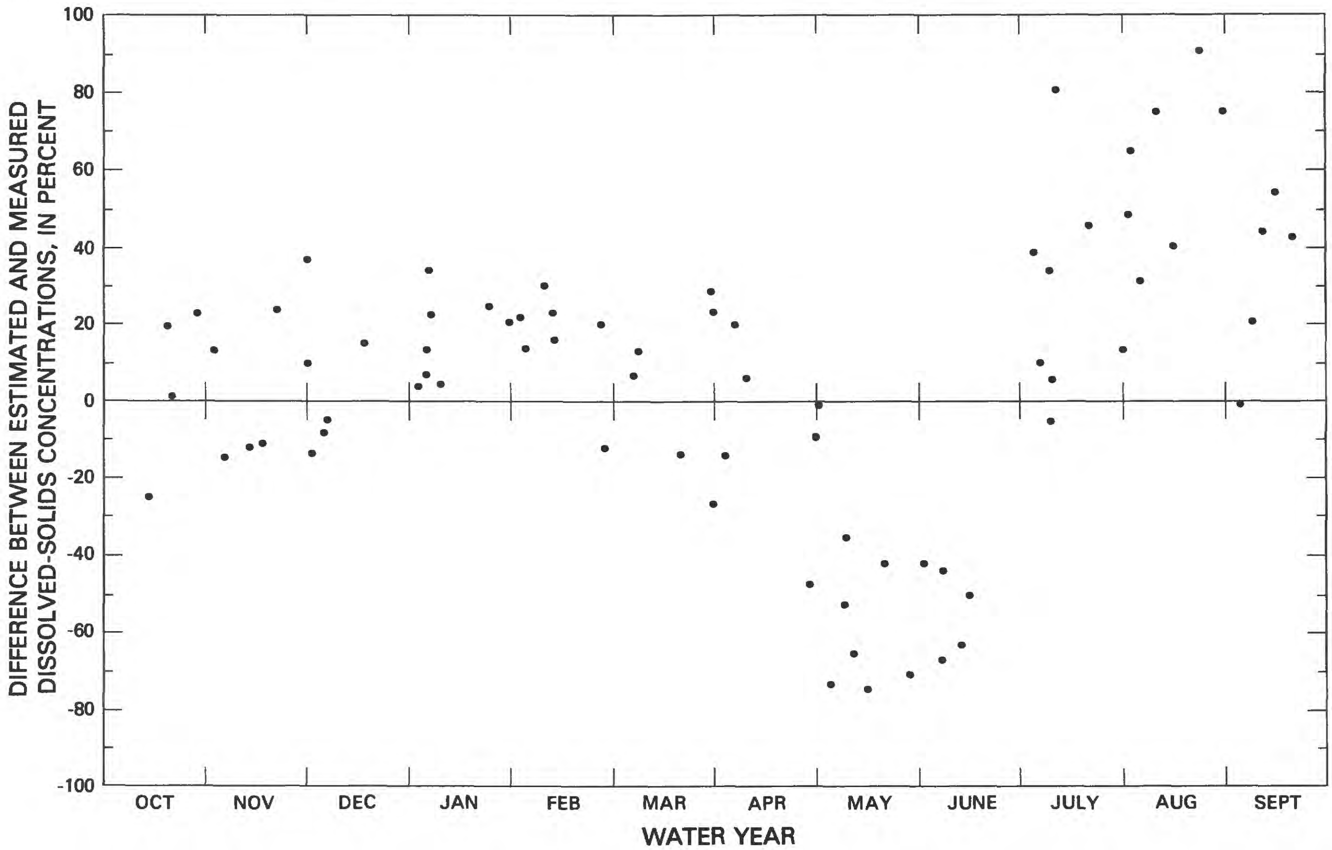


FIGURE 56.—Difference between dissolved-solids concentrations estimated from the two-variable-regression model and dissolved-solids concentrations measured at site 09188500 Green River at Warren Bridge near Daniel, Wyoming (modified from DeLong, 1977).

Equations 4, 5, and 6, in addition to equation 3, have been incorporated into a computer program to produce dissolved-solids-load hydrographs for a period of years, as shown for site 09188500 Green River at Warren Bridge near Daniel, Wyoming (fig. 58). Loads estimated at several sites in a stream can provide quantitative information about the quantity of dissolved solids gained in intervening reaches. By evaluating the chemical composition of dissolved-solids gain, the source of dissolved solids can be delineated (DeLong, 1977).

DESCRIPTION AND APPLICATION OF MATHEMATICAL ACCOUNTING MODELS

Regulatory agencies often need to assess the cumulative effects of several coal mines operating in several different tributaries that eventually flow into a mainstem stream. Parker and Norris (1983) developed a model to assess cumulative effects of mining on Trout Creek drainage and a reach of the Yampa River in Colorado. The model consists of a series of nodes on the stream network that are used to sum water quantity and quality throughout the system. Various mining plans can be inserted into the model to compare the different cumulative effects at downstream sites.

The algorithm for the model is an accounting procedure that sums water quantity and quality in monthly time steps from one or more upstream nodes to a downstream node. The model has input nodes, internal nodes, and output nodes (fig. 59). The input nodes (nodes 1, 2, and 3) are the most upstream nodes where the summation process starts. Internal nodes (nodes 4, 5, and 6) provide for input changes to the system. These changes can be point sources of water from dewatering activities or diffused sources of water such as drainage from a coal-spoil pile within the reach upstream from the node. An output node is any node at which there is a need to determine the model estimates through time and to examine differences in these estimates with various anticipated mining activities. The most downstream node (node 6 in fig. 59) usually would be an output node. If the cumulative effects of coal mining in the area upstream from nodes 4 or 5 (fig. 59) are of interest, nodes 4 or 5 also could be output nodes.

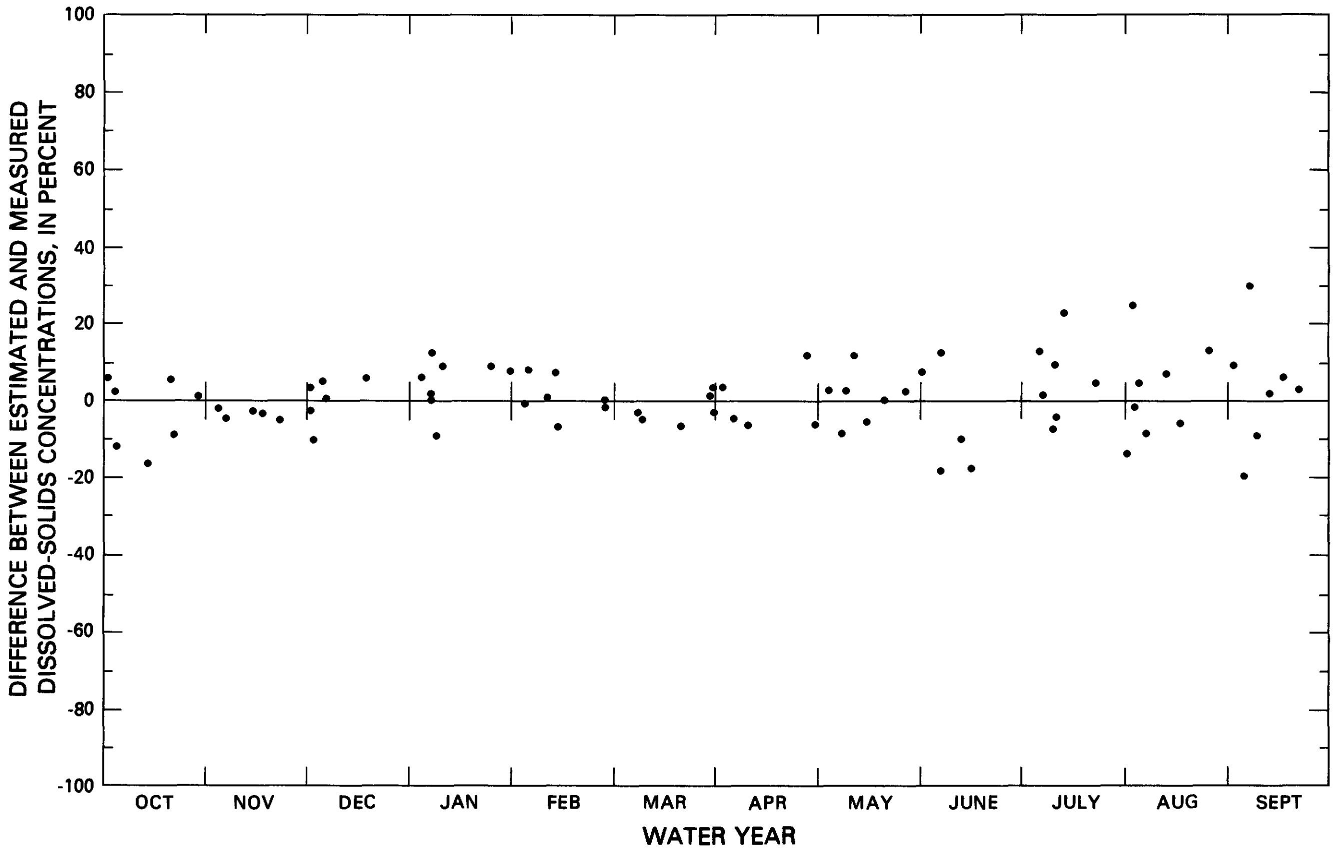


FIGURE 57.—Difference between dissolved-solids concentrations estimated from the multiple-variable-regression model and dissolved-solids concentrations measured at site 09188500 Green River at Warren Bridge near Daniel, Wyoming (modified from DeLong, 1977).

At any node, the surface-water-quantity component, which is mean monthly stream discharge in cubic feet per second, is calculated by the equation:

$$Q_i = \left[\sum_{u=1}^{n} Q_u \right] + Q_r, \tag{7}$$

where Q_i = stream discharge at node i;
Q_u = stream discharge at adjacent nodes immediately upstream from node i;
n = number of adjacent nodes immediately upstream from node i; and
Q_r = incremental stream discharge (increase or decrease) within the reach between node i and adjacent nodes immediately upstream.

The estimate of incremental stream discharge within the reach can be obtained by reading the data or by estimating the data by the equation:

$$Q_r = a + bQ_s, \tag{8}$$

where Q_r = incremental stream discharge (increase or decrease) within the reach;
a and b = the regression coefficients from simple linear regression; and
Q_s = stream discharge at some nearby streamflow-gaging sites.

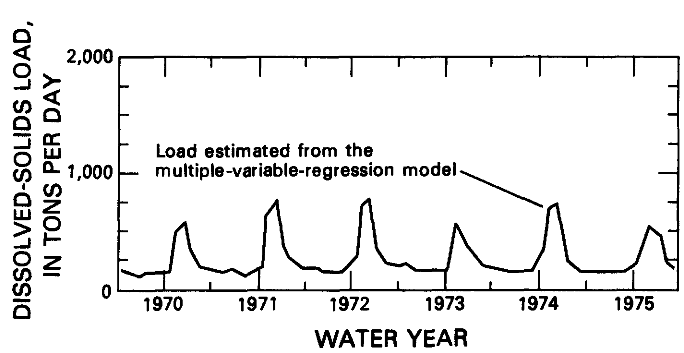


FIGURE 58.—Estimated monthly mean dissolved-solids loads at site 09188500 Green River at Warren Bridge near Daniel, Wyoming (modified from DeLong, 1977).

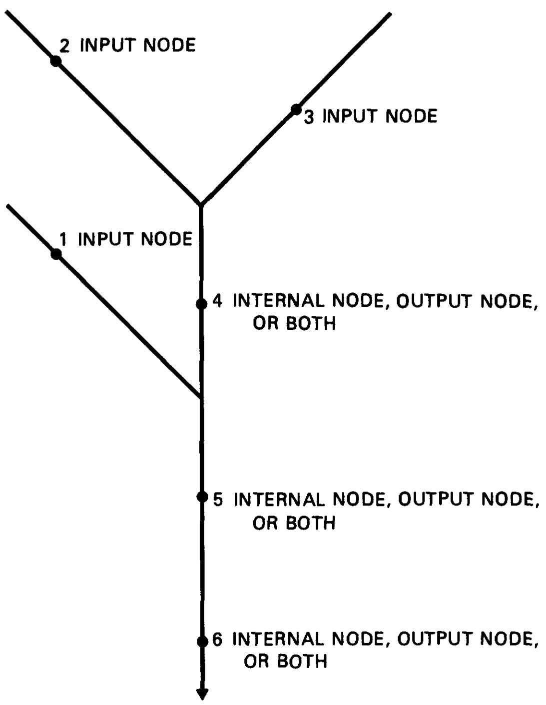


FIGURE 59.—Modified diagram of a simple stream network with nodes and node numbers for the model developed by Parker and Norris (1983).

In the model, several stream reaches have an upstream and a downstream node at a streamflow-gaging site. In these situations, Q_r could be measured directly, and measured stream-discharge data were used. In situations where measured data were not available, Q_r initially was established at zero and modified by altering the regression coefficients in equation 8 during calibration. For each anticipated mining activity, the Mined Land Reclamation Division of the Colorado Department of Natural Resources estimated the quantity of water discharging to the stream.

At each node the surface-water-quality component, mean monthly dissolved-solids concentration in milligrams per liter, is calculated by the mass-balance equation:

$$C_i = \left[\frac{(\sum_{u=1}^{n} Q_u C_u) + Q_r C_r}{(\sum_{u=1}^{n} Q_u) + Q_r} \right], \qquad (9)$$

where C_i = dissolved-solids concentration at node i;
n = number of nodes immediately upstream from node i;
Q_u = stream discharge at nodes immediately upstream from node i;
C_u = dissolved-solids concentration at nodes immediately upstream from node i;
Q_r = incremental discharge; and
C_r = dissolved-solids concentration associated with the incremental discharge within reach.

The dissolved-solids concentration within the reach (C_r) is obtained from the linear-regression equation:

$$C_r = aQ_r^b. \qquad (10)$$

Initial estimates of C_r are obtained from measured data at each node. For input nodes, the measured data indicate the actual value of C_r because C_r is the integrated dissolved-solids concentration for the total reach upstream from that node. However, for internal and output nodes, measured data do not indicate dissolved-solids concentration for the reach between nodes; they indicate an integration of dissolved-solids concentration upstream from each node. Thus, the measured data are not a direct estimate of C_r. Final estimates of the regression coefficients in equation 10 were obtained in the calibration process.

For each anticipated mining activity, the Mined Land Reclamation Division estimated dissolved-solids concentration for water discharging to the stream from the mining activity. During mining operations, the concentration of dissolved solids was 2,860 milligrams per liter for combined surface- and ground-water discharge. For postmining situations, no discharge from a surface-water source was assumed, and the dissolved-solids concentration was estimated at 3,200 milligrams per liter from a ground-water source only.

There can be instances when the stream discharge at the upstream node or nodes is greater than the stream discharge at the next node downstream. The dissolved-solids concentration can be decreased in proportion to the water quantity lost, assuming that water lost in the reach is lost to ground water and, therefore, that the water lost removes the associated dissolved solids. However, some of the dissolved solids assumed lost to ground water may remain on the bed and banks of the stream channel to be removed during the next high flow. In addition, water lost to evapotranspiration leaves the associated dissolved solids in the streamflow. To accommodate these problems, a calibration factor was added to increase the dissolved-solids concentration. This factor was adjusted during the model calibration. Thus, in a losing reach, C_i is decreased to the minimum value and adjusted upward by:

$$C_i = C_i \left[\frac{Q_i}{\sum_{u=1}^{n} Q_u} \right] E_i, \qquad (11)$$

where E_i = calibration coefficient ≥ 1.0.

Stream-discharge data that are input at the various input nodes are obtained either from continuous stream-discharge data or through various regression relations using nearby sites that have continuous stream-discharge data. For water-quality data, linear-regression equations were obtained between the logarithm of instantaneous stream discharge and the logarithm of dissolved-solids concentration. These equations were input directly into the model for each input node.

For each output node that has mean monthly stream-discharge data (either measured or extrapolated), a linear-regression equation between the logarithm of instantaneous stream discharge and the logarithm of dissolved-solids concentration, in milligrams per liter, was obtained from data available at the sites. Using these equations, a dissolved-solids concentration was obtained for each mean monthly stream discharge. Calculation of the load of dissolved solids (tons per month) was obtained from:

$$L = Q \cdot C \cdot K \cdot N_m, \quad (12)$$

where L = dissolved-solids load, in tons per month;
Q = mean monthly stream discharge, in cubic feet per second;
C = dissolved-solids concentration, in milligrams per liter at the mean monthly stream discharge;
K = 0.0027, a conversion constant; and
N_m = number of days in the month.

The calculated values for the period of record are used as the measured values and are compared to modeled values for calibration and error analysis.

Calibration of the model was made so that modeled outputs of stream discharge, dissolved-solids concentration, and dissolved-solids load closely matched measured data at the output nodes. Altered model parameters were the regression coefficients in equations 8 and 10 and the coefficient E_i in equation 11.

During calibration, an attempt was made to decrease the mean square error for each variable throughout the total 72 months the model was run (Parker and Norris, 1983). The error function uses the differences between the logarithms of measured and predicted values. The mean square error is:

$$MSE = \bar{x}^2 + s^2, \quad (13)$$

where MSE = mean square error;
$\bar{x}^2$ = square of the mean of the differences between the logarithms (base e) of measured and model prediction for each model variable for each month; and
s^2 = variance of the differences of the logarithms (base e) between the observed and model prediction for each model variable for each month.

In this equation, the first term ($\bar{x}$) is the bias from the true mean zero and the second term (s^2) is the variance. During calibration, the attempt is made to decrease the bias to zero with a minimum variance (Parker and Norris, 1983).

The calibrated model used streamflow quantity and quality in Trout Creek and the Yampa River from October 1975 to September 1981. Calibrated model output was compared to output from the model that had been perturbed by adding increased stream discharge or different dissolved-solids concentrations resulting from anticipated mining. Estimates of actual discharge of water through a mine to the receiving stream and the associated dissolved-solids concentration were provided by the Mined Land Reclamation Division of the Colorado Department of Natural Resources.

The model was run for a series of anticipated mining activities during which short-term and long-term effects were studied. Short-term effects include surface- and ground-water effects, such as discharge from sediment ponds, discharge from underground mine workings, and discharge of affected waters from shallow ground-water systems that would occur during the mining operation and for a short time following reclamation. The natural flow patterns of the effected ground-water systems are disrupted by mining, and surface and ground waters are mixed. Increased evaporation losses from the sediment ponds are assumed to be offset by increased runoff from disturbed areas.

The long-term effects of mining occur after: (1) Disturbed areas have been reclaimed successfully; (2) surface- and ground-water systems have had sufficient time to reach equilibrium; (3) sediment-control structures have been removed, and the quantity and quality of runoff from the reclaimed areas have returned to premining conditions; and (4) mine-spoils aquifers and underground mine workings have resaturated, and ground water passing through the disturbed area discharges to its premining discharge areas. The quantity of ground-water flows would equal premining quantities, but the quality would be degraded.

A comparison of modeled dissolved-solids concentration for existing conditions and for conditions associated with short-term anticipated mining at Middle Creek at mouth (node 15), is shown in figure 60. In the short-term anticipated mining, the greatest change in model variables was indicated for Middle Creek at

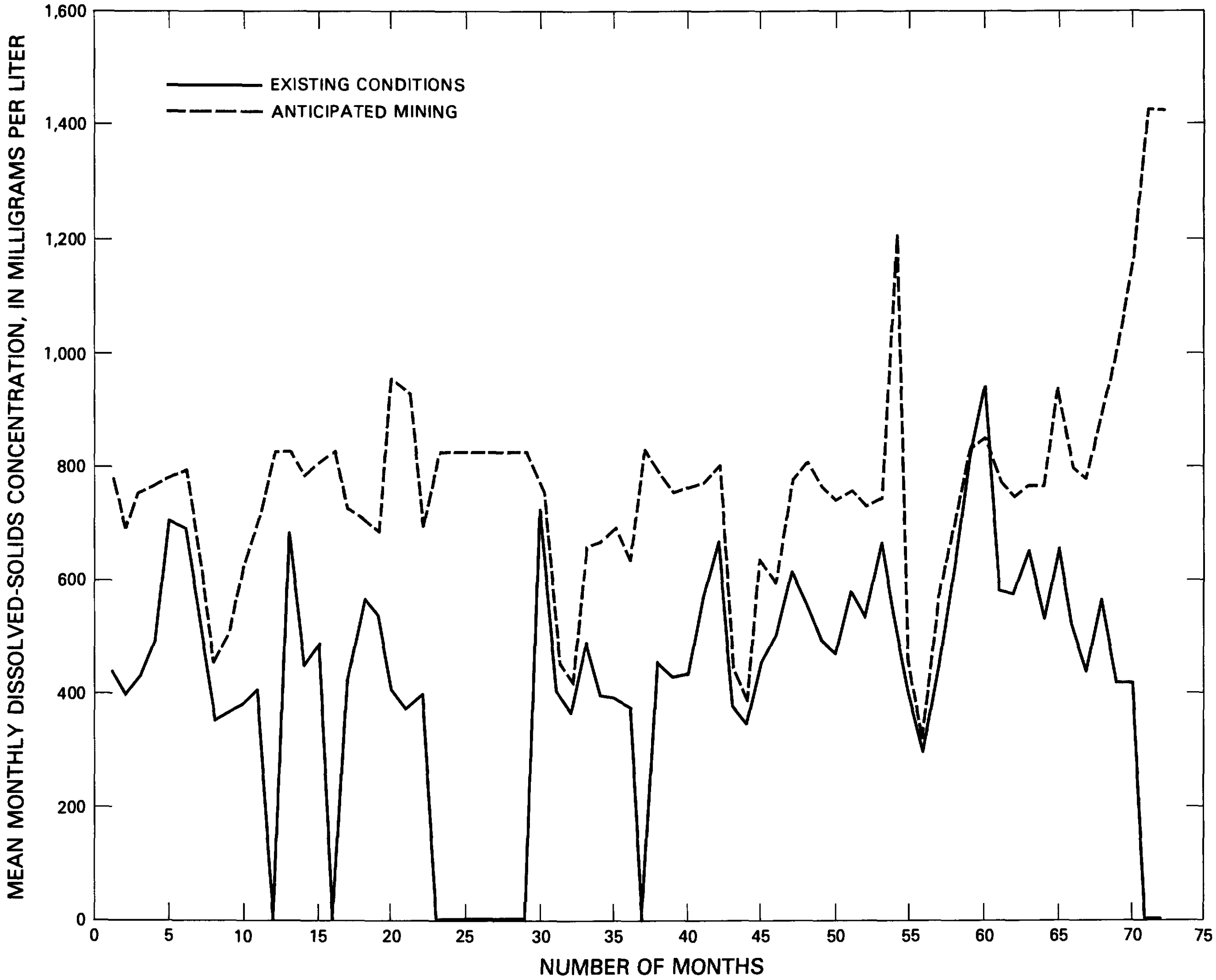


FIGURE 60.—A comparison of modeled mean monthly dissolved-solids concentrations for existing conditions and conditions associated with short-term anticipated mining at Middle Creek at mouth, node 15 (modified from Parker and Norris, 1983).

mouth (node 15) and Fish Creek (node 19). The mean stream discharge is increased by 31 percent at node 15 and decreased by 1 percent at node 19. This primarily is an indication of anticipated dewatering activities directly upstream. The mean monthly dissolved-solids concentration increases by 316 milligrams per liter at node 15 and by 98 milligrams per liter at node 19. The total monthly load of dissolved solids increases to varying degrees at all output nodes. A long-term version of this anticipated mining indicates similar increases in dissolved-solids-concentration values.

DESCRIPTION AND APPLICATION OF MATHEMATICAL ROUTING MODELS

A computer model was developed for determining dissolved-solids load in the Tongue River in Montana, to evaluate cumulative potential effects of strip mining on dissolved-solids concentration at any given number of locations in a stream (Woods, 1981). This model then was modified for use on Rosebud Creek in Montana (Ferreira, 1984). Located within the drainages of both streams are irrigated agricultural areas and several areas of Federal coal that potentially are available for leasing. The model consists of a monthly mass-balance routing of stream discharge and dissolved-solids load down the main stem of each stream and can account for dissolved-solids load coming from each mine area. The main stem of each stream is divided into several reaches. Once the locations of each reach are established as part of the model, the model user can vary the mined acreage, dissolved-solids concentrations in mine spoils, and quantity of irrigated acreage in each reach. The user then can study relative changes in the dissolved-solids concentration from mining and agriculture as they affect the water quality in each reach.

All hydraulic components are accounted for in the model in an effort to provide versatility. The mass balance of discharge between the upstream and downstream ends of each reach is computed by the equation:

$$Q_{OUT} = Q_{IN} + Q_P - Q_E - Q_{ET} + Q_{GW} + Q_T - Q_{SI} + Q_{RI} - Q_{DI} + Q_{IRF} - Q_{OL}, \quad (14)$$

where all units are in acre-feet per month, and
Q_{OUT} = stream discharge at downstream end of reach;
Q_{IN} = stream discharge at upstream end of reach;
Q_P = precipitation received on stream surface;
Q_E = evaporation loss from stream surface;
Q_{ET} = evapotranspiration from riparian vegetation;
Q_{GW} = ground-water inflow or outflow;
Q_T = discharge from tributaries;
Q_{SI} = volume of stream discharge stored as ice;
Q_{RI} = volume of stream discharge released from ice;
Q_{DI} = volume of stream discharge diverted for irrigation;
Q_{IRF} = volume of irrigation return flow; and
Q_{OL} = volume of other water losses.

The mass balance of dissolved solids between the upstream and downstream ends of each reach is computed by the equation:

$$DSL_{OUT} = DSL_{IN} + DSL_{GW} + DSL_T - DSL_{DI} + DSL_{IRF} + DSL_M - DSL_{OL}, \quad (15)$$

where all units are in tons per month, and
DSL_{OUT} = dissolved-solids load at downstream end of reach;
DSL_{IN} = dissolved-solids load at upstream end of reach;
DSL_{GW} = dissolved-solids load in ground-water inflow or outflow;
DSL_T = dissolved-solids load input by tributary streams;
DSL_{DI} = dissolved-solids load diverted by irrigation flow;
DSL_{IRF} = dissolved-solids load returned by irrigation flow;
DSL_M = dissolved-solids load input by mining; and
DSL_{OL} = dissolved-solids load removed with other water losses.

The dissolved-solids concentration at the downstream end of the reach is calculated using the following equation:

$$DSC = \frac{DSL}{Q \cdot f}, \quad (16)$$

where DSC = dissolved-solids concentration, in milligrams per liter;
DSL = dissolved-solids load, in tons per month;
Q = stream discharge, in acre-feet per month; and
f = a factor (0.00136) that converts the product of acre-feet and milligrams per liter to tons.

Other equations and factors used to calculate values for variables contained in equations 14, 15, and 16 are obtained from climatological data, ground-water data, continuous stream-discharge measurements, base-flow measurements, and channel-geometry data. Many of the same regression equations mentioned previously are used to calculate hydrologic variables for each reach. Some of these equations are incorporated in the model; others are used to calculate constant values used in the model as block data.

For Rosebud Creek, initial stream discharge and dissolved-solids concentrations are input at the downstream end of reach 1 (fig. 61). These values are affected directly by input of dissolved solids from mining and water losses from irrigation if acreage involved in these two activities is larger than what presently exists in the drainage of reach 1. The resulting values at the downstream end of reach 1 then are used as input for the upstream end of reach 2.

Within reach 2 and each successive reach, gains and losses to stream discharge and dissolved-solids load are accounted for algebraically. The model step is monthly, and each simulation is for one calendar year (fig. 62). In the model, monthly traveltime of stream discharge and dissolved-solids concentration within each reach and from the headwaters to the mouth are instantaneous.

Simulated monthly streamflow and dissolved-solids load generally were within the 95-percent confidence limits of the mean monthly values calculated for Rosebud Creek at the mouth near Rosebud, Montana. From May through September, the simulated mean monthly streamflows varied by no more than 15 percent of the historical mean values. Except for January, May, and December, the simulated mean monthly dissolved-solids loads varied by no more than 13 percent of the historical mean values.

Simulations based on mining that occurred during 1983 indicated that irrigation return flows composed

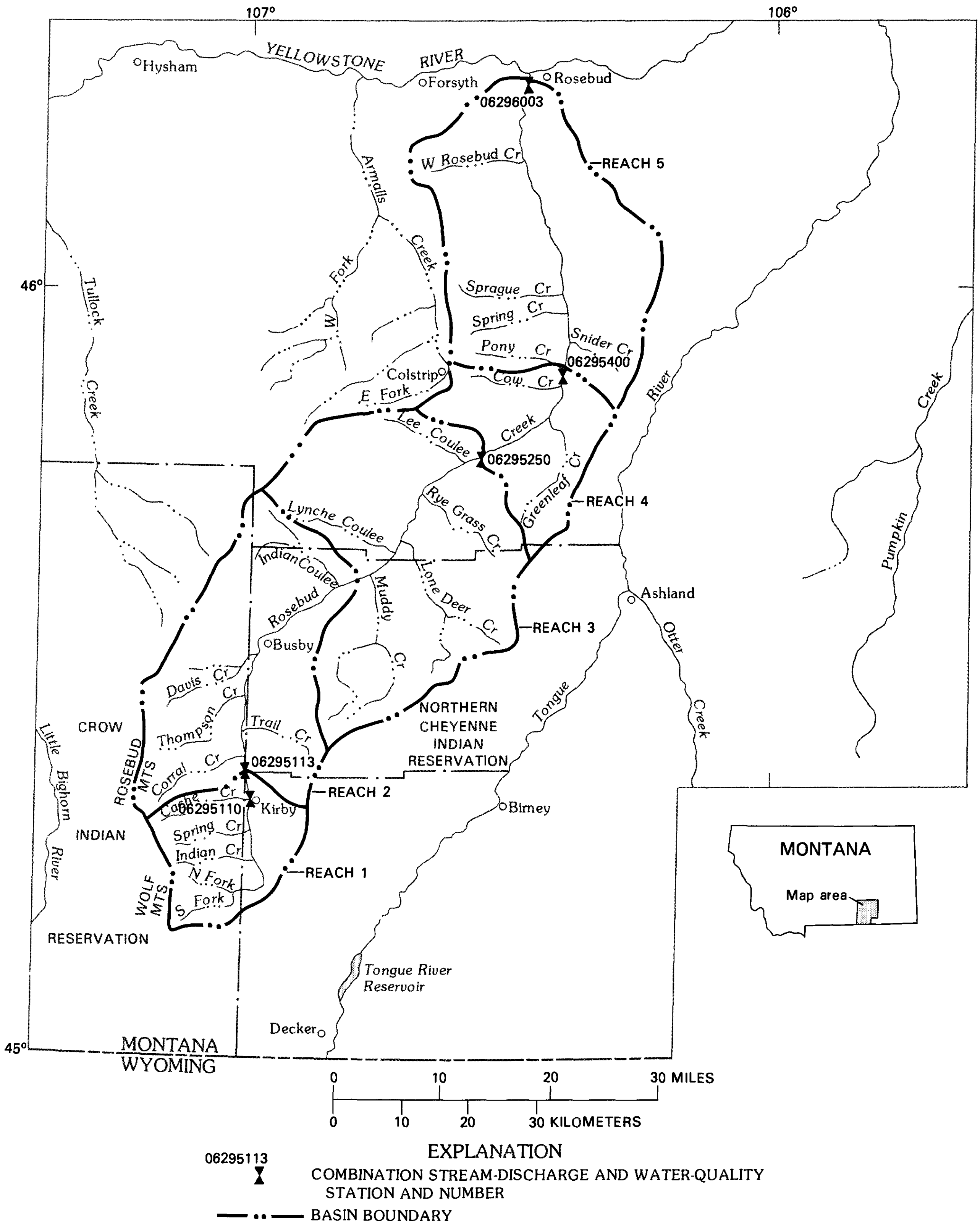


FIGURE 61.—Location of Rosebud Creek, Montana, and reaches simulated by the model developed by Woods (1981) (modified from Ferreira, 1984).

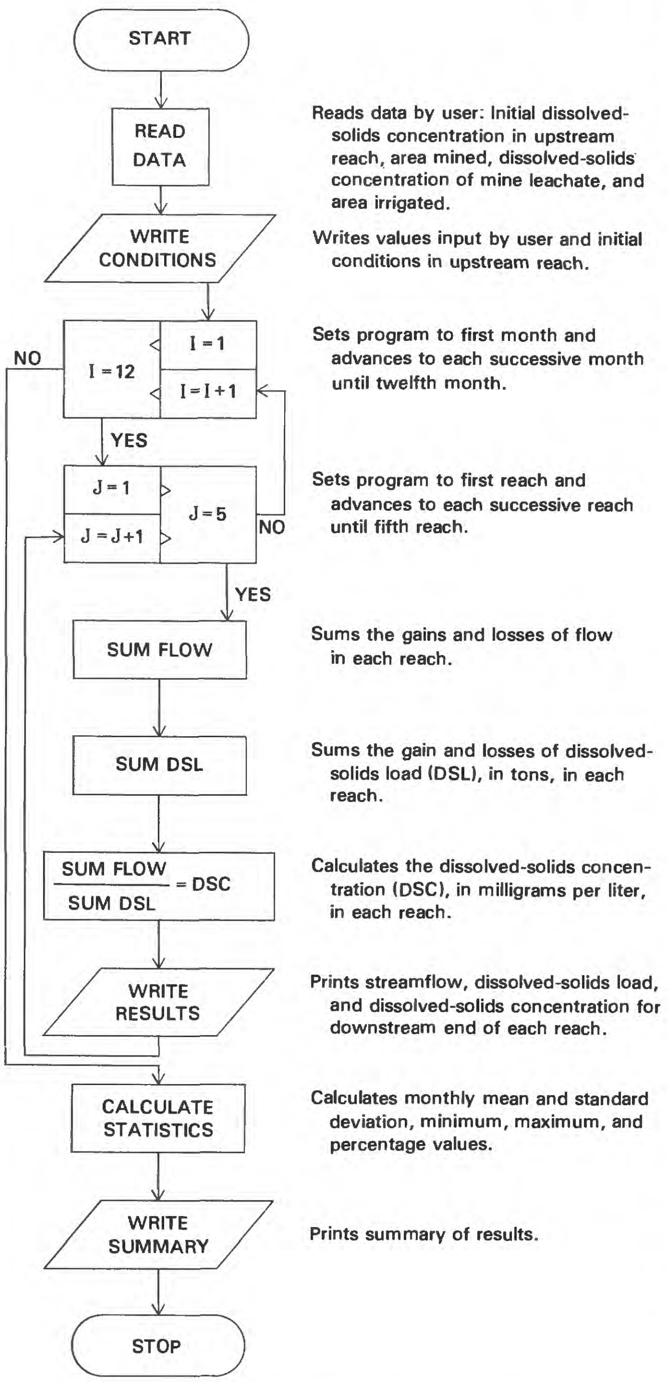


FIGURE 62.—Simplified flow chart of model for calculating monthly dissolved-solids concentration in five reaches of Rosebud Creek, Montana (modified from Ferreira, 1984).

a larger cumulative percentage of dissolved-solids concentration (about 3 percent in reach 5) than mining (about 0.4 percent in reach 5). However, when all areas are mined simultaneously, the cumulative percentage resulting from irrigation in reach 5 (2.5 percent) would be smaller than that resulting from mining (14.7 percent).

Using the Tongue River model, Woods (1981) reported that the simulated mean annual dissolved-solids concentrations would increase by 4.8 percent if all potentially available, federally owned coal were mined. Even with this increase, the dissolved-solids concentration in the Tongue River still would be suitable for irrigation supply (Woods, 1981).

DISCUSSION

All models could be improved with more data. However, budget and time constraints would make some additional data collection impractical. For single-equation models, additional data that indicate extreme hydrologic events or additional variables such as the time factor used by DeLong (1977) could be beneficial in evaluating the effects of mining. For the more complex models, better estimates of mine-derived dissolved-solids load added to the stream, and more accurate delineation of reaches receiving this load would improve the prediction capabilities of the model.

Presently (1985), dissolved-solids loads from mined areas are estimated from water-quality changes measured in mine spoils. Mine-spoil water-quality changes do not account for chemical changes that could occur enroute from the mine to the stream. The stream reaches generally defined as those receiving ground-water flow from a mined area are located on a straight line downgradient from the mine. However, because ground water could be moving downgradient through the alluvium but parallel to the streamflow for some distance before entering the stream, the actual reaches receiving the dissolved-solids load could be different from those specified in each model. Depending on where different mines are located, actual flow paths of mine-spoil water could make a considerable difference when predicting accumulated effects of mining in a given area.

SHALLOW AND DEEP GROUND-WATER FLOW SYSTEMS

By MICHAEL R. CANNON

The ground-water flow system within a drainage basin is composed of a continuous series of ground-water flow paths that originate in areas of ground-water recharge and terminate in areas of discharge. Ground-water flow systems largely are controlled by the topography of the basin and the hydraulic conductivity of the porous soils and rocks through which ground water moves. The topography of the basin establishes the potential energy available to a unit mass of water as it moves from a recharge area in the higher part of the basin to a discharge area in the lower part. The hydraulic conductivity establishes the rate at which a volume of ground water will move through an area of porous soils and rock when affected by the hydraulic gradient (gradient of potential energy).

A typical ground-water basin may contain several aquifers and confining beds and ground-water flow paths of many lengths (fig. 63). Toth (1963) suggested that ground-water flow systems can be classified into three types: (1) A local flow system, which has its recharge area at a topographic high and its discharge area at an adjacent topographic low; (2) an intermediate flow system, which is characterized by one or more topographic highs and lows located between its recharge and discharge areas; and (3) a regional flow system, which has its recharge area at the major topographic high and its discharge area at the bottom of the basin.

The subdivision of ground-water flow into local, intermediate, and regional flow systems is somewhat arbitrary. The size of an area studied often determines how a hydrologist will categorize the flow systems observed in the study area. For instance, in a study of the entire Mississippi River basin, a certain flow system may be designated as a local system, whereas in a study of a small tributary basin to the Mississippi River, the same ground-water flow system may be designated as an intermediate system. For the purposes of this report, local flow systems are those that actively circulate ground water and rapidly respond to changes in rates of recharge and discharge. Local flow systems have relatively short traveltimes, transport a large part of the ground water within a basin, and usually provide most of the base flow to small streams and rivers. Because of their shallow depth and active circulation of ground water, local flow systems are most easily affected by coal-mining activities.

Intermediate flow systems have relatively slow rates of flow and long flow paths but respond faster than regional flow systems to long-term changes in recharge or discharge. Discharge from intermediate flow systems usually is to the medium-sized and largest streams in the basin. Coal-mining activities, such as mine-pit dewatering, can affect intermediate flow systems by decreasing available recharge or increasing discharge from aquifers near the mine pit. Decreases in water levels in an aquifer containing intermediate flow systems generally are small but can have widespread and long-term effects.

Regional flow systems have slow, deep circulation of ground water, have the longest flow paths in the basin, and react slowly to changes in recharge and discharge. Regional flow systems generally contain a vast volume of water in storage but discharge this water slowly as base flow to large rivers or to coastal areas. Water in regional flow systems commonly is more mineralized than water in shallow, local flow systems because of the

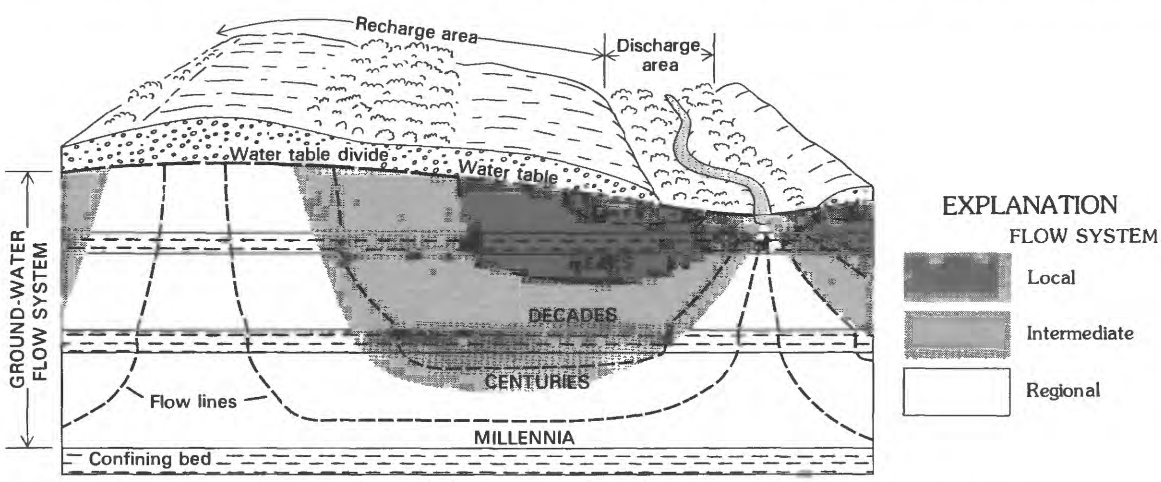
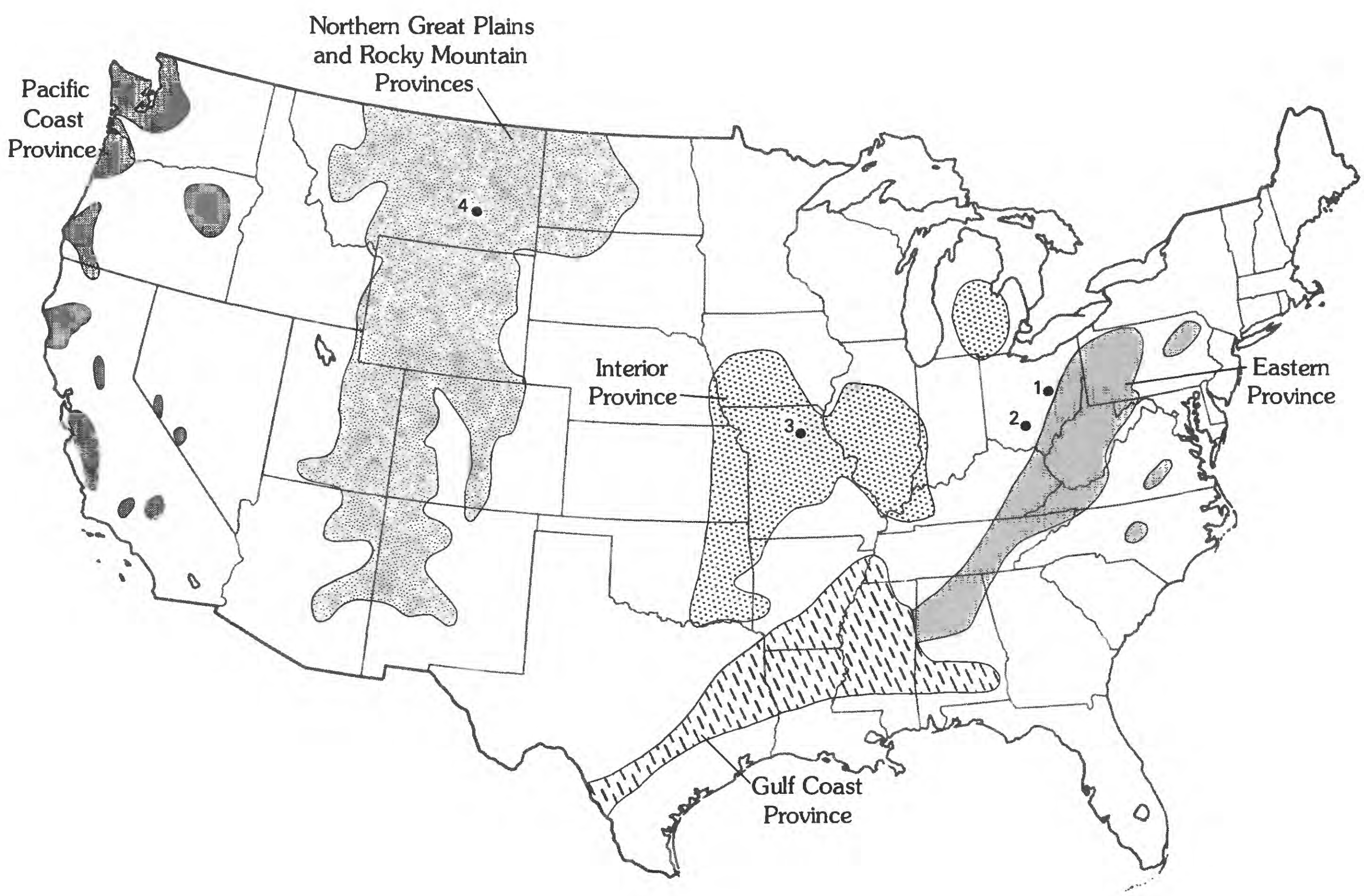


FIGURE 63.—Ground-water flow system of a typical drainage basin (modified from Heath, 1983).

long residence time and long flow paths of the regional flow system. Because of their great depth of flow, large volume of water in storage, and slow rate of flow, effects of coal mining on regional flow systems generally are not severe or are not observed unless the flow system is stressed for a long period of time.

STUDIES OF EFFECTS OF MINING ON GROUND-WATER FLOW SYSTEMS

The U.S. Geological Survey, as part of its coal-hydrology program, has invested considerable time and effort in studying the effects of the surface mining of coal on ground-water systems. Studies have been made in almost all States where coal is mined by surface methods. Studies range from assessments of basic effects such as aquifer dewatering and water-level declines in wells, to detailed studies of the hydraulic properties of mined areas and observed changes in local and regional flow systems. To illustrate how the surface mining of coal can affect the ground-water hydrology of a basin, mine-site studies made by the U.S. Geological Survey are presented for three different coal provinces (fig. 64).



EXPLANATION

4● MINE-SITE STUDY AREA AND SITE NUMBER

1 Jefferson County, Ohio
2 Muskingum County, Ohio
3 Macon-Huntsville area, Missouri
4 West Decker, Montana

FIGURE 64.—Coal provinces and location of selected mine-site study areas.

EASTERN PROVINCE, NORTHERN APPALACHIAN REGION—EASTERN OHIO

Several small watersheds in eastern Ohio were studied to assess the effects of the surface mining of coal on the hydrologic systems (fig. 64) (Helgesen and Razem, 1981; Razem, 1983, 1984; Weiss and Razem, 1984). One of the study sites was a 29-acre watershed in Jefferson County that was drained by a perennial stream. The premining watershed was underlain by nearly flat-lying interbedded shale, sandstone, limestone, and coal of the Pennsylvanian and Permian Systems. Shaly underclay beds below two major coal seams formed bases for two perched aquifers (fig. 65). The perched aquifers represented local flow systems.

Recharge to the upper perched aquifer was from local precipitation, and discharge was to springflow, seepage, and evapotranspiration near the coal outcrop. Additional discharge from the upper perched aquifer was to leakage through the underclay. Recharge to the lower perched aquifer was from leakage from the overlying perched aquifer and from direct infiltration of precipitation where the upper clay layer was absent. Water in the lower perched aquifer moved from the recharge area near the basin divide toward the discharge area at the mouth of the basin. Additional discharge was to leakage through the clay at the base of the aquifer where it eventually was drained through the mined Pittsburgh No. 8 coal bed.

During mining of the upper coal bed (Waynesburg No. 11 coal bed in fig. 65), water levels in the two perched aquifers declined abruptly. Springflow from the top aquifer, which supplied base flow to the stream, decreased and eventually ceased completely (Razem, 1984). By the time mining was completed, most of the upper perched aquifer had been removed and replaced by mine spoils that were regraded to approximate the premining topography.

Wells installed in the mine spoils initially were dry, but most indicated a saturated thickness of 3 to 4 feet after 1½ years. In the part of the upper perched aquifer not removed by mining, water levels did not recover to premining levels because of improved drainage of the aquifer toward the mined area. In the second perched aquifer, which was not mined, water levels were as much as 40 feet higher than premining levels. The higher water levels were the result of the removal or disturbance of the clay layer during mining and the resultant increased leakage from the mine spoils to the lower aquifer.

Surface mining of the upper coal bed had several effects on the local ground-water flow. The rate of infiltration of precipitation into the mine spoils seemed to be less than infiltration rates to the undisturbed basin. The

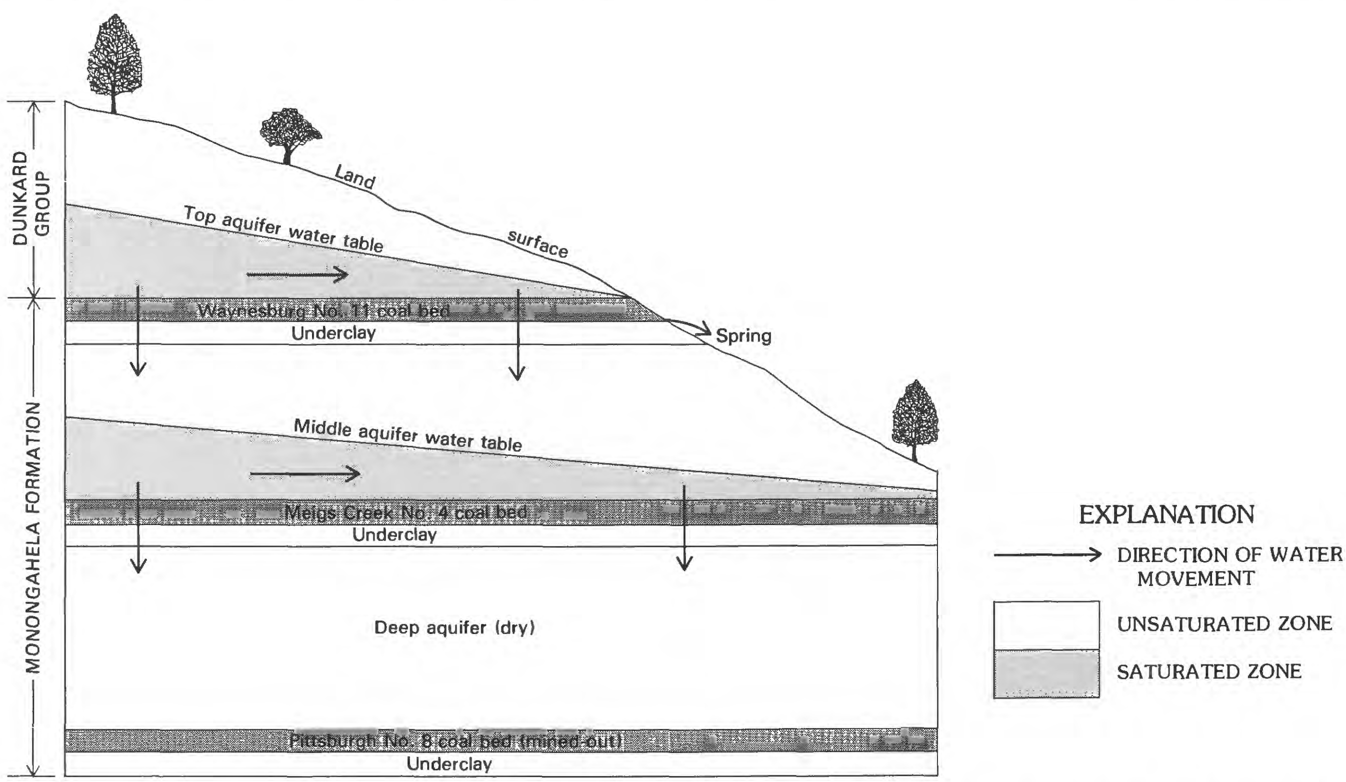


FIGURE 65.—Schematic section of ground-water occurrence and flow at a watershed in Jefferson County, eastern Ohio (from Razem, 1984).

decrease was caused by the destruction of the soil structure and compaction of the soil overlying the mine spoils. Discharge from the upper aquifer decreased in volume, and the upper aquifer no longer discharges to springs or seeps. Discharge from the upper aquifer (now a spoils aquifer) occurs as downward leakage into the lower perched aquifer. The mine spoils also had a larger hydraulic conductivity and storage than the premining bedrock aquifer.

Similar geologic conditions and effects of mining on ground-water flow systems were observed at a 43-acre watershed in Muskingum County, Ohio (fig. 64) (Weiss and Razem, 1984). The premining watershed was characterized by nearly flat lying sedimentary rocks of the Pennsylvanian System. Underclay beneath the two major coal beds formed bases for perched ground-water flow systems, producing three separate aquifers underlying the watershed. Mining in the basin removed the upper coal bed and the top perched aquifer and replaced the bedrock with spoil material. Water levels in the spoils are at a much lower altitude than existed in the premining aquifer because of a larger hydraulic conductivity in the spoils, areal variations of the hydraulic characteristics of the confining bed, and a slower rate of recharge from precipitation caused by removal of vegetation and compaction of topsoil. Recharge to the middle aquifer decreased by 25 percent because of decreased leakage from the overlying aquifer and less recharge from precipitation than in the premining basin. Discharge from both the upper and lower perched aquifers decreased following mining, and springs fed by discharge from the upper perched aquifer were transformed to a zone of seeps.

INTERIOR PROVINCE, WESTERN REGION—MACON-HUNTSVILLE AREA, MISSOURI

The Macon-Huntsville area of north-central Missouri (fig. 64) has been the site of extensive coal mining since the late 1800's (Hall and Davis, 1986). Almost all coal produced there since the mid-1960's has been mined by surface methods. Because of the hilly topography of the area, contour mining is the most commonly used mining method; overburden is removed in successive strips that follow the contour of the land surface. Spoils are placed in strips in the mined-out areas as the mining operation advances (fig. 66). Highwall lakes, which occupy the last mine cut, are a characteristic feature of the mined area after reclamation or abandonment.

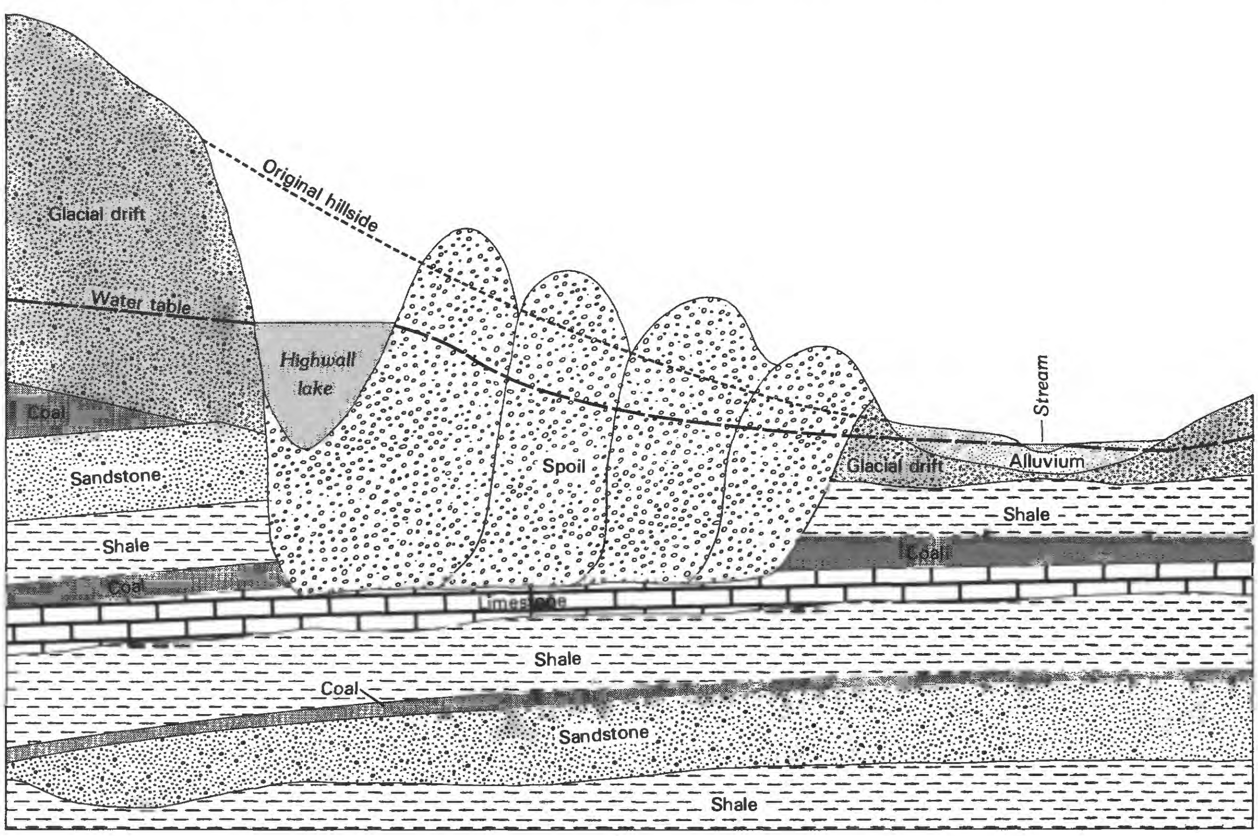


FIGURE 66.—Generalized hydrogeologic section through an abandoned surface mine, Macon-Huntsville area, Missouri (modified from Hall and Davis, 1986).

Shallow aquifers of the area occur within alluvium, glacial drift, and bedrock. The bedrock is of Pennsylvanian age and is composed of shale, limestone, sandstone, and coal. Recharge to the shallow alluvial aquifer occurs by infiltration of precipitation and by lateral and probably vertical flow from adjacent aquifers. Recharge to glacial drift occurs by infiltration of precipitation and lateral flow from adjacent aquifers. Based on a ground-water flow model, a possible range of annual recharge to glacial drift is 0.2 to 5.2 inches. Recharge to bedrock aquifers probably occurs by infiltration of precipitation and vertical flow from glacial drift. The rate of recharge to bedrock is unknown but probably is small. Natural discharge from the shallow-bedrock and glacial-drift aquifers generally is to alluvium along the stream valleys; discharge from alluvium generally is to streams.

Aquifers have developed in the mined areas where coal and overburden have been replaced with mine spoils consisting of a heterogeneous mixture of glacial drift and broken bedrock. Recharge to the spoils aquifer is from precipitation and lateral and vertical flow from adjacent aquifers, although precipitation probably is the major source of recharge. The spoils are fairly permeable and generally more permeable than the alluvial, glacial-drift, and bedrock aquifers; the potential rate of infiltration ranges from 0.2 to 0.6 inch per hour.

Long-term effects of surface mining on the shallow flow systems primarily result from the replacement of glacial drift and bedrock with more permeable spoils. The porosity of the spoils also is greater than the porosity of the undisturbed overburden materials. The greater porosity and permeability have resulted in greater rates of recharge to mine-spoil aquifers than to nonmined aquifers of the area.

NORTHERN GREAT PLAINS AND ROCKY MOUNTAIN PROVINCES—WEST DECKER, MONTANA

The West Decker Mine in Montana (fig. 64) produces more than 5 million tons of coal per year from the combined Anderson-Dietz 1 coal beds in the Tongue River Member of the Paleocene Fort Union Formation. The principal shallow coal aquifer in the area is the Anderson-Dietz 1 coal aquifer (Davis, 1984b). Other shallow aquifers are the Dietz 2 coal aquifer, clinker-and-alluvium aquifer, and mine-spoils aquifer (fig. 67). Important factors affecting the hydrologic regime of the West Decker Mine area are the semiarid climate that limits the available recharge, the very permeable clinker beds that provide maximum infiltration from the limited recharge, and the location of the mine near the Tongue River valley that is a major discharge area for ground-water flow systems.

The Anderson-Dietz 1 coal aquifer is about 50 feet thick in the West Decker area and is a source for stock and domestic water supplies. Recharge to the Anderson-Dietz 1 coal aquifer is by infiltration of precipitation, by upward leakage from the Dietz 2 coal bed, and by lateral flow from aquifers north and west of the mine site. A large part of recharge to the ground-water system is from infiltration of precipitation in areas of outcropping clinker (Davis, 1984a). Natural discharge from the Anderson-Dietz 1 coal aquifer primarily is to the Tongue River or to alluvium and clinker in the Tongue River valley (fig. 67). The West Decker Mine is located in the discharge area of an intermediate or regional flow system; some of the water discharging from the Anderson-Dietz 1 coal aquifer may originate as recharge in the topographic highs 10 to 15 miles west of the mine.

Mining of the Anderson-Dietz 1 coal bed has caused water levels to decline in shallow aquifers near the mine and has modified the location of the discharge area for the coal aquifer. After 1 year of mining, water levels in the Anderson-Dietz 1 coal aquifer had declined more than 50 feet at the mine pit, about 20 feet within ¼ mile north, west, and south of the mine, and 10 feet or more at a distance of 1½ miles southwest of the mine (Van Voast, 1974). After 3 years of mining, the cone of depression caused by the mine pit had extended farther to the north, south, and west of the mine. Water-level declines of about 3 feet were measured during 1 year of observation at a well more than 2 miles west of the mined area (Van Voast and Hedges, 1975). East of the mine, water-level declines were much less extensive because of recharge induced from the Tongue River Reservoir and nearby alluvium and clinker. In the area east of the mine, the ground-water gradient reversed, and ground water now flows from the river toward the mine. Water levels in wells completed in the unmined Dietz 2 coal aquifer also declined as a result of increased vertical leakage upward to the Anderson-Dietz 1 coal bed.

Placement of overburden material behind the advancing mine pit has created a spoils aquifer composed of a rubble zone at the base of the spoils that generally is confined by relatively impermeable clay in the overlying spoils. Therefore, recharge to the spoils primarily occurs as lateral flow from the Anderson-Dietz 1 coal aquifer, and infiltration of precipitation is not considered substantial. The spoils aquifer has an average hydraulic conductivity of 2.8 feet per day, a median hydraulic conductivity of 1.8 feet per day, and an effective porosity of 0.4 percent (Davis, 1984b). The hydraulic conductivity of the spoils aquifer is somewhat smaller than the hydraulic conductivity of local coal aquifers, which have an average hydraulic conductivity of 5.2 feet per day and a median hydraulic

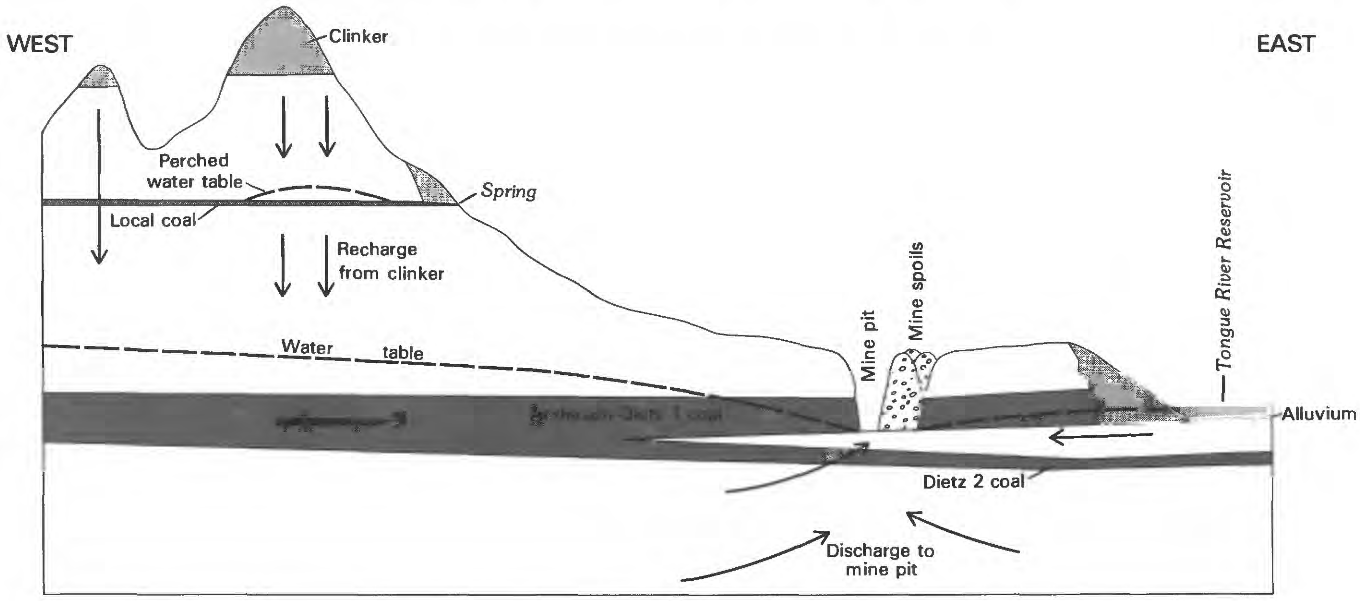


FIGURE 67.—Generalized hydrogeologic section, West Decker Mine, Montana.

conductivity of 2.2 feet per day. The effective porosity of the spoils aquifer is very similar to that of the coal aquifers, which have an effective porosity of at least 0.3 percent.

SUMMARY OF EFFECTS OF SURFACE MINING ON GROUND-WATER FLOW SYSTEMS

Hydrologic studies of surface-mine sites have indicated that surface mining of coal almost invariably has some effect on the flow of ground water at or near the mine site. Because surface mining alters the land surface only to relatively shallow depths, the mining primarily affects local flow systems within shallow aquifers. Decreases in water levels in an aquifer containing intermediate flow systems generally are small but can have widespread and long-term effects. Regional flow systems can be affected by mining; however, effects on water levels or flow rates within regional flow systems generally are not severe or are not observed unless the flow system is stressed for a long period of time.

The effects of surface coal mining on ground-water systems can be classified into short-term effects, those that occur during mining and reclamation operations, and long-term effects, those that are permanent or continue long after final reclamation. The most common short-term effects of surface coal mining on ground water include dewatering of shallow aquifers, decreases in discharge to springs and small streams, and lowering of water levels in wells. These short-term effects generally dissipate, at least in part, after mining is completed and local flow systems become reestablished within the mined area.

Long-term effects of surface mining include the destruction of springs and shallow aquifers, alteration of recharge rates, some local decreases in static water levels, and changes in the rate and direction of ground-water flow. Long-term effects almost always are caused by the replacement of overburden materials with spoils materials that have considerably different hydraulic characteristics than the original overburden. The change in the shape of the land surface after mining also contributes to long-term changes in the location of ground-water recharge and discharge.

GEOCHEMISTRY OF MINE SPOILS

By Robert E. Davis

Surface mining of coal entails removal of overburden, the material above the coal, generally in successive furrows or strips. After the initial strip or cut is removed, the broken and mixed overburden is placed in a previous cut. In some areas, the overburden or coal, or both, are aquifers. These aquifers are destroyed by mining. However, the replaced overburden, called mine spoils, may become saturated, thus producing a new aquifer. At some surface coal mines, the last cut may be left open and eventually may fill with water, forming a highwall or final-cut lake.

One of the potential hydrologic effects of surface coal mining is a change in the quality of ground water associated with the saturated mine spoils from premining conditions. The effects vary between mine areas and are dependent on the geochemical processes that predominate in an area. These processes are dependent on the source and quality of recharge to the spoils, the mineralogy of the spoils, and the biological activity in the spoils.

A number of studies of the geochemical processes related to mine-spoils aquifers have been done in the central and western United States. The studies summarized in this report were done in Montana (Davis, 1984b), Colorado (Williams and Hammond, 1988), Oklahoma (Slack, 1983), and Missouri (Hall and Davis, 1986). Locations of the major coal provinces and selected mine-spoils study areas are shown in figure 68. The effects of surface mining generally observed in these studies include increases in the concentrations of dissolved solids and certain trace elements. Acidic pH values, generally associated with coal mining in some parts of the eastern United States, were not observed.

GENERAL GEOCHEMICAL PROCESSES

The geochemical processes that result in the observed changes in chemical composition of ground water in the mine spoils initially occur in the soil zone and unsaturated zone. During periods of infiltration of rain or snowmelt, carbon dioxide gas (CO_2) from the atmosphere and organic decay reacts with the infiltrating water (H_2O) forming carbonic acid (H_2CO_3):

$$CO_2 + H_2O \rightleftharpoons H_2CO_3. \qquad (17)$$

The resulting acid dissociates and results in the formation of bicarbonate ions (HCO_3^-), carbonate ions (CO_3^{2-}), and hydrogen ions (H^+):

$$H_2CO_3 \rightleftharpoons H^+ + HCO_3^-, \qquad (18)$$

$$HCO_3^- \rightleftharpoons H^+ + CO_3^{2-}. \qquad (19)$$

The effect of these reactions is a slight increase in the concentrations of bicarbonate and carbonate and the production of a slightly acidic environment that is conducive to dissolution of carbonate minerals such as calcite ($CaCO_3$) and dolomite [$CaMg(CO_3)_2$]:

$$CaCO_3 + H^+ \rightleftharpoons Ca^{2+} + HCO_3^- \qquad (20)$$

$$CaMg(CO_3)_2 + 2H^+ \rightleftharpoons Ca^{2+} + Mg^{2+} + 2HCO_3^-. \qquad (21)$$

Reactions 20 and 21 result in an increase in the concentrations of calcium (Ca^{2+}), magnesium (Mg^{2+}), and bicarbonate ions and a decrease in the concentration of hydrogen ions.

The slightly acidic environment resulting from reactions 18 and 19 also can cause hydrolysis of feldspar minerals, such as anorthite ($CaAlSi_2O_8$), albite ($NaAlSi_3O_8$), and microcline ($KAlSi_3O_8$), and the formation of clay minerals such as kaolinite [$Al_2Si_2O_5(OH)_4$]:

$$CaAlSi_2O_8 + 2H^+ + H_2O \rightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+}, \qquad (22)$$

$$2NaAlSi_3O_8 + 2H^+ + 9H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 4H_4SiO_4 + 2Na^+, \qquad (23)$$

$$2KAlSi_3O_8 + 2H^+ + 9H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 4H_4SiO_4 + 2K^+. \qquad (24)$$

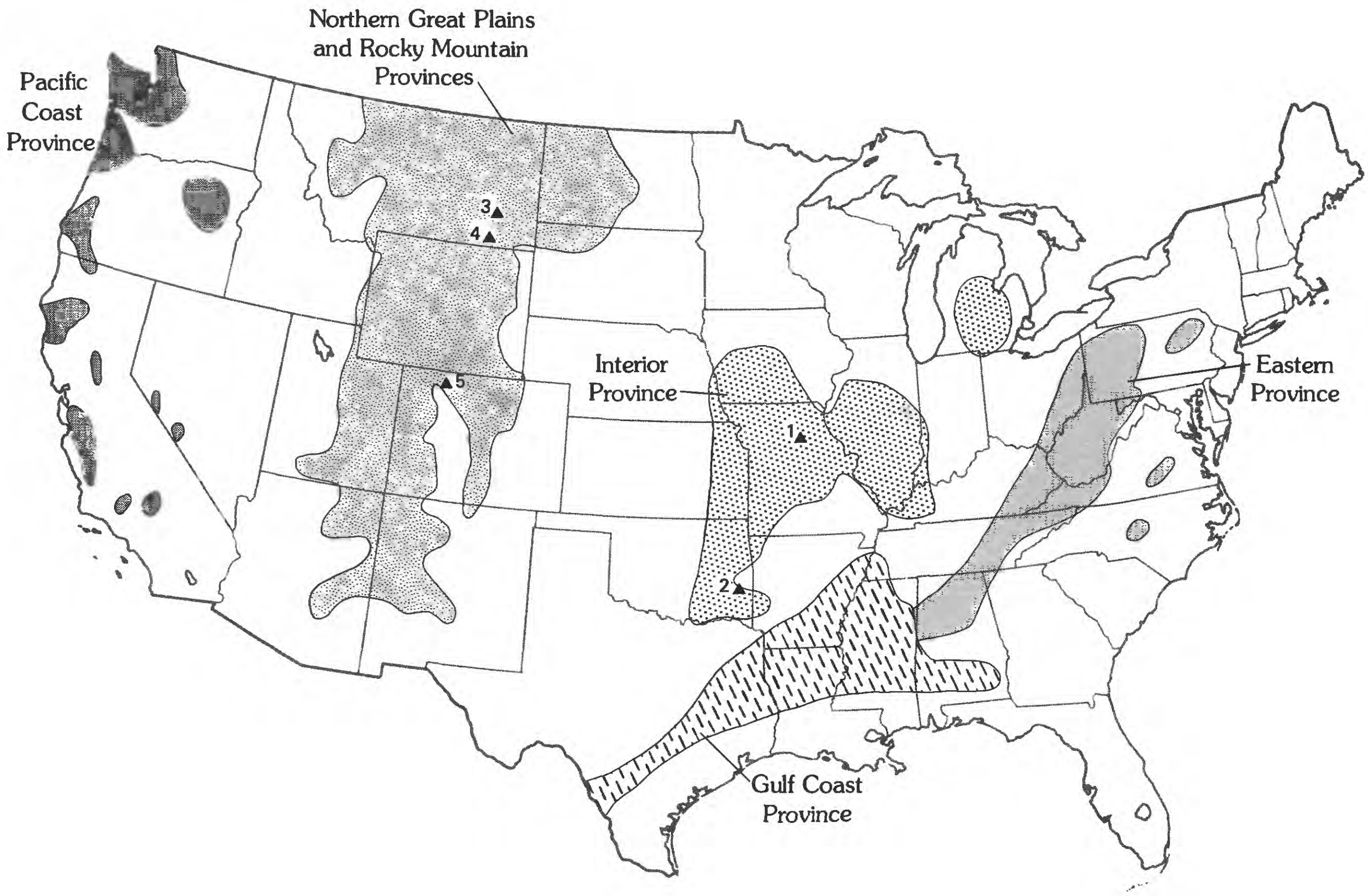
The result of reactions 22, 23, and 24 is an increase in the concentrations of calcium (Ca^{2+}), sodium (Na^+), and potassium (K^+) and a decrease in the concentration of hydrogen ions. However, in a system containing carbonate minerals, reactions 22, 23, and 24 probably do not have a large effect on the system.

Sulfate ions (SO_4^{2-}) may be added to solution as a result of oxidation of sulfide minerals such as pyrite (FeS_2) or by dissolution of sulfate minerals such as gypsum ($CaSO_4 \cdot 2H_2O$):

$$FeS_2 + 15O_2 + 14H_2O \rightleftharpoons 4Fe(OH)_3 + 8SO_4^{2-} + 16H^+, \qquad (25)$$

$$CaSO_4 \cdot 2H_2O \rightleftharpoons Ca^{2+} + SO_4^{2-} + 2H_2O. \qquad (26)$$

The oxidation process may be catalyzed by sulfur-oxidizing bacteria such as *Thiobacillus ferroxidans*,



EXPLANATION

4▲ MINE AREA—Numeral corresponds to mine areas in the following list

1 Abandoned mines, Missouri
2 Abandoned mine, Oklahoma
3 Big Sky Mine, Montana
4 West Decker Mine, Montana
5 Seneca Mine, Colorado

FIGURE 68.—Coal provinces and location of selected mine-spoils study areas.

Ferrobacillus ferroxidans, and *Thiobacillus thioxidans*. The source of oxygen (O_2) in reaction 25 probably is atmospheric. The sulfate ions produced in reaction 25 either are transported in solution to the aquifer or are precipitated as gypsum, probably as a result of evapotranspiration. The precipitated sulfate minerals may be dissolved later and transported to the aquifer by deeply percolating recharge water. The hydrogen-ion concentration or acidity resulting from reaction 25 is buffered by additional dissolution of carbonate minerals and feldspar minerals, if present, as in reactions 20, 21, 22, 23, and 24. Consequently, concentrations of calcium, magnesium, sodium, potassium, and bicarbonate may be increased.

Adsorption and ion-exchange reactions also may be important processes in soil and in unsaturated and saturated zones. Generally, the most prevalent reaction involves calcium and sodium and may be expressed as:

$$Na_2X + Ca^{2+} \rightleftharpoons CaX + 2Na^+ , \quad (27)$$

where X represents the solid-host species, such as a clay mineral or organic material. If proceeding from left to right, reaction 27 results in an increase in sodium concentration and a decrease in calcium concentration, which forces additional dissolution of carbonate minerals to maintain equilibrium. Magnesium and potassium also may be involved in reactions similar to reaction 27.

During anaerobic conditions, sulfate may be reduced to sulfide by bacteria:

$$SO_4^{2-} + 2CH_2O \text{ (organic material)} \xrightarrow[\text{bacteria}]{\text{sulfate-reducing}} HS^- + HCO_3 + H_2O + CO_2. \quad (28)$$

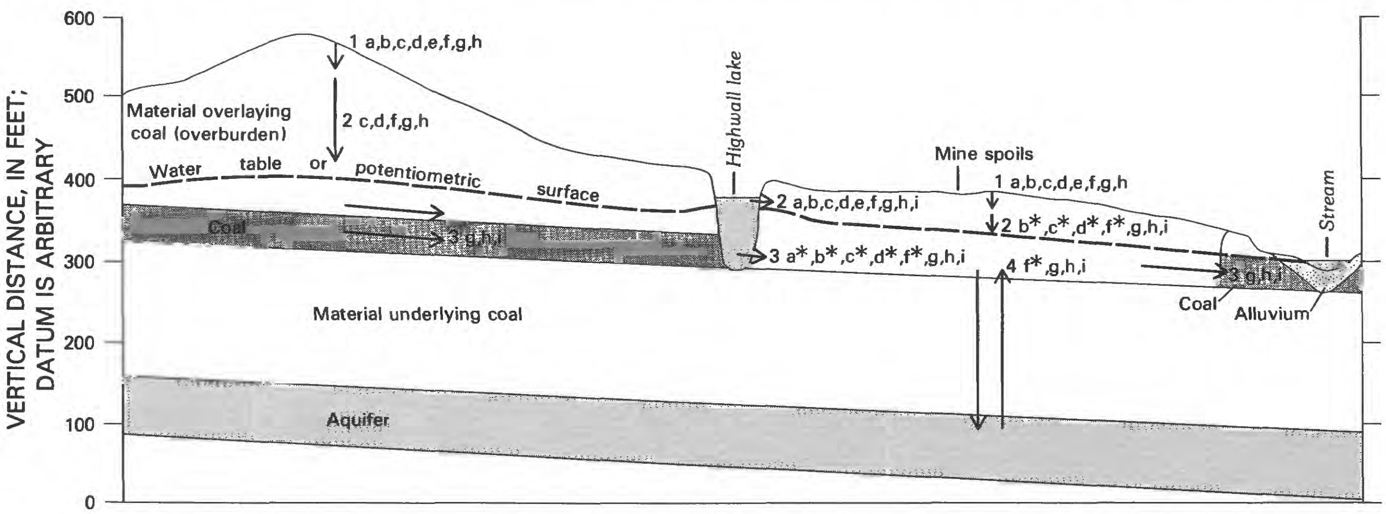
Sulfate-reducing bacteria *Desulfovibrio desulfuricans* are known to exist in at least some coal-mining areas (Dockins and others, 1980). Reaction 28 results in a decrease in sulfate concentration and an increase in bicarbonate concentration.

The reactions above illustrate the general geochemical processes that may occur in the mine spoils; therefore, ground water in the mine spoils primarily will contain some combination of calcium, magnesium, sodium, potassium, bicarbonate, and sulfate ions. The concentrations and types of ions are dependent on which of the geochemical processes predominate. Possible major hydrologic and geochemical processes are shown diagrammatically in figure 69.

EVOLUTION OF MINE-SPOILS WATER QUALITY AT SELECTED SITES

ABANDONED MINES, MISSOURI

Dissolved-solids concentrations in water from wells in or near mine spoils at three abandoned, unreclaimed mine sites in north-central Missouri (mine area 1, fig. 68) ranged from 1,890 to 4,660 milligrams per liter and averaged 2,900 milligrams per liter (Hall and Davis, 1986). The mine spoils consist of glacial drift of Quaternary age and bedrock of Pennsylvanian age disturbed by mining. The drift is composed of poorly sorted sand,



EXPLANATION

→ GENERAL DIRECTION OF GROUND-WATER FLOW

POSSIBLE HYDROLOGIC PROCESSES

1 Infiltration of precipitation
2 Flow through unsaturated zone
3 Horizontal flow through saturated zone
4 Vertical flow from underlying aquifer

POSSIBLE GEOCHEMICAL PROCESSES

a Carbon dioxide production from oxidation of organic matter
b Oxidation of sulfide minerals
c Dissolution of carbonate minerals
d Hydrolysis of feldspar minerals
e Precipitation of sulfate minerals because of evapotranspiration
f Dissolution of sulfate minerals
g Ion exchange and (or) adsorption
h Precipitation of carbonate minerals
i Sulfate reduction
* Processes resulting from disruption and exposure of spoils during mining. These processes probably affect only the initial volumes of water passing through the spoils

FIGURE 69.—Generalized section of hypothetical mine area and major hydrologic and geochemical processes.

silt, and clay and some well-sorted sand lenses. Dissolved-solids concentrations in water from the drift ranged from 239 to 1,280 milligrams per liter and averaged 602 milligrams per liter. The bedrock is composed of shale, limestone, sandstone, and coal. Dissolved-solids concentrations in water from the bedrock ranged from 580 to 883 milligrams per liter and averaged 754 milligrams per liter.

Specific constituents observed in greater concentrations in water from mine spoils include calcium, magnesium, sulfate, iron, and manganese. Water from the mine spoils is a calcium magnesium sulfate type, whereas water from the drift is either a calcium magnesium bicarbonate or calcium magnesium sulfate type; water from the bedrock is either a sodium bicarbonate or calcium bicarbonate type. Water from highwall lakes is similar to water from the mine spoils.

The major minerals in the mine spoils are quartz, calcite, dolomite, and various nonsodic clays. Pyrite, gypsum, and several iron-oxide minerals also are present.

Climate in the area is humid. Recharge to the drift occurs by infiltration of precipitation and lateral flow from adjacent aquifers. Recharge to bedrock probably occurs by infiltration of precipitation and vertical flow from the drift. The rates of recharge to the drift and bedrock are unknown. Recharge to the mine spoils is from infiltration of precipitation and flow from adjacent aquifers. Precipitation probably is the major source of recharge, both directly and indirectly as flow from highwall lakes.

Mass-transfer calculations using the computer program BALANCE (Parkhurst and others, 1982) indicate that the main geochemical processes that result in the observed water quality in the mine spoils may include oxidation of pyrite, dissolution of gypsum, dissolution and precipitation of calcite, dissolution of dolomite, consumption of oxygen gas, consumption and release of carbon dioxide gas, precipitation of iron oxide minerals, and release of relatively small quantities of sodium ions by exchange or adsorption. Saturation indices determined using the computer program WATEQF (Plummer and others, 1976) indicate that water from all sources are near saturation with respect to quartz, calcite, and dolomite. Water from wells in the drift and the bedrock is undersaturated with respect to gypsum; water from wells in or near the mine spoils is saturated with respect to gypsum. The difference probably results from oxidation of sulfide minerals and dissolution of gypsum in the unsaturated zone on surfaces freshly exposed by mining.

Ages of the mine spoils at the three mines differ. At these mines, spoils were emplaced during 1940, during 1952, and during 1968. Statistical comparisons indicate that differences in general water quality exist between the three mine-spoils areas, but the differences cannot be attributed to age. Therefore, the major changes determined in water quality occurred within 12 years or less and have persisted for more than 40 years.

Most of the geochemical processes that result in the measured increases in dissolved-solids concentrations occur in the unsaturated zone. Therefore, any attempts to improve water quality in the mine spoils probably would benefit from decreasing the volume of water recharging the mine spoils by vertical infiltration.

ABANDONED MINE, OKLAHOMA

Ground water in saturated mine spoils at an abandoned, unreclaimed coal mine in eastern Oklahoma (mine area 2, fig. 68) predominantly is a sodium sulfate type (Slack, 1983). The average dissolved-solids concentration was 1,990 milligrams per liter in 57 water samples from 6 wells completed in the mine spoils. Water from the wells is similar in quality to water in two nearby highwall ponds. Except for dissolved solids, iron, manganese, and sulfate, constituent concentrations generally do not exceed drinking-water regulations of the U.S. Environmental Protection Agency (1986a, 1986c).

The coal that was mined was part of the Pennsylvanian Hartshorne Sandstone, which is overlain by the Pennsylvanian McAlester Formation. The Pennsylvanian McAlester Formation mainly consists of silty shale and several sandstone layers. X-ray diffraction analyses of mine-spoils material, which contains the Hartshorne Sandstone and the McAlester Formation, indicate that the spoils predominantly consist of quartz, kaolinite, chlorite, illite, and mica. Also generally present, in quantities less than a few weight percent, were smectite, calcite, feldspars, pyrite, gypsum, and siderite.

The mechanisms of recharge were not discerned. However, because of a relatively humid climate, recharge from infiltration of precipitation probably is a major factor. The geochemical processes that result in the spoil water quality probably include oxidation of sulfide minerals, dissolution of sulfate minerals, dissolution of carbonate minerals, hydrolysis of feldspar minerals, and ion exchange or adsorption.

BIG SKY MINE, MONTANA

Dissolved-solids concentrations in water from saturated mine spoils at the Big Sky Mine in southeastern Montana (mine area 3, fig. 68) average about 3,700 milligrams per liter, whereas dissolved-solids concentrations in water from coal (subbituminous C) aquifers in the area average about 2,700 milligrams per liter (Davis, 1984b).

The specific constituents for which increases in concentration were measured include calcium, magnesium, potassium, bicarbonate, and sulfate. Water from both aquifers is mainly a calcium magnesium sulfate type.

The coal is part of the Tongue River Member, which in this area is sandier than near the West Decker Mine (see "West Decker Mine, Montana" section). Overburden samples from an area near the Big Sky Mine generally contained, in general descending order of abundance, quartz, dolomite, kaolin, feldspars, mica, and calcite. Samples associated with mine spoils also contained gypsum. The clay fraction generally consisted of kaolinite and illite.

Climate in the area is semiarid. Recharge to the coal aquifers is by infiltration of precipitation in areas of hydraulically connected clinker and, probably to a lesser extent, by infiltration of precipitation through the sandy overburden. The quality of ground water in the coal aquifers primarily is determined by dissolution of silica, sulfate, and carbonate minerals in the unsaturated zone. Because of the lack of sodic clay in the overburden, exchange of calcium and magnesium for sodium is not predominant. Sulfate reduction probably decreases the sulfate concentration and increases bicarbonate concentration (Dockins and others, 1980), although this process apparently is not predominant either.

Recharge to the mine-spoils aquifer occurs as lateral flow from the coal it replaces and as vertical infiltration of precipitation. The main geochemical processes that result in the increased dissolved-solids concentration in the spoils include oxidation of pyrite, dissolution of the resultant gypsum, and dissolution of carbonates.

Saturation indices determined using the computer program WATEQF (Plummer and others, 1976) substantiate the geochemical processes listed above. Water from the lignite aquifers is saturated or supersaturated with respect to quartz, calcite, and dolomite and saturated to slightly undersaturated with respect to gypsum. Water from the mine spoils generally is saturated to supersaturated with respect to quartz, calcite, dolomite, and gypsum. The general state of saturation or supersaturation of water from the mine spoils indicates that the dissolved-solids concentration is near maximum and will not increase substantially assuming solute sources and temperature do not change.

In summary, the increases in dissolved-solids concentration in water from the mine-spoils aquifer at the Big Sky Mine primarily result from oxidation of sulfide minerals, dissolution of the resultant sulfide minerals, and limited dissolution of carbonate minerals. The dissolved-solids concentration in water in the mine spoils probably will not change in the near future, although the concentration may decrease if the mine-spoils water flows through a coal aquifer.

WEST DECKER MINE, MONTANA

Dissolved-solids concentrations in water from saturated mine spoils at the West Decker Mine in southeastern Montana (mine area 4, fig. 68) average about 2,500 milligrams per liter, whereas dissolved-solids concentrations in water from coal (subbituminous C) aquifers in the area average about 1,400 milligrams per liter (Davis, 1984b). The specific constituents for which increases in concentration were measured include calcium, magnesium, sodium, potassium, bicarbonate, and sulfate. Water from both aquifers is mainly a sodium bicarbonate type, although water from the mine spoils tends to have a larger percentage of total milliequivalents per liter of calcium plus magnesium and of sulfate plus chloride.

The coal aquifer is part of the Tongue River Member, which in this area consists of calcareous shale, siltstone, sand and sandstone, and coal beds. Overburden samples from an area near the West Decker Mine primarily contained quartz, layer silicates, and the clay-mineral groups smectite, illite, chlorite, and kaolin. Also present, in general descending order of abundance, were feldspars, carbonates such as calcite and dolomite, calcium siderite and siderite, and pyrite. Gypsum was detectable in only two of the samples.

Climate in the area is semiarid. Recharge to the coal aquifer is by infiltration of precipitation in areas of hydraulically connected clinker, which is baked, fused, and fractured rock that results from burning of underlying coal beds. Recharge to the coal aquifer also occurs as vertical leakage from an underlying coal bed. The chemistry of ground water in the coal aquifer predominantly is determined by the dissolution of silica, sulfate, and carbonate minerals in the recharge areas. The sulfate minerals probably result from oxidation of pyrite in the recharge areas. Most of the calcium and magnesium from dissolution of the carbonate minerals is exchanged for sodium with either sodic clays in the clinker or with the coal itself. Sulfate reduction probably decreases the sulfate concentration and increases the bicarbonate concentration (Dockins and others, 1980).

Recharge to the mine-spoils aquifer primarily occurs as lateral flow from the coal it replaces. Infiltration of precipitation through the mine spoils probably is not a substantial source of recharge because of the large concentration of clay in the mine spoils. Therefore, the geochemical processes that result in increased dissolved-solids concentrations probably occur in the saturated zone. These processes probably include dissolution of gypsum formed from oxidation of pyrite in the overburden during mining, dissolution of carbonates, and ion exchange or adsorption.

Saturation indices determined using the computer program WATEQF (Plummer and others, 1976) substantiate the geochemical processes listed above. Water from the coal aquifers is supersaturated with respect to quartz, undersaturated to saturated with respect to calcite and dolomite, and undersaturated with respect to gypsum. Water from the mine spoils is supersaturated to saturated with respect to quartz, calcite, and dolomite and undersaturated with respect to gypsum. The undersaturation with respect to gypsum for mine spoils and lignite aquifers indicates limited quantities of pyrite and gypsum in the overburden and mine spoils or a lack of surface recharge through the overburden and mine spoils, or both. The general state of saturation or supersaturation with respect to other minerals for water in the mine spoils indicates that the dissolved-solids concentration is near maximum and will not increase substantially assuming solute sources and temperature do not change.

In summary, increases in dissolved-solids concentration in water from the mine-spoils aquifer at the West Decker Mine primarily result from oxidation of limited quantities of sulfide minerals and dissolution of the resultant sulfate minerals, dissolution of carbonate minerals, and cation-exchange or adsorption reactions. The dissolved-solids concentration in water in the mine spoils probably will not change in the near future, although the concentration may decrease if the mine-spoils water flows through a coal aquifer.

SENECA MINE, COLORADO

Investigations at the Seneca Mine in northwestern Colorado (mine area 5, fig. 68) were limited to defining water movement, water chemistry, and geochemical processes in the upper 6 feet of the unsaturated zone (Williams and Hammond, 1988). Material above the two coal beds being mined consists of soils developed on material derived from the Cretaceous Iles Formation and Williams Fork Formation. These formations vary in composition from sandstone to shale. The clay fraction of the sediments consists primarily of kaolinite and illite and has very little smectite.

The area has a semiarid climate and receives about 16 inches of precipitation annually. Recharge to all shallow aquifers in the mine area is from infiltration of precipitation. Recharge to the undisturbed system is estimated to be one-half inch per year. Recharge to the mine spoils ranges from 2 to 6 inches per year because of a greater infiltration rate near the land surface. However, recharge to the mine spoils is decreasing because of continuing natural compaction of the spoils.

Water in the upper 6 feet of the spoils is a calcium magnesium sulfate type. Dissolved-solids concentration ranged from an average of 3,960 milligrams per liter during 1978 to an average of 3,560 milligrams per liter during 1979. The average concentrations of the major ions were 460 milligrams per liter for calcium, 370 milligrams per liter for magnesium, 111 milligrams per liter for sodium, 2,540 milligrams per liter for sulfate, and 224 milligrams per liter for bicarbonate.

The primary geochemical processes that affect the water quality in the unsaturated zone are dissolution of carbonate minerals, oxidation of sulfide minerals, and dissolution of gypsum that results from oxidation of sulfide minerals. Carbonic acid, that results from absorption of carbon dioxide from the atmosphere, decaying organic matter, and plant respiration enhances the dissolution of carbonates. Pyrite oxidation, which also enhances carbonate dissolution, occurs as new reaction surfaces are exposed to an oxidizing environment during disruption by mining. The sulfate produced may be precipitated as gypsum during periods when evapotranspiration rates are rapid and later may be dissolved by deeply percolating recharge water. Saturation indices determined using the computer program WATEQF (Plummer and others, 1976) indicate that the water generally is saturated or supersaturated with respect to calcite, dolomite, and gypsum.

MINE DRAINAGE

By ARTHUR N. OTT

In the Eastern United States, acid mine drainage is the most acute issue associated with coal mining. In the Western United States, nonacid (saline) drainage is an issue, although it is much less severe and far more local than acid mine drainage is in the Eastern United States. Acid mine drainage results from mining in a humid environment and diminishes in severity as precipitation lessens in a westward direction and as the sulfur content in coal decreases (coals in the Western United States generally contain less sulfur than coals in the Eastern United States).

The most substantial production of acid mine drainage occurs in the Appalachian regions of the Eastern United States, an area that encompasses about 111,000 square miles from northern Pennsylvania to central Alabama. The acid mine drainage within these regions primarily occurs in Pennsylvania, Ohio, West Virginia, and Kentucky, possibly because more than 90 percent of the coal is located in these States. Also, more coal has been mined in the Northern Appalachian region than in the Southern Appalachian region, which has resulted in more pyritic material being disturbed and subject to oxidation in the Northern Appalachian region than in the Southern Appalachian region.

Acid mine drainage does not seem to be a significant issue in the Western United States. Wentz (1974a) reported that acid mine drainage was not an issue in Colorado and believed this was because of the minimal sulfur content of coal in the Western United States. Wentz (1974a) stated that 65 percent of the bituminous, subbituminous, and lignite reserves in the United States, which occur primarily west of the Mississippi River, contain 1 percent or less total sulfur, whereas 43 percent of the reserves in the Eastern United States contain more than 3 percent total sulfur. The infrequent occurrence of acid mine drainage in the Western United States also can be attributed to relatively deep soils that contain calcareous material, small quantities of annual precipitation, and, conversely, large evapotranspiration levels and buffered ground waters. In contrast, the Eastern United States has coals that have a large sulfur content, annual precipitation nearly twice as much as that of the Western United States, and soils that are shallow and relatively acid.

PRODUCTION OF ACID MINE DRAINAGE

The chemical characteristics of water that drains from a coal-mine site are dependent on the geologic, hydrologic, and topographic features that are associated with the mine site. When the rock material overlying the coal seam is non-calcareous and the material or the coal seam contains fine-grained pyrite (iron sulfide), oxygen and water can combine to oxidize the pyrite and produce iron sulfate and sulfuric acid. Pyrite oxidation produces a strongly acidic solution. This acidic environment may cause dissolution of large concentrations of aluminum and manganese and toxic metals such as chromium, cadmium, lead, copper, zinc, and nickel in the mine drainage. These metals will remain dissolved as long as the solution remains strongly acidic.

The production of acid that is associated with coal mining primarily is attributed to the oxidation of sulfur. Even though sulfur occurs in coal in organic and inorganic forms, it is the inorganic, pyrite sulfur that is the most reactive. Further, Caruccio and others (1976) have reported that not all pyrite sulfur is acid producing. Pyrite that has grain sizes larger than 400 micrometers or that has crystals of cubical or triangular shape are inert and, therefore, are nonacid producing. Conversely, pyrite that morphologically occurs as clusters of crystal spheres approximately 25 micrometers in diameter, called framboidal pyrite, is very reactive and acid producing. Furthermore, the distribution of framboidal pyrite has been determined to be relatively abundant in coal formed in the marine, brackish-water environment as opposed to coal formed in the freshwater environment.

Stumm and Morgan (1970) summarized the major mechanisms believed to be involved in the production of acid mine drainage:

The dissolution of pyrite and the oxidation of sulfide to sulfate,

$$FeS_2 + \frac{7}{2}O_2 + H_2O \rightleftharpoons Fe^{+2} + 2SO_4^{-2} + 2H^+; \quad (29)$$

the oxidation of ferrous iron,

$$Fe^{+2} + \frac{1}{4}O_2 + H^+ \rightleftharpoons Fe^{+3} + \frac{1}{2}H_2O; \quad (30)$$

the oxidation of pyrite by ferric iron,

$$FeS_2 + 14Fe^{+3} + 8H_2O \rightleftharpoons 15Fe^{+2} + 2SO_4^{-2} + 16H^+; \text{ and} \quad (31)$$

the precipitation of ferric iron,

$$Fe^{+3} + 3H_2O \rightleftharpoons Fe(OH)_3 + 3H^+. \quad (32)$$

Nordstrom (1977) stated that acid mine drainage is the most acidic of all weathering reactions primarily because of the oxidation of sulfur to sulfate and discussed the following sequence of reactions that describe the decomposition of pyrite. Pyrite is abiotically oxidized to ferrous iron and sulfur:

$$FeS_2 + \frac{1}{2} O_2 2H^+ \rightleftharpoons Fe^{+2} + S_2 + H_2O. \quad (33)$$

Ferrous iron is rapidly oxidized and hydrolyzed at approximately neutral pH and equalizes the change in pH shown by equation 33:

$$Fe^{+2} + \frac{1}{4} O_2 + \frac{5}{2} H_2O \rightleftharpoons Fe(OH)_3 + 2H. \quad (34)$$

The sulfur product shown by equation 33 is oxidized to sulfate and is the reaction that decreases the pH:

$$S_2 + 3O_2 + 2H_2O \rightleftharpoons 2SO_4{}^{-2} + 4H^+. \quad (35)$$

Equations 33 and 35 can be combined to yield equation 29, and equations 30 and 32 can be combined to yield equation 34. As the pH decreases, ferric iron concentration increases, and ferric iron becomes the dominant oxidizer of pyrite when pH is less than 3 (eq. 31). Oxidation of sulfur to sulfate, however, causes nearly all the acidity. The quantity of ferric iron available for the oxidation of pyrite would be minimal at a pH of 3 in a purely abiotic system. However, microbial catalysis (the oxidation of ferrous iron by *Thiobacillus ferroxidans*) increases the normally slow reaction rate by several orders of magnitude.

According to Kleinmann and others (1981) the acid-production sources for coal-mine drainage occur in a three-stage sequence that is dependent on the activity of *Thiobacillus ferroxidans* and solution Eh (oxidation-reduction potential) and pH. During the first stage, reactions represented by equations 29 and 34 are the mechanisms involved. Reaction 29 proceeds abiotically and by direct biotic oxidation. Reaction 34 proceeds abiotically but lessens as the pH decreases. Solution chemistry during this stage is indicative of a pH in excess of 4.5 (slightly acidic) and large sulfate and small iron concentrations.

A change from the abiotic to the biotic oxidation of ferrous iron initiates the second stage. The mechanisms operative for the second stage are the same reactions involved during the first stage. Reaction 29 continues to be driven abiotically and biotically. Reaction 34, however, proceeds at a rate determined primarily by biotic activity. The solution chemistry indicates the increased acidity. The pH now ranges from 2.5 to 4.5, the solution contains large quantities of sulfate, and acidity and total iron concentrations are increased. Total iron is represented by a small ferric/ferrous iron ratio. A decrease in $Fe(OH)_3$ precipitation and a concurrent increase in iron solubility at a pH less than 3 results in increased ferric iron activity.

The third stage begins as the pH approximates 2.5. The mechanisms operative during the third stage involve reactions represented by equations 30 and 31. Reaction 30, the oxidation of ferrous to ferric iron, is entirely bacterially mediated and affects the rate of reaction 31. The combined effects of the bacterial oxidation of ferrous iron, reduction of ferric iron by pyrite, and formation of ferric oxyhydroxides and ferric sulfate determine the steady-state activity of ferric iron, while the availability of ferric iron is limited by the rate of reaction 30. The solution chemistry now would have a pH of 2.5 or less (very acidic) and large concentrations of sulfate and total iron. Iron is composed of a large ferric/ferrous iron ratio.

As previously discussed in this section, the production of acid primarily occurs because of the oxidation of pyritic sulfur by ferric iron to ferrous sulfate. The resulting iron sulfate and associated aluminum sulfate salts are an additional source of acidity. Dissolution of these salts in distilled water results in a solution pH of about 2.0. These salts generally occur in areas of acid mine drainage; however, the occurrence of these salts only recently has been ascertained. It also is possible that much of the present-day acidic discharge is derived from past mining processes that produced these acid iron and aluminum salts.

QUANTITY AND QUALITY OF ACID MINE DRAINAGE

Underground mines below the ground-water table usually have a continuous discharge, while underground mines located where the water table fluctuates above and below the mine level produce intermittent discharge. Mines need to be dewatered during the active mining phase, which partially dewaters the ground-water system in the mine area and increases the discharge in the adjacent surface-water flow system. For some horizontal coal seams and for coal seams that dip away from the mine opening, mining causes dewatering of the overlying strata. When mining activities cease, the mined cavity eventually will flood (because of not being pumped) and ground water will return to premining levels. If the coal seam dips toward the mine opening, the ground-water flow system will dewater the mine cavity continuously by gravity drainage, regardless of the mining status (U.S. National Research Council, 1981a). In contrast, discharge from surface mines generally is intermittent and usually coincides with precipitation.

Evaluation of effects of acid mine drainage on the water quality of streams is very subjective. For example, in a summary of surface-water quality for the

Eastern Province (Wetzel and Hoffman, in press) report that of 1,500 sites that were sampled at least 4 times during 1972–82, the median values at only 25 sites either equaled or exceeded the criteria for pH, total iron, total manganese, and dissolved sulfate established by the Federal Water Pollution Control Administration (1968) to delineate deterioration by acid mine drainage. The criteria for all four constituents may not have been simultaneously exceeded in a single analysis; however, the median for a minimum of four values for total iron, total manganese, and dissolved sulfate and the minimum value for pH equaled or exceeded the level. These are stringent criteria.

Water-quality property or constituent	Criteria for acid mine drainage[1]
pH (units)	less than 6.0
Total iron (micrograms per liter)	greater than 500
Total manganese (micrograms per liter)	greater than 500
Dissolved sulfate (milligrams per liter)	greater than 75

[1]Established by Federal Water Pollution Control Administration (1968).

Biesecker and George (1966) determined that 194 sites (61 percent) were measurably affected by acid mine drainage based on studies of 318 sites in the Appalachian region that have drainage areas larger than 100 square miles. This determination was based on samples that contained concentrations of sulfate greater than 20 milligrams per liter. If the previous sulfate criterion of greater than 75 milligrams per liter is used, the number of sites decreases from 194 to 124. Furthermore, if the pH criterion of less than 6.0 is used, the number of sites affected decreases to 61. If the criterion used by the Appalachian Regional Commission (1969) listed below is applied to the 1965 sulfate data, the number of sites decreases further to 41. Thus, instead of there being 61 percent of the 318 sites considered affected by acid mine drainage, there only would be 13 percent of the sites affected by acid mine drainage.

Water-quality property or constituent	Criteria for acid mine drainage[1]
pH (units)	less than 6.0
Acidity/alkalinity (milligrams per liter)	net alkalinity, less than 20
Hardness (milligrams per liter)	greater than 250
Suspended solids (milligrams per liter)	greater than 250
Dissolved solids (milligrams per liter)	greater than 500
Total iron (micrograms per liter)	greater than 1,500
Aluminum (micrograms per liter)	greater than 500
Manganese (micrograms per liter)	greater than 1,000
Sulfate (milligrams per liter)	greater than 250

[1]Appalachian Regional Commission (1969).

A new concept for evaluating the effect of acid mine drainage on a stream or river system is net alkalinity. This concept, used by Rozelle and others (1976), provides an assessment of the acid-alkaline balance within the system. The net alkalinity is defined as the difference between the alkalinity of a sample determined by titration using a standard acid to a pH of 4.5 and the acidity determined by titration using a standard base to a pH of 8.3. If the alkalinity is greater than the acidity, net alkalinity is positive, pH generally will exceed 6.0, and alkaline conditions prevail. Positive net alkalinity provides a measure of the alkaline reserve or capacity of the system to neutralize acid input. If the acidity is greater than the alkalinity, the net alkalinity is negative, the stream or system is considered acid and usually, but not necessarily, has a pH of less than 6.0. To illustrate the usefulness of the concept, a stream that receives 100 pounds per day of positive net alkalinity could be expected to assimilate or neutralize 100 pounds per day of acid input without decreasing the pH to less than 6.0.

CLASSIFICATION OF ACID MINE DRAINAGE

A classification devised by Hill (1968) that differentiates acid mine drainages based on their most prominent chemical characteristics is listed in table 6. Although there are four numbered classes, three classes

TABLE 6.—*Acid mine drainage classes*
[Modified from Hill, 1968]

Water-quality property or constituent	Class 1, acid discharges	Class 2, partially oxidized and (or) neutralized	Class 3, oxidized and neutralized and (or) alkaline	Class 4, not oxidized and neutralized
pH (units)	2–4.5	3.5–6.6	6.5–8.5	6.5–8.5
Acidity ($CaCO_3$) (milligrams per liter)	1,000–15,000	0–1,000	0	0
Ferrous iron (milligrams per liter)	500–10,000	0–500	0	50–1,000
Ferric iron (milligrams per liter)	0	0–1,000	0	0
Aluminum (milligrams per liter)	0–2,000	0–20	0	0
Sulfate (milligrams per liter)	1,000–20,000	500–10,000	500–10,000	500–10,000

are identified by oxidation designations: partially oxidized, oxidized, and not oxidized. These designations seem to be related to the form of the iron. According to Nordstrom (1977), acid mine drainage should be well suited to relating oxidation-reduction measurements to the ferrous/ferric iron redox potential.

Another way to classify acid mine drainage is to use dual-acidity titration curves (Ott, 1986). Even though dual-acidity titration curves do not directly measure the redox potential, the shape formed by these curves is dependent on the ferrous/ferric iron ratio as shown in figure 70.

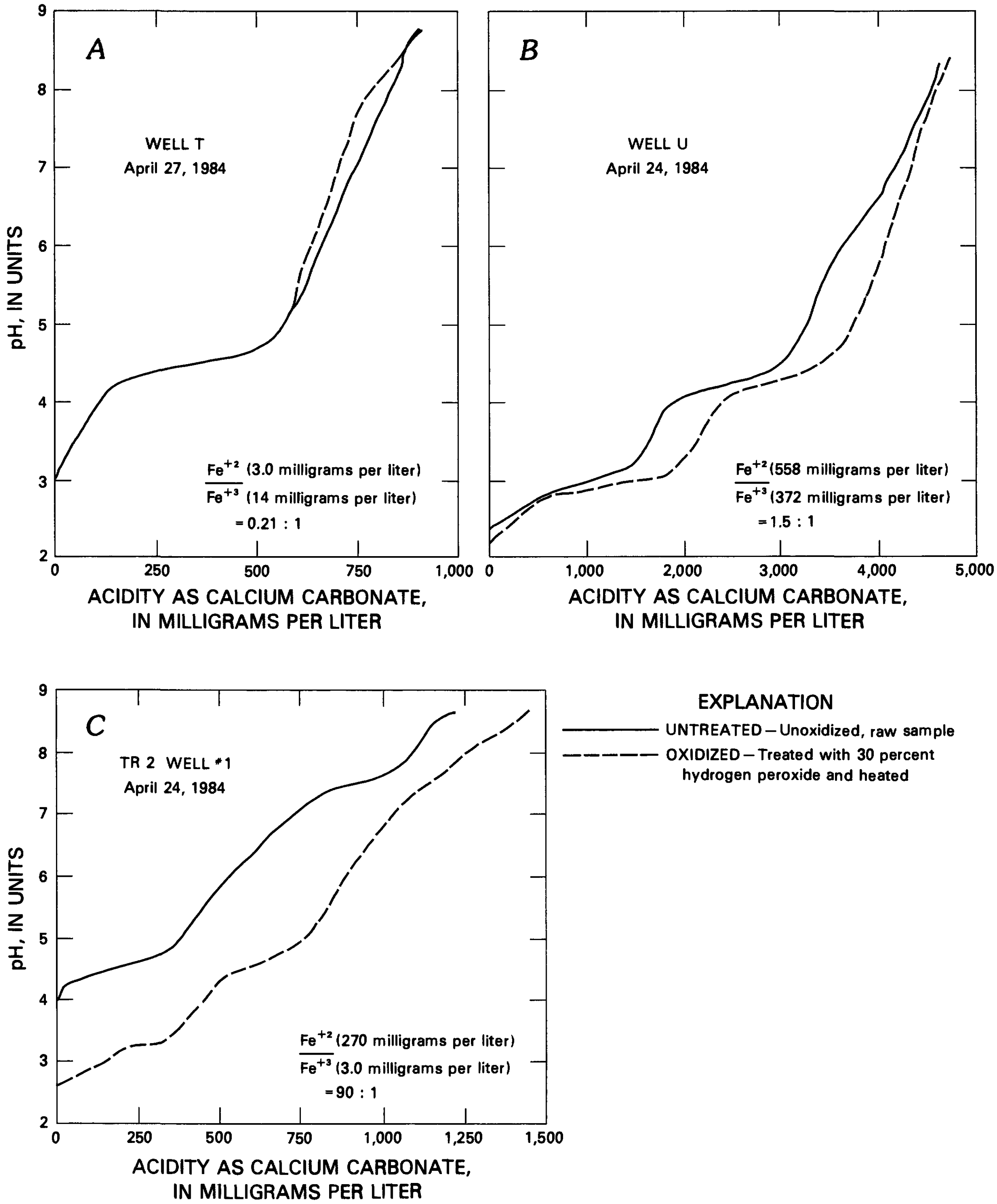


FIGURE 70.—Titration curves of untreated and oxidized ground-water samples containing different ferrous/ferric (Fe^{+2}/Fe^{+3}) iron ratios. *A*, well T; *B*, well U; and *C*, TR 2 well 1.

The acidity titration curve of the untreated sample from well T (fig. 70*A*) is nearly superimposed on the titration curve of the oxidized sample treated with hydrogen peroxide (H_2O_2). The iron composition of the untreated sample is about 20 percent ferrous iron and about 80 percent ferric iron. The dual curves (fig. 70*B*) that represent a sample from well U, whose iron composition is 60 percent ferrous iron, are somewhat divergent, while the dual curves (fig. 70*C*) that represent a sample from TR 2 well 1, whose iron composition is about 99 percent ferrous iron, are completely divergent. The samples as shown in figure 70 can be classified as follows: 70*A*, oxidized; 70*B*, partially oxidized; and 70*C*, not oxidized.

Another use for acidity titration curves is as "fingerprints" that seem to change little with time (figs. 71-73) as long as substantial geochemical changes do not occur (Ott, in press). For example, the curves remain similar even though a 10-month period of time elapsed between sample collections (fig. 71). Also, changes in ionic concentration due to dilution (fig. 73) do not seem to cause the characteristic shape of the curve to change.

The mine-drainage classification by Hill (1968) discussed at the beginning of this section was based on the concentrations of the principal chemical constituents as determined in the laboratory. Mine discharge also can be classified onsite by estimating the concentrations of chemical constituents from onsite determinations. In addition, Lovell (1973) determined that a reasonable correlation between specific conductance and sulfate concentration exists. Ott (1986) used regression equations derived from acidity titration curves to estimate concentrations of ferrous iron, ferric iron, aluminum, and total acidity.

NONACID MINE DRAINAGE

As indicated by Hill's mine-drainage classification (Hill, 1968), all mine drainage is not acidic. Nonacidic drainage may occur where pyrite is: (1) Massive rather

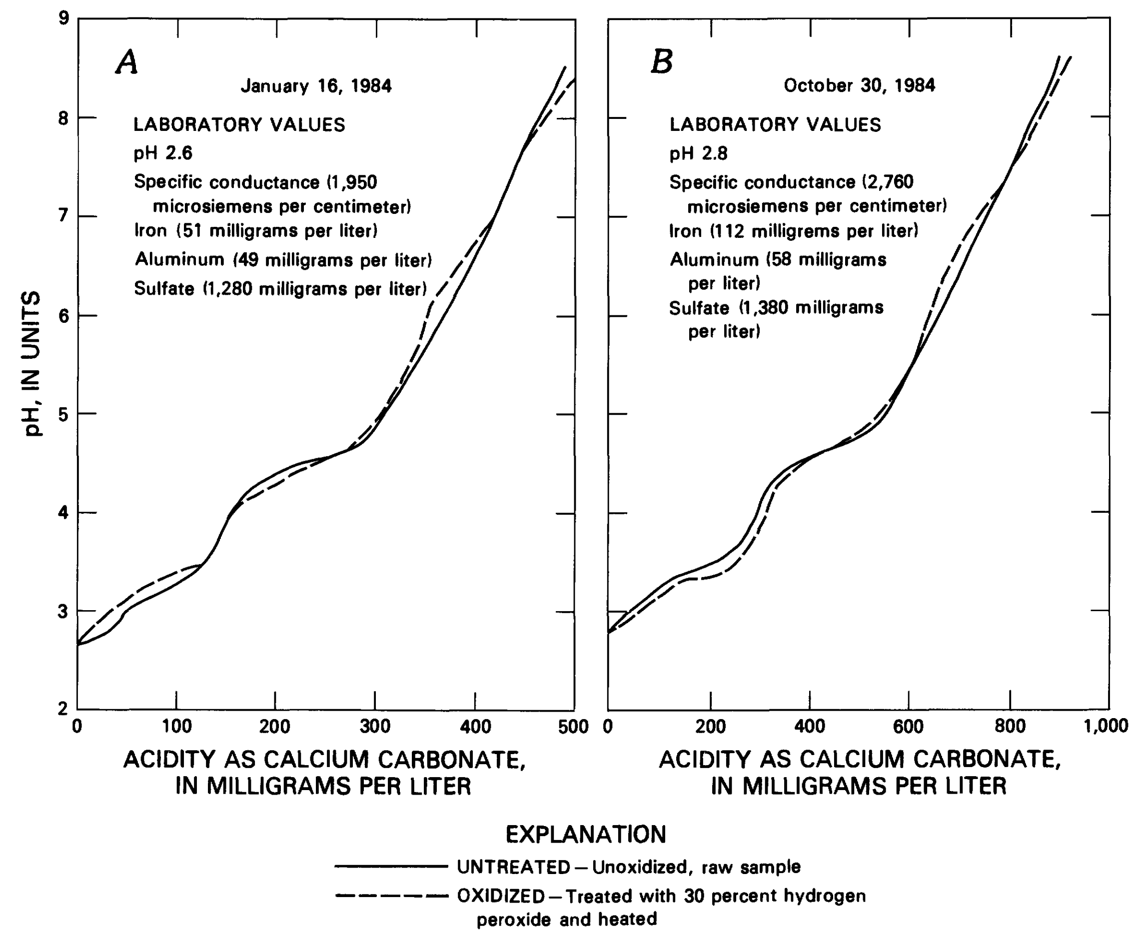


FIGURE 71.—Similar titration-curve characteristics provided by different samples collected from seep (site 2), Clarion County, Pennsylvania. *A*, Sample collected January 16, 1984; and *B*, Sample collected October 30, 1984. (Fifty-milliliter samples titrated with 0.1 Normal sodium hydroxide.)

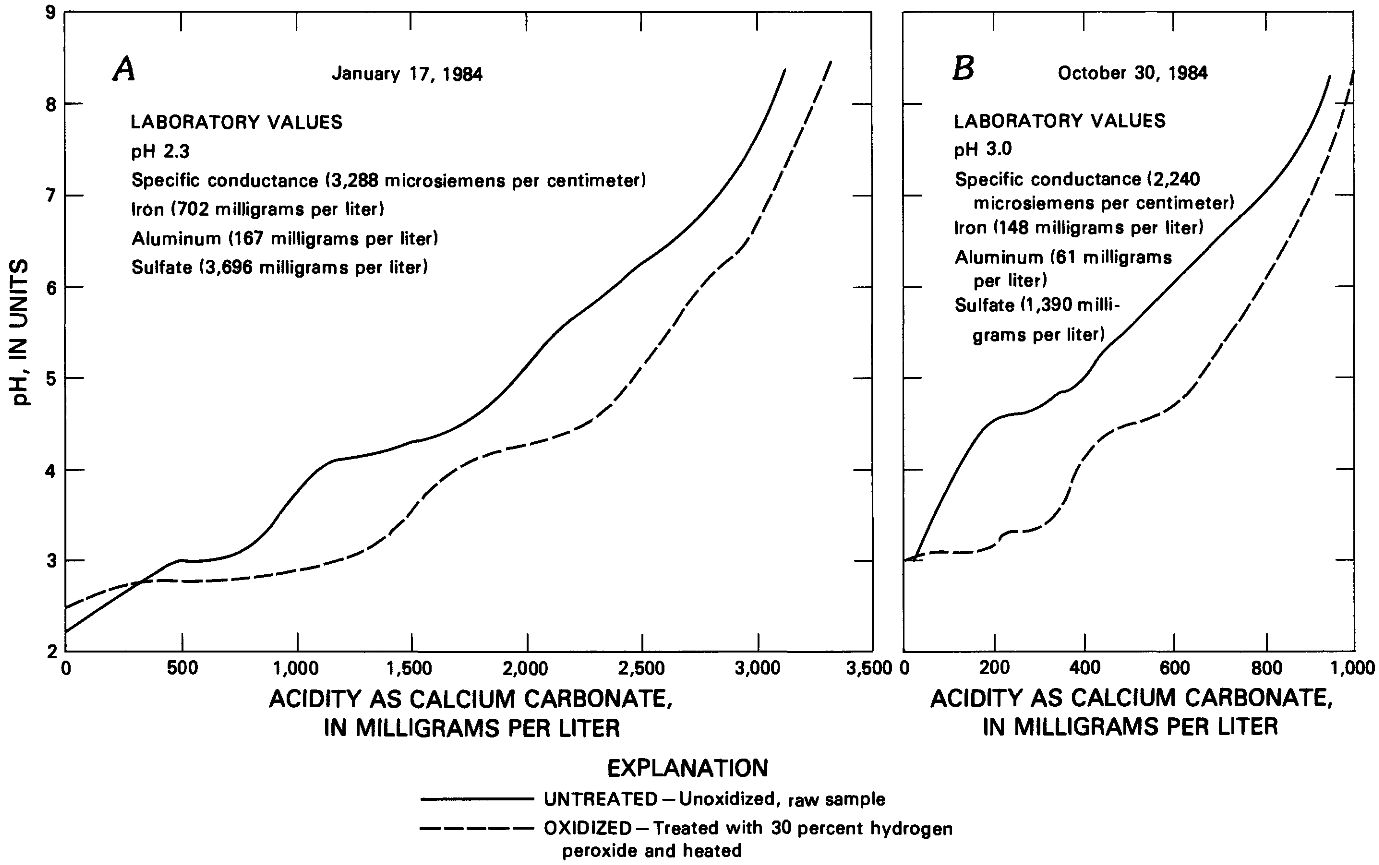


FIGURE 72.—Similar titration-curve characteristics provided by different samples collected from well 4K, Clarion County, Pennsylvania. *A*, Sample collected January 17, 1984; and *B*, Sample collected October 30, 1984. (Fifty-milliliter samples titrated with 0.1 Normal sodium hydroxide.)

than fine grained or framboidal; (2) of small sulfur content; or (3) overlain by calcareous material. Based on results from leaching studies and onsite observations, Caruccio and others (1976) concluded that pyrite morphology was considerably different among similar sulfur-content pyrite samples that did and did not produce acid. The nonacid-producing pyrite was massive and most grains were larger than 400 micrometers. Smaller grained cubical or triangular pyrite crystals that range from 5 to 10 micrometers also were determined to be inert. Williams and others (1982) determined positive exponential relations among both acidity and sulfate and total sulfur concentrations in laboratory leaching studies. These relations indicate that acid is not produced in shale that has small sulfur content or in coal that has small pyrite content. Based on laboratory and onsite observations, Williams and others (1982) determined that the equivalent of 1 foot of limestone is sufficient to inhibit or neutralize all the acid produced from the oxidation of 10 feet of brackish shale that has a 3 percent sulfur content.

As long as alkalinity exceeds acidity in percolating mine water, the only major effect on mine discharge exposed to acid-producing pyrite is a larger than normal sulfate concentration. The catalyzing iron bacteria are excluded, and the iron and possibly the aluminum solubility is kept to a minimum.

Where a calcareous overburden exists over a coal, a nonacidic drainage from a mine area may occur; however, this is not always the situation because carbonate solubility is dependent on the pH and the partial pressure of carbon dioxide (CO_2). According to Caruccio (1973), water in contact with carbonates at a partial pressure equal to $10^{-3.5}$ atmospheres do not generate sufficient alkalinity to effectively neutralize acid production. The solubility of carbonates is much less than that of sulfides at atmospheric conditions, and thus greater acidities than alkalinities can be produced, which can result in an acidic environment. In order for percolating mine water to benefit from the acid-neutralizing properties of bicarbonate, the water requires large partial pressures of CO_2 before contacting carbonate material. This requirement can be met by conditions in the soil. Soil air contains a CO_2 content that

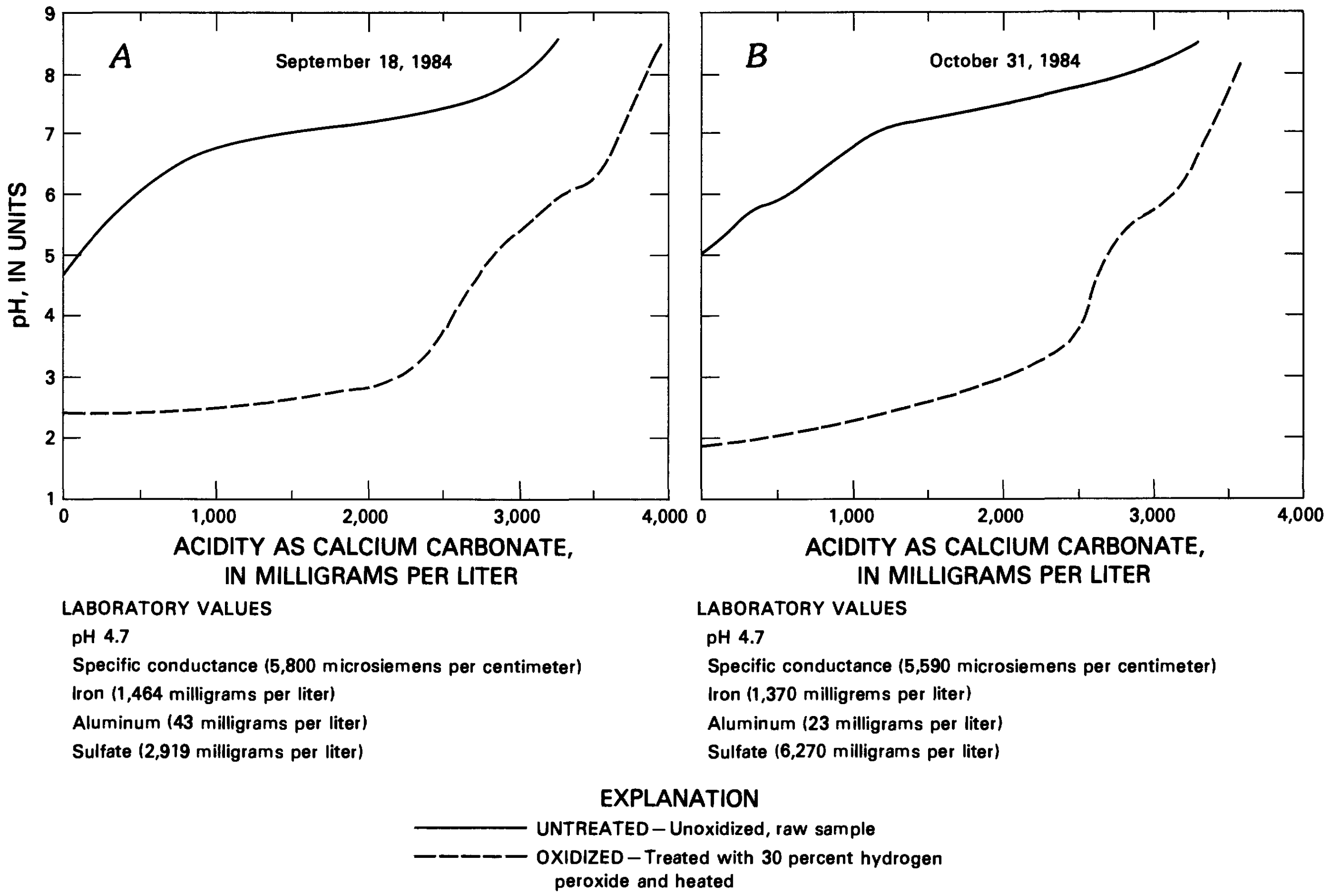


FIGURE 73.—Similar titration-curve characteristics provided by different samples collected from well C-2, Clarion County, Pennsylvania. *A*, Sample collected September 18, 1984; and *B*, Sample collected October 31, 1984. (Fifty-milliliter samples titrated with 0.1 Normal sodium hydroxide.)

ranges from 0.3 percent to about 10 percent. In general, as CO_2 increases, oxygen content decreases. In nearly all instances, the CO_2 content increases with soil depth because CO_2 is heavier than the other gases and therefore sinks into the lower layers. Thus, the porosity and moisture content of the lower soil horizons and the underlying rock formation determine whether CO_2 accumulates in the subsoil and unsaturated zone or whether it disperses into underground fractures or other passageways.

SEDIMENTATION

By RANDOLPH S. PARKER

At the time of the initiation of the Surface Mining Control and Reclamation Act of 1977 (PL 95-87), there was an immediate interest in "natural" suspended-sediment production in the areas of coal mining and in the changes in suspended-sediment production resulting from the mining activity. Perhaps no other phase of the hydrologic cycle received such attention during 1978. One reason for this attention was the engineering requirements for designing structures to contain sediment produced on the mine site. Unfortunately, sufficient data were not available to appropriately answer many of the design questions. Therefore, the importance of suspended-sediment-data collection was established early in the program, but the actual collection of these data was extremely slow.

The slow start can be attributed, in part, to the typical issues faced in any sediment study. Streamflow-gaging sites designed to collect suspended-sediment data are very expensive and manpower intensive. Suspended-sediment concentrations are quite variable in time, and these concentrations usually are related to a variety of other hydrologic, climatic, and land-use factors. To understand these relations, many of these other factors also need to be monitored. This monitoring tends to increase the cost of sediment-data collection.

Attempts to predict changes in the suspended-sediment concentration and load that occur because of coal mining need to rely substantially on the knowledge of how other components of the water balance change. Whether the infiltration rate increases or decreases in a reclaimed area directly affects the quantity of erosion and initial transport of sediment. Changes in the magnitude of the evapotranspiration component by coal mining directly affects the volume of available surface runoff and that, in turn, affects available energy to detach and transport sediment particles. Knowledge of changes in the quantity of sediment are related directly to the knowledge of changes in the other components of the water balance. Unfortunately, the changes in these components are not well defined.

SEDIMENT-DATA-COLLECTION APPROACH AND CONSIDERATIONS

There are many difficult decisions on where within a watershed to locate sediment-data collection sites. One approach, monitoring the outlet of a basin in which a variety of land uses occur upstream, enables only the definition of the sediment characteristics of the integrated effects of these land uses. A second approach, monitoring segments of a watershed in order to partition the effects within a watershed, multiplies the cost of data collection and manpower needs. The first approach would not, it seemed, provide the necessary predictive capabilities. The second approach was far too expensive and manpower intensive to be practical.

Certain problems are not unique to sediment-data collection or research. Results of disturbance by coal mining on the water resources within a watershed are difficult to study because of the tenuous nature of coal economics. Coal mining is subject to the economics of energy production. Coal is not mined and stockpiled, but it is removed and land is disturbed as the demand for coal increases. Because of this situation, there is little control of land use during the study. Because of the inability to control land use within a watershed during the period needed to collect hydrologic information, sediment studies have incorporated a multiwatershed approach. By using this approach, land-use changes and the response of the water resource are carefully documented. By compiling a sufficient number of different basins and land-use situations, the response of the water resource to various land-use changes may be identified. This technique necessitates monitoring many different basins.

Although there are some merits to the multiwatershed approach, there are some disconcerting factors that indicate basic problems with this method. Primarily, there is the myriad of hydrologic responses possible within a basin because of the temporal interactions among coal mining and the weather and climate. For example, the effects of coal mining on sediment load during high flow are different than during low flow, and if particular stages of the mining activity are completed during the low-flow season, effects may be lessened. In addition, there is the spatial interaction between the extent of mining activity and where this activity is located within the watershed. Thus, when the area of disruption within a watershed is doubled, the sediment load does not necessarily double.

Synoptic studies can supply much of the background information about an area and even indicate changes that occur because of mining activity. However, suspended-sediment data need to be collected during high flows, and this necessitates data collection only at certain times of the year. Rainfall simulators have been developed and tested on rehabilitated slopes in order to facilitate data collection (Lusby and Toy, 1976), but there are problems with the capability of this technique to model natural precipitation.

There is another aspect to suspended-sediment data collection that concerns the disruption of downstream channels as a result of changes in sediment input upstream. An increase in suspended sediment can result in storage of the sediment in the downstream channel, which causes increased bank erosion. A decrease in sediment from upstream can result in degradation of the bed and banks of the downstream channel. Downstream channel changes may occur from a single upstream disruption. Because effects can occur far downstream from changes in the sediment input upstream, difficulties in monitoring are increased. In Tennessee, for example, suspended-sediment yields have increased as much as 200 times since coal mining began. Instead of a stable, armored channel that was narrow and lined with mature trees, the channel downstream from mining became more than twice as wide and had numerous gravel bars, and the banks showed indications of recent erosion (Osterkamp and others, 1984).

Examples of sediment storage and subsequent flushing occurs in various coal-mining areas in the Eastern United States. The number of years necessary to remove this stored material is unknown. In the Western United States, there is some concern that decreases in sediment resulting from entrapment in sediment ponds will result in bed and bank scour to downstream channels.

SEDIMENT-DATA-COLLECTION ACTIVITIES

Data collection of suspended sediment at streamflow-gaging sites has continued near many coal-mining sites throughout the United States. These sediment-data-collection sites have been funded through a variety of sources. Some of the early sediment-data collection began as a cooperative program between the U.S. Bureau of Land Management and the U.S. Geological Survey. During the mid-1970's, the U.S. Bureau of Land Management needed to collect hydrologic data to assess the hydrologic effects of coal mining in Western States where Federal coal was to be leased. This cooperative program began as a long-term modeling effort, and a number of streamflow-gaging sites for sediment-data collection were established within small watersheds.

The U.S. Geological Survey provided financial support for collection of sediment data in 19 small basins in the Eastern and Interior Provinces (Kilpatrick and others, in press). This set of data provides information about sediment from rainfall-runoff events in the small basins from Pennsylvania to Alabama. These basins ranged from 0.17 to 5.08 square miles in area and included basins with and without mining activity. Sediment data were collected primarily from 1981 through 1983, although some basins have different periods of record.

Additional funding of streamflow-gaging sites for sediment-data collection was provided by the U.S. Geological Survey's contract streamflow-gaging-sites program. This program established a network of streamflow-gaging sites in regions of actual or anticipated coal mining by contracting the operation of the sites and data collection to private companies. The purpose of this program was to serve as a system of environmental monitoring to assess the effects of coal mining and associated reclamation on the surface waters of the given region. Because of this purpose, many of the streamflow-gaging sites in this program were located downstream on larger tributaries and not downstream from individual coal-mining operations.

In some regions, sediment data were available from previous work. Summarizing these data into general equations provided estimating techniques for analyzing effects from coal development. One such study was done in southeastern Montana (Lambing, 1984). This study examined sediment-yield data for 121 sites including reservoir sedimentation surveys, sediment sampling at streamflow-gaging sites, and indirect estimation of sediment yields based on physical characteristics of the basin. Multiple regressions were used to estimate sediment yields for small ungaged basins.

In many areas, sufficient data are not available to assess premining hydrology or to evaluate potential changes to the hydrologic regime as a result of mining. To provide the necessary hydrologic evaluation in these instances, some methods have been summarized (Frickel and others, 1981; Hadley and others, 1981; Shown and others, 1981, 1982). Methods described include estimating erosion and sediment yield in the particular area by using the Universal Soil Loss Equation and reservoir sedimentation surveys.

Because of the interaction between the various components of the water balance and sediment movement, watershed models have been used to investigate this complex system. Such models enable sequences of algorithms to be linked together for water and sediment movement. For example, PRMS (Precipitation-Runoff Modeling System) has programs to detach soil particles from the upland slopes and transport sediment downstream. In PRMS, sediment detachment and movement on the overland flow planes is done only during storms and is the sum of the rainfall detachment rate of sediment and the overland flow detachment rate of sediment (Leavesley and others, 1983, p. 37). Each of these components is computed using equations described by Smith (1976) and Hjelmfelt and others (1975). The sediment computed from the overland flow planes is transported through the channel system as a conservative substance. Sediment detachment and deposition in the channel are not included in the model. Thus, sediment removed from the overland flow planes is transported directly through the channel network to the mouth of the system. Each of these components has a number of parameters that need to be determined.

Hydrologic data collected from two watersheds have been used in the PRMS modeling system in Wyoming. Modeling has been done for surface water and sediment (Rankl, 1987). One of these watersheds is a natural basin, and the other is an artificial drainage basin established on a reclaimed area. Rankl uses the model to help identify sediment-source areas within the watersheds and to provide a basis for comparison between the mined and unmined areas.

Modifications to PRMS have been done to calculate scour through rilling on disturbed areas and deposition within diversion terraces (Reed, 1986). Within this same modification, there is an allowance to route eight different size classes of sediment depending on the distribution of the soil material and to route the water-sediment mixture through a sediment pond. These algorithms have been tested on several watersheds in Pennsylvania.

Use of models undoubtedly will increase because they enable the user to examine many components of the water balance and to identify their interactions. These interactions become extremely important when attempting to identify changes that occur from mining activity. Improvements in PRMS have been suggested by Carey and Simon (1985). A sizable data base for use in modeling has been developed as a result of the cooperative efforts between the U.S. Bureau of Land Management and the U.S. Geological Survey, but analysis of this data base has only just begun.

EASTERN PROVINCE

Studies done in the Eastern Province indicate sediment yields that range from 23 to 900 tons per square mile per year (Harkins and others, 1981; Quinones and others, 1981; Ehlke and others, 1982b). Although this is a fairly large range in sediment yields, the disruption of a watershed by human activities increases sediment yields dramatically. Basically, these increases are the result of removal of the protective cover of vegetation. There are problems with identifying the changes in sediment yield associated with a particular land use. In many basins, coal mining occurs concurrently with logging, agriculture, road construction, and urban development.

There are several examples of the changes in sediment yield because of coal-mining activity, although more data are needed to provide a better definition of the actual changes. In West Virginia, a comparison of two basins, one mined and the other unmined, indicated the mined basin had a sediment yield 240 times greater than the unmined basin within a unit-discharge range of 2 to 10 cubic feet per second per square mile (Ehlke and others, 1982a). Another comparison in West Virginia was between an unmined basin and a basin where 20 percent of the area was mined. The unmined basin had a sediment yield of 730 tons per square mile, at a unit discharge of 10 cubic feet per square mile. The mined basin had a sediment yield of 3,650 tons per square mile for the same unit discharge (Ehlke and others, 1982b).

In coal area 16 in Virginia and Tennessee (pl. 1), a comparison of an unmined basin with a basin in which 9 percent of the watershed has been disturbed by mining indicates a substantial increase in sediment yield. At a unit discharge of 3 cubic feet per square mile, the unmined basin had a sediment yield of 7 tons per square mile. At the same unit discharge, the mined basin had a sediment yield of 110 tons per square mile. Additionally, the unmined basin had sediment concentrations that ranged from 1 to 7 milligrams per liter, whereas concentrations in the mined basin ranged from 34 to 1,030 milligrams per liter (Hufschmidt and others, 1981).

In another comparison in Tennessee, the mined basin of New River (382 square miles) had 20 times more sediment during 1 year than the contiguous mined basin of Clear Fork (272 square miles) (Parker and Carey, 1980). This difference occurred even though the drainage area of New River is not that much larger than the drainage area of Clear Fork, and even though only about 7 percent of the New River basin is mined as compared to 1 percent of the Clear Fork basin.

Hubbard (1976) reported sediment yields of 300,000 tons per square mile in an extensively mined area of Alabama. Undisturbed areas in this region of Alabama have sediment yields that range from 20 to 800 tons per square mile (Harkins and others, 1981, p. 40–41). These reported differences in sediment yields indicate that sediment concentration and sediment yield increase with the onset of mining. These increased sediment yields may be of short duration because of reclamation. In addition, the sediment concentrations that occur in the smaller disturbed basins often are decreased downstream by dilution from larger receiving streams (Harkins and others, 1980).

Flint (1983, table 12, p. 32–33) computes a regional average sediment yield (in tons per square mile) for the Eastern Coal Field of Kentucky by using 28 selected streamflow-gaging sites. The computed regional average for sediment yield is 486 tons per square mile, and the standard deviation is 460 tons per square mile. This regional average is shown in figure 74; the shaded area represents plus and minus one standard deviation of this regional average. In this same coal region, Curtis and others (1978) monitored a number of extensively mined basins. Comparing eight of these basins during January 1, 1974 through December 31, 1975 with respect to area disturbed by coal mining indicates a definite trend (fig. 74). The sediment yield from these basins ranged from 732 to 21,000 tons per square mile. Where more than 3 percent of the area is disturbed, there is a relation between area disturbed and sediment yield that can be described in the power form of the equation:

$$Y = 370\, D^{1.50}, \qquad (36)$$

where Y = mean annual sediment yield, in tons per square mile; and
D = area of the basin disturbed, in percent.

Basins that have less than 3 percent of the area disturbed by mining may be within the variability of the sediment yield of the region (fig. 74). Perhaps there is a threshold of disruption within these basins below which little evidence of sediment-yield increase can be identified. If this is true, more data will be needed to adequately identify these relations.

In other basins in Kentucky, the change in sediment yield with changes in discharge indicates that the relation shown in figure 74 may not be so direct. In Kentucky, comparisons of the Red River and Goose Creek in coal area 14 to the extensively mined Troublesome Creek in coal area 14 indicate that during low and medium flows, substantially more sediment is generated from the mined basin than from the unmined basins, but that during high flows, less sediment is generated from the mined basin than from the unmined basins (Quinones and others, 1981, p. 54–55). This determination is made from a comparison of the sediment-rating curves for these basins, and these curves are defined using 30 to 40 data values. Therefore, these determinations are somewhat tenuous, but they do indicate additional factors that need to be defined and studied to fully understand sediment movement.

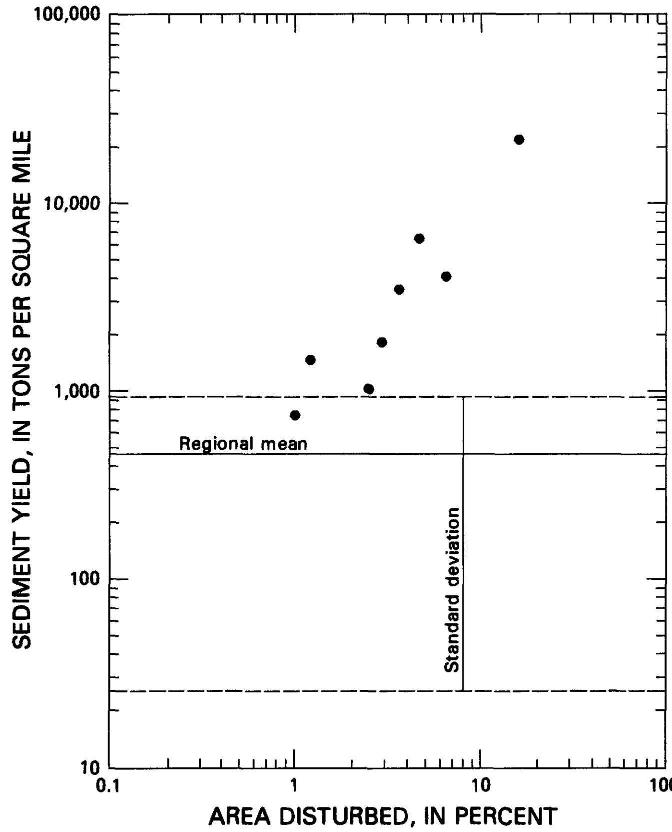


FIGURE 74.—Relation between percent of area disturbed and sediment yield for the Eastern Coal Field of Kentucky (modified from Curtis and others, 1978, p. 18). A comparison is made with the regional mean sediment yield computed by Flint (1983, p. 32).

NORTHERN GREAT PLAINS AND ROCKY MOUNTAIN PROVINCES

This area encompasses a variety of climatic regimes, and these climates affect sediment movement. In the northern areas from Montana and North Dakota through the central Rockies of Colorado, stream discharge results primarily from snowmelt. In this type of environment, the larger stream discharges occur during the snowmelt season of March through July, and most of the sediment is transported during this period. Frozen soils that exist at the onset of snowmelt can inhibit infiltration and lead to increased streamflow, but this condition can prevent soil movement and thus decrease sediment input (Slagle and others, 1984).

Differences identified in sediment yields in these snowmelt regions generally are ascribed to changes in geology. For example, two areas mapped in Montana with respect to sediment yield have three categories: less than 10, 10 to 100, and greater than 100 tons per square mile. These three categories are mapped primarily with respect to geology (Slagle and others, 1983; Slagle and others, 1984).

In parts of Montana, Wyoming, and northern Colorado, the form of the precipitation is affected by altitude. At the lower altitudes, intense summer thunderstorms are important in sediment transport. At the higher altitudes, sediment transport is related to stream discharges that occur during the snowmelt season. The effect of altitude in ultimately affecting sediment movement is increased because there usually is a change in the geology with increasing altitude. An example of this situation occurs in coal area 54, an area along the border between Wyoming and Colorado (Kuhn and others, 1983). The lower altitude areas have a cover of short prairie grass and the bedrock is sandstone, siltstone, and shale. The higher altitudes have a forest cover, and the bedrock is granite, schist, and gneiss. Estimates for the sediment yields for these two areas are reported in acre-feet per square mile. In order to maintain common units for sediment yield in this report, it is assumed that the sediment has a specific weight of 80 pounds per cubic foot (Guy, 1970, p. 33). Given this assumption, the higher altitudes have sediment-yield estimates of 1.7 to 44 tons per square mile, while the lower altitudes have estimates of 17 to 190 tons per square mile. These ranges are different by an order of magnitude.

Further to the south, in the coal regions in Colorado, Utah, and New Mexico, most of the annual precipitation occurs as intense summer thunderstorms. These storms are infrequent but can move large quantities of sediment. Again, geology is a major factor in affecting the differences in sediment yields. For example, in a study in central Utah, estimates of sediment yield range from 3 to 5,200 tons per square mile. The larger yields are from the lowlands where the bedrock is predominantly shale and sandstone. The higher altitudes consist of the Wasatch Plateau and the Book Cliffs where the bedrock is primarily sandstone, shale, and limestone, and the estimates of sediment yield generally are smaller (Lines and others, 1984).

Because of the infrequent nature of precipitation in areas of intense summer thunderstorms, sediment yields calculated from observed data are rare. Instead, many estimates for sediment yield are derived from indirect methods that account for sediment-yield changes based on geology, slope, vegetation, and land use. An example of such a method is the PSIAC method (Pacific Southwest Inter-Agency Committee Water Management Subcommittee, 1968). Results from this method are reported in acre-feet per square mile and are converted in this report to tons per square mile using the above assumption of a specific weight of 80 pounds per cubic foot.

Using the PSIAC method in northwestern New Mexico, the area was divided into three categories: (1) Mesa tops, clinker hills, and dry lake beds, which have sediment yields as much as 700 tons per square mile; (2) low-altitude badlands and gullied alluvial plains, which have intermediate sediment yields of 700 to 2,000 tons per square mile; and (3) moderate-to-steep badlands, which have sediment yields estimated at 2,000 to 5,500 tons per square mile (U.S. Bureau of Land Management, 1977b).

In southeastern Colorado, movement of sediment primarily is produced by intense summer thunderstorms. The geology of an area dramatically affects changes in sediment concentration and sediment load. Headwater streams transport substantially less sediment where they drain areas of limestone and igneous and metamorphic rock of Precambrian age. In lower reaches underlain by the Raton and Poison Canyon Formations, suspended-sediment concentrations range from 50,000 to 200,000 milligrams per liter during peak flows, and sediment yields can range from 300 to 2,840 tons per square mile (Abbott and others, 1983).

AQUATIC BIOLOGY

By David A. Peterson

Aquatic biota often are used as indicators of the quality of the aquatic environment, and this quality may indicate the effects of coal mining. The biota are adapted to the environmental conditions in the stream; different conditions support different biota. Because their lifespan ranges from months to years, the organisms inhabiting streams reflect conditions within the recent past that might not be discernible in an instantaneous sample. The use of benthic invertebrates and algae as water-quality indicators has been well documented (Wilhm and Dorris, 1966; Larimore, 1974; Lowe, 1974). During water-quality studies of coal-mining areas, the U.S. Geological Survey has sampled benthic invertebrates more frequently than algae.

Benthic invertebrates that occur in streams generally are immature insects such as mayfly nymphs (Ephemeroptera), dragonfly and damselfly nymphs (Odonata), caddisfly larvae (Trichoptera), and midge, blackfly, deerfly, and other true fly larvae (Diptera). Some insects such as beetles (Coleoptera) and true bugs (Hemiptera) can be aquatic during both immature and adult stages. Aquatic invertebrates that are not insects include snails, leeches, aquatic earthworms, and crustaceans. Benthic invertebrates occur within or on the substrate of the stream bottom, including submerged objects such as vegetation and logs. Drifting invertebrates are those that are temporarily suspended in the streamflow current.

Two common methods for sampling benthic invertebrates are the Surber-sampler and the kick-net methods. The Surber sampler delineates an area of 1 square foot; substrate within the square-foot area is agitated causing invertebrates to float downstream into a catch net. The kick net is a dip net, hand held downstream from the area where the user is agitating the substrate by kicking. Surber samplers are used for quantitative studies, whereas kick nets are used for qualitative studies. An Ekman grab sampler with spring-loaded jaws is useful for sampling pools. Drifting invertebrates in streams are sampled by placing a net in an undisturbed riffle for a given length of time.

Algae sometimes are collected during water-quality studies from either the periphyton or the phytoplankton. Periphyton refers to algae attached to the substrate, whereas phytoplankton refers to algae suspended in water. Through photosynthesis, algae and larger aquatic plants are the primary producers in the aquatic food chain; they also provide habitat for other aquatic organisms. Periphyton commonly are sampled by scraping natural substrates or by placing artificial substrates in the stream for 30 days or more. Phytoplankton are collected by immersing a water-sampling bottle in the water at the desired location and depth.

BIOLOGICAL STUDIES IN COAL PROVINCES

Biological data have been reported for some coal areas in the United States. Locations of coal areas that have coal-area hydrology reports that include discussion of benthic invertebrates and (or) algal data are shown in figure 75.

Several interpretive studies done in these provinces are described in the following sections. In addition, biological surveys done by State agencies are described in some of the coal-area hydrology reports for these provinces. The reports about coal areas 25–42 in the Interior Province generally did not contain biological information.

EASTERN PROVINCE

Effects of coal mining on aquatic biota are much different in the Eastern United States than in the Western United States because of the occurrence of acid mine drainage in the Eastern United States. Indicators of acid mine drainage are concentrations of dissolved sulfate larger than 75 milligrams per liter, total iron and manganese concentrations larger than 500 micrograms per liter, pH less than 6.0, and acidity concentrations larger than alkalinity concentrations (U.S. Department of the Interior, 1968).

Effects of acid mine drainage on benthic invertebrates were noted during biological reconnaissance in several Eastern States from 1979 to 1980. Kick-net samples collected from some of the streams in Pennsylvania yielded no benthic invertebrates, whereas others did not contain a biological community (two or more species of benthic invertebrates), as defined by the U.S. Office of Surface Mining (1979). Inverse relations between numbers of benthic-invertebrate taxa and indicators of acid mine drainage were noted. Herb and others (1981b, p. 48) determined that streams in coal area 5 (fig. 75) that had no benthic invertebrates had a mean dissolved-sulfate concentration of 162 milligrams per liter, whereas streams that had five or more benthic invertebrate taxonomic orders had a mean dissolved-sulfate concentration of 24 milligrams per liter (significant at the 95 percent confidence level). Similar reports on coal areas 1, 2, 3, and 5 (table 1) also noted poorly developed (diversity and size) benthic-invertebrate communities associated with acid mine drainage.

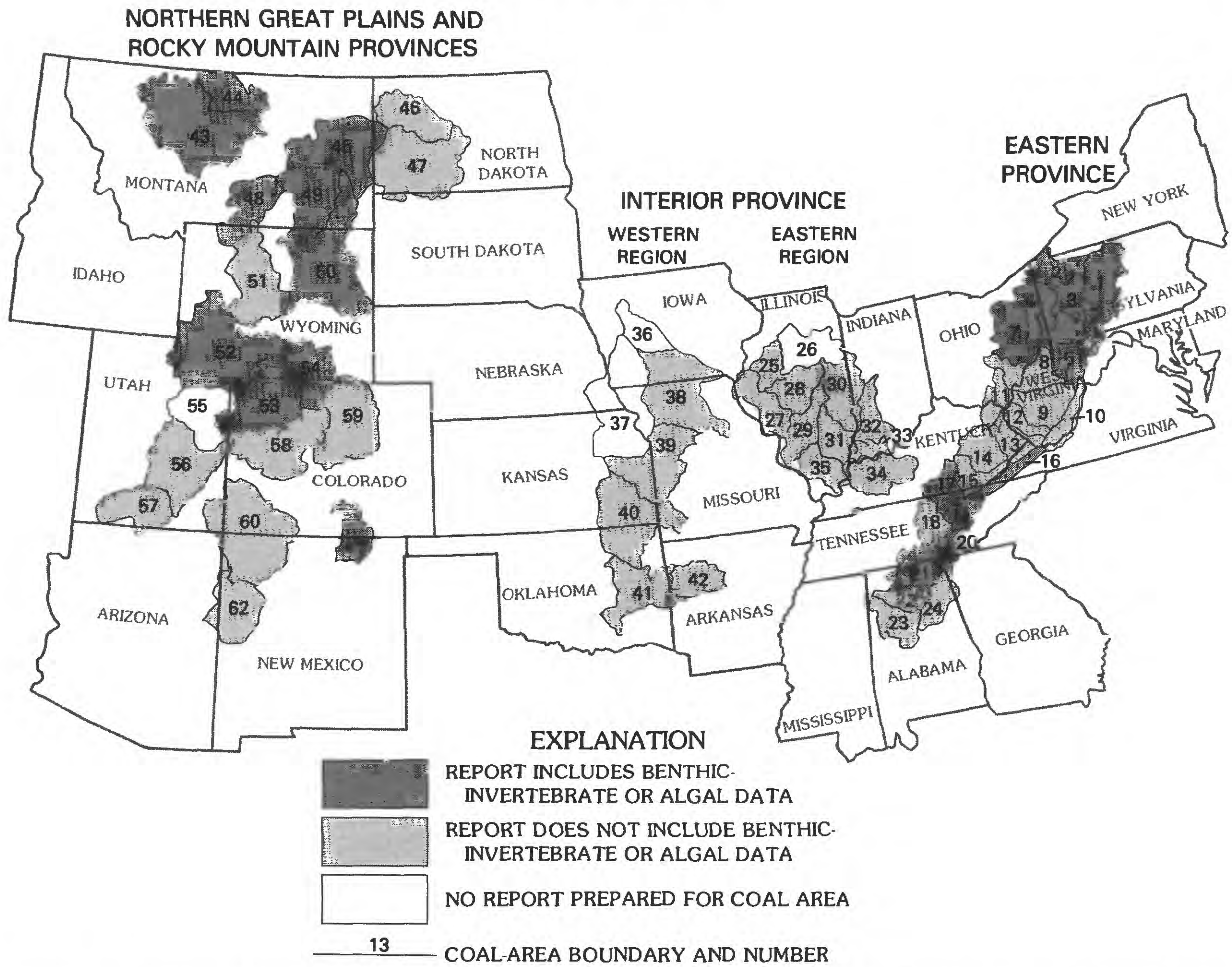


FIGURE 75.—Locations of coal areas that have coal-area hydrology reports that include discussion of benthic invertebrate and (or) algal data.

The benthic-invertebrate surveys in Tennessee and adjacent States during 1980–81 indicated that water quality of the streams ranged from excellent to poor. The Shannon-Weaver diversity index and a biotic index were used to describe the health of the benthic-invertebrate communities in coal areas 16, 17, 19, 20, and 21 (table 1). The Shannon-Weaver diversity index measures the diversity of the community; larger values indicate diverse, well-balanced communities under a minimum of stress (pollution); small values indicate stressed communities, dominated by a few taxa (Wilhm and Dorris, 1966). The values of the diversity index ranged from 1.81 to 3.82. The biotic index measures the benthic-invertebrate community using pollution-tolerance ratings of the taxa.

Statistical techniques were used to determine the effects of water quality in streams of Tennessee on the benthic-invertebrate communities. Using analysis of variance procedures, Bradfield (1986b) reported significantly fewer taxa, smaller densities and diversities, and a larger percentage of Diptera in streams that have pH values less than 6.0 and streams that have relatively large values of dissolved constituents and specific conductance (associated with land-use effects, including coal mining), than in streams that have pH values larger than 6.0 and relatively small values of dissolved constituents and specific conductance (relatively not affected). The dissolved-constituent concentrations were calculated using mean concentrations of manganese, iron, and sulfate. The decreased number of taxa, density, and diversity adversely affects the ability of the benthic-invertebrate community to process instream detritus and decreases the food source for higher trophic levels.

Relations between the characteristics of the benthic-invertebrate communities and water quality also were tested using multivariable regression techniques (Bradfield, 1986b). Correlation coefficients between number of taxa and density with dissolved-constituent concentrations, specific conductance, and pH were less than

0.55. This indicates that the selected water-quality variables accounted for less than 30 percent of the variability in the number of taxa and density. The correlation is poor partly because community characteristics are not linearly related to water-quality variables. Dissolved-manganese concentrations accounted for more of the benthic-invertebrate-community variability than the other water-quality variables. Dissolved-manganese concentrations were negatively correlated with number of taxa (fig. 76), density, diversity, and percent Ephemeroptera; the dissolved-manganese concentrations were positively correlated with percent Diptera.

Dissolved-manganese concentrations, number of taxa, and percentage of Diptera and Ephemeroptera may be useful indicators of the effects of coal mining on streams in Tennessee. In addition, nonparametric cluster analysis of benthic-invertebrate samples collected from Tennessee streams during 1982–83 indicate a species group of Ephemeroptera that may be useful in identifying the effects of coal mining (Bradfield, 1986a).

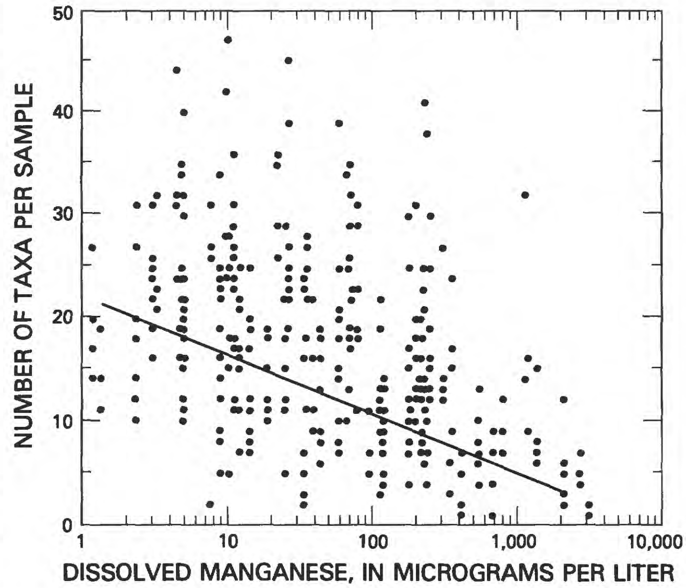


FIGURE 76.—Relation between number of benthic-invertebrate taxa per sample and mean concentration of dissolved manganese (from Bradfield, 1986b). The negative slope of the regression line indicates that the number of taxa per sample decreases as the dissolved-manganese concentration increases.

NORTHERN GREAT PLAINS AND ROCKY MOUNTAIN PROVINCES

The effects of coal mining on water quality of streams in the Northern Great Plains and Rocky Mountain Provinces, such as increased concentrations of dissolved solids and turbidity, have the potential to affect stream biota. Changes in the quantity or timing of water in a stream also may affect the biota, because much of the coal in the Western United States is mined in semiarid areas.

BENTHIC INVERTEBRATES IN STREAMS

The relation between specific conductance and benthic-invertebrate communities was examined by Klarich and Regele (1980). They reported an inverse relation between diversity-taxa richness of the benthic-invertebrate community and specific conductance in streams in southeastern Montana. Stream communities were divided into categories of large, moderate, and small diversity-taxa richness, based on Margalef and Shannon-Weaver diversity indices and the ratio between the number of taxa collected and the number of taxa expected for a given number of samples. Streams with large diversity-taxa richness (relatively good quality) had a mean specific conductance of 1,135 microsiemens per centimeter, compared to streams with moderate diversity-taxa richness that had a mean specific conductance of 2,580 microsiemens per centimeter, and streams with small diversity-taxa richness that had a mean specific conductance of 3,215 microsiemens per centimeter. Benthic-invertebrate density was not related to specific conductance. These findings were based on Surber samples collected from natural substrates in 35 streams. Klarich and Regele (1980) also discussed the equitability and percentage similarity of the benthic-invertebrate communities and compared samples from natural and artificial substrates.

Benthic-invertebrate communities in the southern Powder River basin, the major coal-mining area in northeastern Wyoming, were examined during 1980 and 1981. Average benthic-invertebrate density and median Shannon-Weaver diversity in the Belle Fourche River, an ephemeral stream, were smaller upstream from a coal mine than downstream from the mine (fig. 77). Differences between the sites may be the result of intermittent flow from a tributary, diversion of the stream around the mine, infrequent discharge pumped from the mine pit, or a combination of these factors (Peterson, in press). The samples were collected from pools at the two sites using an Ekman grab sampler. In this study, the benthic invertebrates were identified to the genus level; identifications to species level are necessary to better ascertain whether community-composition changes occurred that were not detected at the genus level.

Effects of coal mining on water quality and benthic invertebrates, when present, may be difficult to separate from other factors such as agriculture. In northwestern Colorado, Britton (1983) studied benthic-invertebrate communities in six streams upstream and

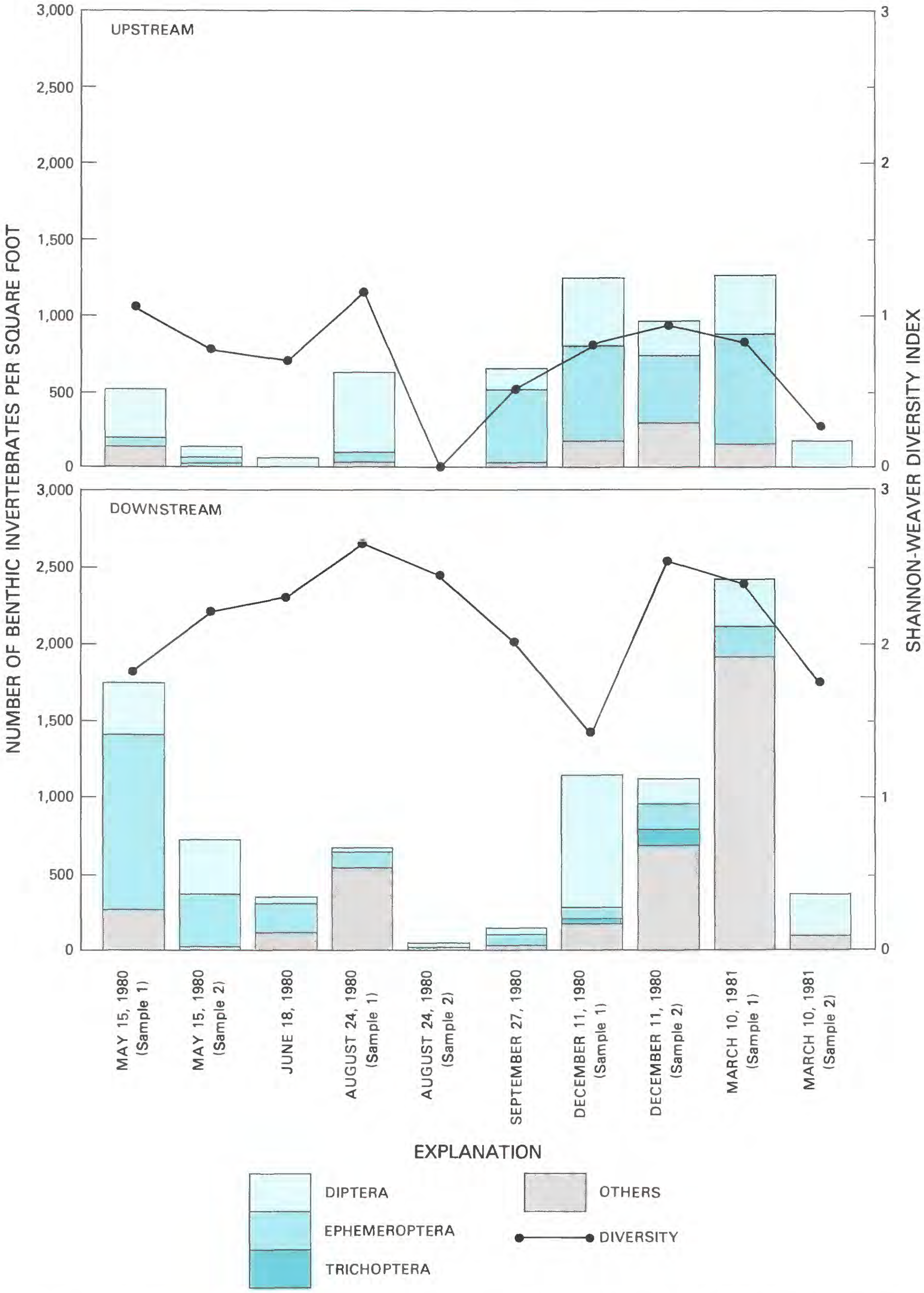


FIGURE 77.—Composition, density, and diversity of benthic invertebrates from the Belle Fourche River, upstream and downstream from a coal mine in northeastern Wyoming (from Peterson, in press).

downstream from coal mines. Benthic-invertebrate communities changed in the downstream direction, but the changes could not be attributed solely to mining. For example, benthic-invertebrate density and specific conductance in Trout Creek were larger downstream from coal mining (sites Tr-2 and Tr-3) than upstream from mining (site Tr-1), but a small change in substrate unrelated to coal mining also was noted. Community composition changed in the downstream direction from a well-balanced community of several functional groups to a community composed largely of Dipteran Chironomids (fig. 78).

Changes in streamflow type such as those that might be caused by addition or depletion of water because of coal mining may result in changes in the composition of the benthic-invertebrate community. The relation of flow type to the benthic-invertebrate community was reported by Peterson (in press) in a study of perennial, intermittent, and ephemeral streams in northeastern Wyoming. The benthic-invertebrate communities that inhabit perennial streams generally were similar to each other because of the taxa adapted to flowing water, and communities of ephemeral streams generally were similar to each other because of the taxa adapted to

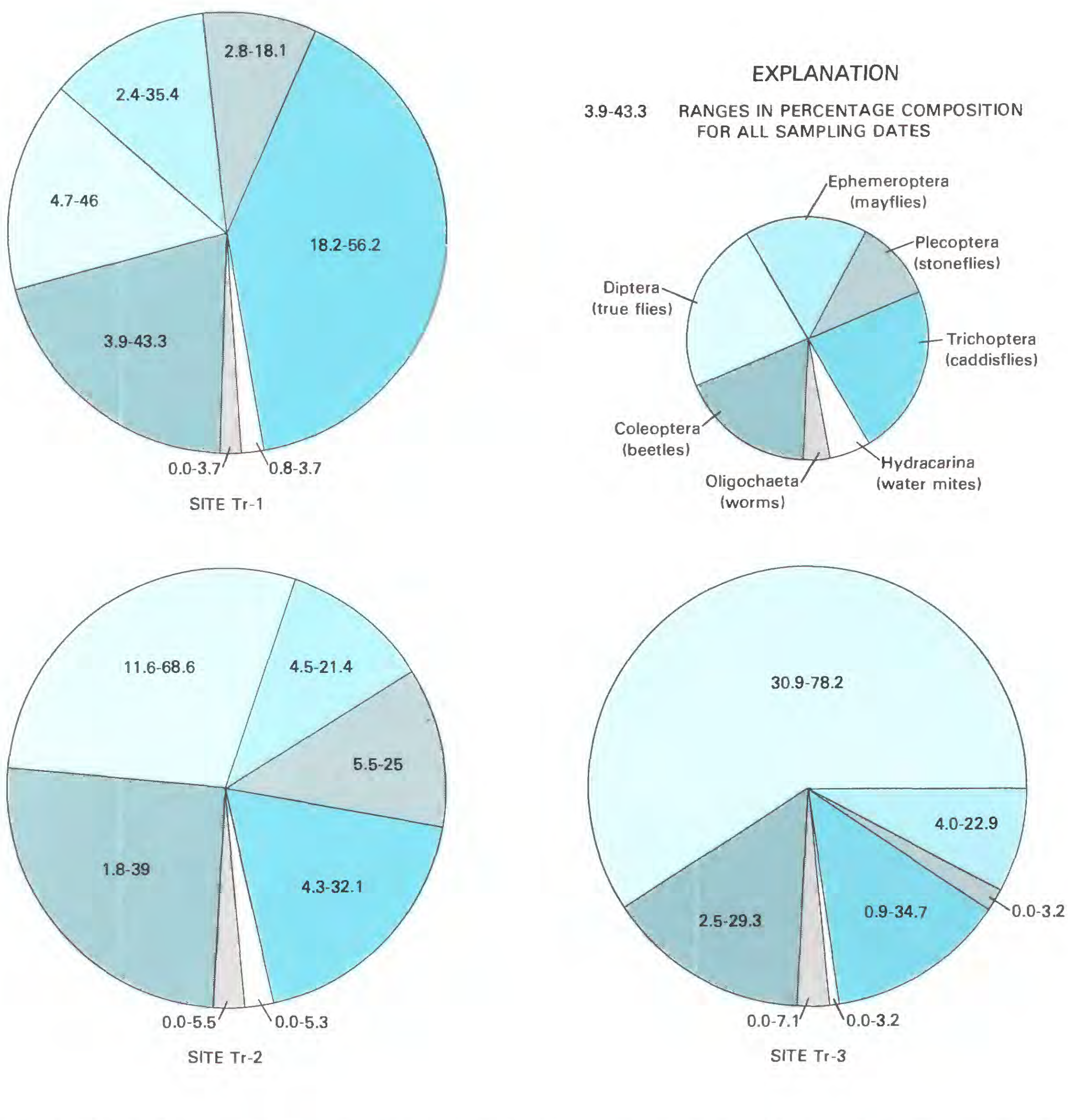


FIGURE 78.—Change in mean percentage composition of benthic-invertebrate taxonomic groups in the downstream direction in Trout Creek, northwestern Colorado (from Britton, 1983). The sites are labeled in downstream order, from Tr-1 to Tr-3.

standing water, based on Jaccard coefficients of community similarity and a cluster diagram. Benthic-invertebrate communities of intermittent streams did not form a comparable cluster.

Invertebrate Drift in Streams

Invertebrates drifting in streams have been studied because of their potential importance in estimating time for invertebrate recolonization of streams reclaimed following mining and also as a measure of the invertebrate community. Rates of drift generally were larger in perennial streams than in intermittent or ephemeral streams of northeastern Wyoming, indicating that a reclaimed or disturbed reach in a perennial stream would be recolonized faster than a reclaimed reach of an intermittent or ephemeral stream (Peterson, in press). A study of invertebrate drift in two streams of northeastern Wyoming during 1977 indicated behavioral (voluntary) drift of invertebrates in a stream at normal stage, compared to catastrophic drift in a stream flooded by rainfall (Wangsness and Peterson, 1981). The catastrophic drift contained many types of invertebrates that normally do not occur in drift. The catastrophic drift may aid in distributing invertebrates, as well as alleviating the effects of scour during floods.

Phytoplankton and Periphyton

In Scofield Reservoir, Utah, concentrations of mercury originating from coal particles have caused concern for water users but have not exceeded current State standards (Stephens, 1985). The study of the effects of coal mining on the reservoir was done in cooperation with the U.S. Bureau of Land Management. Nonpoint sources contributed most of the pollution to the reservoir, particularly phosphorus and nitrogen. Large nutrient concentrations were associated with late summer blooms of the blue-green algae *Aphanizomenon flos-aquae* and *Anabaena flos-aquae* and resultant fish kills.

Biota of strip-mine ponds abandoned 20 years previously were compared to native ponds in northeastern Wyoming by Wangsness (1977). Phytoplankton, periphyton, and benthic-invertebrate communities were less diverse in strip-mine ponds than in native ponds. Sloughing of the banks of strip-mine ponds may have been a factor in the differences.

Samples of phytoplankton and bacteria were collected from 12 reservoirs in eastern Montana during a study done in cooperation with the U.S. Bureau of Land Management (Ferreira and Lambing, 1984). The study evaluated the suitability of the reservoirs for fish propagation, waterfowl habitat, livestock watering, and recreational use.

Periphyton in streams of southeastern Montana were surveyed by Bahls (1980). Specific conductance within the range of 239 to 6,400 microsiemens per centimeter did not seem to have an overriding or adverse effect on the structure of periphyton communities. At values less than 6,400 microsiemens per centimeter, diatom diversity increased with specific conductance. Previous work in Montana by Miller and others (1978) indicated decreased diatom diversity associated with saline seeps and specific conductance values greater than 7,500 microsiemens per centimeter.

A study in southeastern Montana (Bahls and others, 1984) demonstrated the use of diatoms of the periphyton and phytoplankton as indicators of water quality. Many of the diatom species are useful as indicators of dissolved solids, suspended sediment, and temperature, which are three variables likely to be affected by surface mining and related activities (Bahls and others, 1984).

SUMMARY AND ADDITIONAL DATA NEEDS

By BRUCE P. VAN HAVEREN[5] and DONALD A. GOOLSBY

During the early 1970's, knowledge of hydrology and mining relations was obscured by uncertainties and, perhaps, a few misconceptions. For example, many scientists surmised that large volumes of water would be needed for reclamation processes in addition to that derived from natural precipitation. Today (1985), nearly all reclamation is done without supplementary water. Predicted large-scale withdrawals of surface water for use in coal-fired powerplants and coal-gasification and liquefaction operations have not materialized because these industries have not developed in the Western United States at the rate once expected.

During 1973, the National Academy of Sciences did a study of the rehabilitation potential of coal lands in the Western United States (National Academy of Sciences, 1974). In their report, the National Academy of Sciences discussed the adequacy of hydrologic data in the semiarid Western United States. The report stated that, for the areas being considered for coal development, serious gaps existed in the quantitative data about surface-water quality and aquatic biota. In addition, streamflow data for tributary streams and ground-water data were seriously deficient in the semiarid coal regions of the Western United States. The National Academy of Sciences (1974) report indicated the need for two distinct levels of hydrologic investigations—regional and site specific. Both levels of investigation were incorporated into the U.S. Geological Survey and U.S. Bureau of Land Management coal-hydrology program. Regional-scale appraisals would enable evaluation of the effects of several proposed mining operations in a large drainage basin and would include bench-mark stations for long-term monitoring of hydrologic changes. Site-specific investigations would answer questions about hydrologic changes that result from specific mining operations. Site-specific data also were needed to design measures to mitigate any onsite or offsite effects on water resources and to prepare reclamation plans.

By 1985, the occurrence of water resources and natural hydrologic processes in the major coal regions were better understood, and the general direction and magnitude of hydrologic changes resulting from surface mining can now (1985) be predicted more accurately. Throughout all coal regions, the most significant accomplishment of the coal-hydrology program was the expansion of the hydrologic data base. That data base, in addition to results from site-specific hydrologic investigations, provided for a much greater understanding of hydrologic processes in coal regions.

The surface- and ground-water hydrology of small areas (potential coal-lease tracts) was investigated thoroughly in the Green River and Hams Fork, Powder River, Bighorn Basin, Wind River, and Fort Union coal regions. Specific attention was focused on small watersheds less than 30 square miles in area. The results of those investigations aided development of mining and reclamation "best management practices" that maximize postmining landform stability and minimize disruption of surface hydrologic processes. In addition, much was learned about the hydrology of alluvial fill in small headwater valleys. This information has contributed to a better understanding of the hydrologic function of alluvial valley floors.

Site-specific studies done in Montana indicated that wells and shallow aquifers removed by mining may not be the only available water supply; wells drilled to deeper, unaffected aquifers could replace water supplies used during mining. Where saturated coal beds are mined, substantial problems may occur because of aquifer dewatering and leaching of soluble material from mine spoils.

In the larger watersheds, more than 30 square miles in area, attention was focused on characterizing surface-water and ground-water chemical quality. Because much of this data collection has preceded any extensive development of coal resources, an important data base now exists. These baseline data will be invaluable for future monitoring of effects of coal development on water quality.

Studies indicate that local decreases in water tables will occur within 1 to 2 miles of surface mines, but regional effects of coal mining on ground water are unlikely. The largest regional effect on water resources in the Powder River basin probably will be caused by increases in population and land-use changes, rather than by mining activities.

An accomplishment of the coal-hydrology program applicable to all coal regions was the increased knowledge of the areal extent and hydrogeologic properties of key aquifers. A better understanding of the relation between coal and ground-water systems now (1985) exists. For example, studies indicate that the alluvium of the Powder River valley is not a significant aquifer, and that the regional movement of ground water in shallow aquifers in northeastern Wyoming is not as important as local movement. Primarily, the local flow systems within shallow aquifers will be affected by mining rather

[5]U.S. Bureau of Land Management.

than the regional flow systems. In all the coal regions, the general effects of mine dewatering now (1985) can be predicted. In the Fort Union region, the principal geochemical processes that affect ground-water quality were identified, and the effects of mining on these processes were determined. For many surface-mining situations, the length of time that water of deteriorated quality will exist in mine spoils can be determined.

In terms of funds expended, nearly 15 percent of the total coal-hydrology-program funds was spent on developing predictive methods and simulation models. This effort was coincident with the general increase in the use of computers for large-scale, data-base manipulation and system simulation. For example, equations were developed using channel geometry and basin-characteristic techniques to predict average annual runoff. Methods to indirectly determine peak discharge also were developed for all the coal regions in the Western United States. A model to simulate surface hydrologic processes in small watersheds, including sediment yield, was developed and calibrated for use in the Western, Fort Union, Powder River, Bighorn Basin, Wind River, Green River, Hams Fork, and San Juan River regions.

In the Eastern coal province, substantial progress was made in determining specific relations between mining and hydrologic processes. For example, mining generally decreased peak flows and increased low flows. The discharge of conservative chemical constituents from small streams in the Appalachian regions was correlated with the age of coal mines in the contributing watersheds. A study in Alabama indicated that the dissolved-solids concentration will reach a maximum after about 7 years of mine operation and return to premining levels after about 15 years of mine operation. The effects of mining on stream-water quality were less in mined basins that were reclaimed under present reclamation laws than in basins reclaimed under previous systems.

One of the most important long-term issues associated with surface mining in the Western United States is the potential for degradation of water quality by leaching of soluble salts from mine spoils. Water samples obtained from mine spoils in Colorado and Montana have indicated consistently larger dissolved-solids concentrations than samples obtained from nearby undisturbed aquifers. Salinity models were developed to predict the effect of leachates from mine spoils on the dissolved-solids concentration of receiving streams. Modeling of dissolved solids in Rosebud Creek, Montana, has indicated that irrigation return flow accounts for a larger percentage of dissolved-solids loading than does mining at present (1985) levels. However, during full-scale mining, the percentage due to mining would exceed that of irrigation. Most of the geochemical processes that result in increased dissolved-solids concentrations occur in the unsaturated zone. Therefore, it would be advantageous to minimize vertical infiltration of water through mine spoils.

Acid mine drainage is not expected to become a major issue in the Western United States because coal from that area typically has a small sulfur content. However, coal regions in the Eastern United States have considerable acid mine drainage due to a larger sulfur content in the coal, larger precipitation quantities, and decreased alkalinity concentrations in the soil and overburden.

The soundness of coal-leasing decisions that involve water resources depends, in part, on the technical adequacy of the hydrologic data used in support of those decisions. Decisions based on insufficient or poor quality data have a great degree of uncertainty about them. The ability to make sound leasing decisions, in which water-resource issues are at stake, has improved as a result of the coal-hydrology investigations. At the land-use planning stage, the U.S. Bureau of Land Management uses hydrologic data to identify water-resource values and potential water-related issues. Prior to 1975, it was difficult to predict even the nature of potential coal development and water-resource issues; the direction and magnitude of the effects on water resources could not be predicted at that time. By 1980, a substantial hydrologic data base had been acquired in the coal regions. Although some monitoring data were available from existing mines, the U.S. Bureau of Land Management still did not have a definitive concept of probable effects, particularly ground-water related effects. These data uncertainties contributed to the deferral of many land-use planning decisions (U.S. Congress, 1984).

However, by 1983 the data collected and the investigations done during the previous 8 years had begun to produce valuable information that was sufficient to identify and address the major water-resource issues related to coal leasing at the land-use planning stage. For example, baseline water-quality data for the eastern half of Wyoming now (1985) are considered adequate for assessing effects of future mining.

One of the major decision points in Federal coal leasing has been the unsuitability criteria, which are environmental suitability tests by which all potential coal-lease tracts are reviewed before lease approval (U.S. Bureau of Land Management, 1985). Four of the twenty criteria apply to water resources: flood plains, municipal watersheds, National resource waters, and alluvial valley floors. Identification and mapping of flood plains is a detailed, site-specific process, best suited for analysis at the mine-planning stage. Flood-frequency analysis techniques were developed that enable determination of the 100-year flood flows for streams, including ephemeral drainages, in the major coal regions. Furthermore, sufficient methods now exist to predict the effects of surface-mine development on downstream flood plains.

Municipal watersheds may not be mined unless it is determined that mining will not impair the quantity or quality of a public water-supply system (U.S. Bureau of Land Management, 1985). Sufficient information is available for all the coal regions to evaluate the potential effects of surface coal mining on a municipal watershed. Because detailed development data are needed for hydrologic analysis purposes, those evaluations would need to be made at the mine-planning stage.

National resource waters are high-quality surface waters identified in State water-quality-management plans. Mining is to be excluded from Federal lands having such waters. A one-quarter mile buffer zone also is to be included, but this zone may be decreased or eliminated if the management agency can show it is not necessary for protection of the resource. Again, from a hydrologic standpoint, this situation needs to be analyzed in detail using specific mine plans.

Disruption of the surface- and ground-water hydrology of alluvial valley floors is of particular concern in the Powder River, Bighorn Basin, Wind River, Green River, Hams Fork, Fort Union, Denver, and Raton coal regions. Alluvial valley floors often support grass-hay production that is crucial to ranching and farming operations. Water is supplied either by flood irrigation or by natural subsurface means. Land owners are concerned that any disruption of hydrologic systems that are associated with alluvial valley floors will decrease the productivity of their hay meadows. Given detailed mine plans, hydrologists should be able to predict with reasonable certainty the hydrologic changes that may occur because of surface mining. However, at this time (1985), sufficient information about the hydraulic properties of mine spoils is not available to enable the prediction of hydrologic effects of mine reclamation and the resultant consequences for an alluvial valley floor system that depends on shallow aquifers for its subirrigation.

In summary, it seems that the hydrologic data base is adequate in most of the coal regions to address water-resource issues at the land-use planning and lease-approval stages. However, less information is available to prescribe specific regulations for water-resource protection at mine sites. In addition, the ability to predict cumulative effects of and prescribe regulations for multiple coal-development sites within a large watershed is not fully developed at this time (1985).

Sufficient hydrologic knowledge presently (1985) exists to prescribe measures that will maximize the rehabilitation of the water resources affected by mining. But, because of limited numbers of studies that describe hydrologic responses of mine-land rehabilitation, it is more difficult to predict long-term hydrologic trends of mined and rehabilitated lands. This knowledge eventually will be derived from ongoing studies of postmining hydrologic systems.

At the beginning of the coal-hydrology program, many needs existed for hydrologic information. These needs and the data-collection programs, hydrologic investigations, and research activities designed to meet these needs have been described in previous sections of this report. Many of these needs have been met, and much has been learned during the decade of the coal-hydrology program. Data have been obtained to define baseline hydrologic conditions in coal areas where little or no prior data existed, and much has been done to improve the understanding of hydrologic principles and processes as they pertain to coal mining. However, some needs have not been fully met and, as in many scientific efforts, knowledge gained during the coal-hydrology program has generated new questions and needs that were not known at the beginning of the program. A summary of some of the more important remaining needs for coal-hydrology information follows.

* Additional information is needed about the hydraulic properties of mine spoils and coal aquifers such as anisotropy and fracture control of flow, to enable prediction of downgradient, ground-water flow patterns and their effects on water quality.
* Additional research is needed to determine how chemical and microbiological processes such as ion exchange, sulfate reduction, and mineral equilibria can affect the recovery potential of contaminated aquifers that are downgradient from mine spoils.
* Additional work is needed to develop techniques to predict and quantify the cumulative hydrologic effects, particularly in terms of water quality and sediment, of multiple mines in the same drainage basin. A determination of cumulative effects is required by the Surface Mining Control and Reclamation Act and is needed by the Office of Surface Mining Reclamation and Enforcement to permit new mines and to renew permits for existing mines.
* Additional information and analysis is needed in the Interior coal province to determine if the postmining water quality in areas reclaimed to Surface Mining Control and Reclamation Act standards is substantially different from unreclaimed areas.
* During the final years (1982–84) of the coal-hydrology program, an intensive effort was begun to obtain precipitation, runoff, suspended-sediment, and water-quality data for 19 small

basins of varying land uses and hydrologic settings. Land use ranged from forested areas that had no mining to intensively mined basins. The hydrologic information was collected on a storm-event basis using automatic monitoring and sampling equipment. Curtailment of funds for coal-hydrology studies has prevented detailed analysis and interpretation of these data. Additional analysis of the data base is needed to determine how accurately models and other techniques developed during the coal-hydrology program can predict effects of mining on sedimentation and water quality. Techniques and models that are successful in predicting effects would be very useful to regulatory agencies.

* In the Western United States, several case studies are needed to document long-term hydrologic changes caused by surface mining. Ideally, these studies would begin prior to mining and continue during and after the mining process. The primary purpose of these studies would be to provide hydrologic information to test, calibrate, verify, and refine concepts, hypotheses, and models about the hydrologic effects of mining and to determine the effectiveness of reclamation efforts. A number of studies begun during the coal-hydrology program obtained hydrologic information prior to and during mining. However, no studies in the coal provinces in the Western United States have followed mining operations through the entire cycle from premining to postreclamation.

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