HYDROLOGIC-INFORMATION NEEDS FOR OIL-SHALE DEVELOPMENT, NORTHWESTERN COLORADO

Compiled by O. James Taylor

U.S. GEOLOGICAL SURVEY

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METRIC CONVERSIONS

Multiply inch-pound unit	*By*	*To obtain SI unit*
acre-foot (acre-ft)	1.234×10^{-3}	cubic hectometer
acre-foot per year (acre-ft/yr)	1.234×10^{-3}	cubic hectometer per year
barrel (bbl)	1.59×10^{-1}	cubic meter
barrel per day (bbl/d)	1.59×10^{-1}	cubic meter per day
barrel per year (bbl/yr)	1.59×10^{-1}	cubic meter per year
cubic foot per second (ft^3/s)	2.832×10^{-2}	cubic meter per second
foot (ft)	3.048×10^{-1}	meter
foot squared (ft^2)	9.29×10^{-2}	meter squared
gallon per day (gal/d)	3.785×10^{-3}	cubic meter per day
gallon per minute (gal/min)	3.785×10^{-3}	cubic meter per minute
gallon per ton (short) (gal/ton)	4.17×10^{-2}	cubic meter per megagram
inch (in.)	2.54	centimeter
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter
ton (short) per day (ton/d)	9.070×10^{-1}	metric ton per day
ton (short) per year (ton/yr)	9.070×10^{-1}	metric ton per year

GLOSSARY

Aboveground retort.--A large vessel used to heat crushed oil shale and cause the decomposition of the contained kerogen into shale oil.

Acid rain.--Precipitation of low pH that is attributed to emissions of the oxides of sulfur and nitrogen to the atmosphere.

Anisotropy.--A condition in which properties differ according to the direction of measurement.

Aquifer.--A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Aquifer test.--A field procedure used to determine the transmissive and storage characteristics of an aquifer. Commonly consists of measurement of the hydraulic or chemical response of the aquifer to a pumped well, injection well, changes in stream stage, or tracers.

Artesian aquifer.--See confined aquifer.

Bed material.--Sediment that makes up the streambed and moves only occasionally.

Bedload.--Material moving on or near the streambed by jumping, sliding, and rolling actions induced by streamflow.

Benthic invertebrate.--An animal without a backbone that lives in or on the bottom of an aquatic environment.

Biota.--All the plant and animal populations living together in an environment.

Confined aquifer.--An aquifer containing ground water that is enclosed under pressure between relatively impermeable or significantly less permeable material, and from which water will rise above the top of the aquifer if the aquifer is penetrated by a well.

Contaminant.--A chemical constituent that is present in a concentration that degrades the quality of water.

Desorption.--Removal of sorbed constituents.

Digital model.--See mathematical model.

Dissolved-solids concentration.--The dissolved constituents in water expressed as the weight of constituents per unit volume of water, without regard to the type of constituent.

Drawdown.--Lowering of the water table or potentiometric surface caused by the extraction of ground water by pumping, by artesian flow from a well or bore hole, or by a spring emerging from an aquifer.

Evapotranspiration.--Loss of water by evaporation from wet surfaces and by transpiration through plants.

Eutrophic.--Characterized by abundant nutrients that support plant and animal life whose decay depletes shallow water of oxygen during the summer.

Fracture.--A planar break in rock or sediment caused by mechanical failure in response to stress.

Fresh shale.--See unretorted shale.

Gain-and-loss study.--A series of surface-water flow measurements in a reach of a stream to determine increases or decreases in streamflow attributable to interchanges between the stream and associated aquifer.

Gaining stream.--A stream or reach of a stream in which flow is being increased by inflow of ground water.

Ground-water discharge.--Loss of water from a ground-water reservoir.

Ground-water divide.--The line or surface of separation between adjacent ground-water flow systems, such that ground water on one side of the divide flows in one direction, and ground water on the other side flows in another direction.

Ground-water recharge.--Addition of water to a ground-water reservoir.

Harmonic analysis.--A technique used to portray a seasonal cycle of some parameter, such as stream temperature. The technique often uses a first-order harmonic function--for example, a sine function.

Hydraulic conductivity.--The rate at which water may be transmitted through a unit area of an aquifer under a unit hydraulic gradient.

Hydraulic gradient.--Change in hydraulic head per unit length of flow path.

Hydrologic transport.--Movement of dissolved or suspended material by means of solution or suspension in ground or surface water.

In-situ retort.--In general, an underground zone within the oil-shale deposits in which the ore is blasted into small fragments. Hot fluids are injected into the zone, or it is ignited in order to separate shale oil, vapors, and water that are collected from a network of wells. The retorted shale remains in place after burning is complete.

Kerogen.--The solid bituminous mineraloid substance in oil shales that yields oil when the shale undergoes destructive distillation.

Leachate.--A liquid that has percolated through a porous medium, such as an in-situ retort or spoil pile of retorted shale, and has dissolved soluble constituents.

Least-square regression.--A statistical procedure for finding the best-fitting equation to relate a desired dependent variable to a set of independent variables.

Losing stream.--A stream or reach of a stream that is losing water to the ground-water reservoir.

Mass balance.--An accounting of the amounts of the components of a process or system, in order to derive information on the source, migration, or fate of any component.

Mathematical model.--One or more mathematical equations used to represent and to simulate the response of a system to natural or man-induced conditions.

Modified in-situ retort.--In general, an underground zone within oil-shale deposits in which part of the ore is mined and the remainder is blasted into small fragments. Natural gas, air, and possibly steam are injected, as carbon contained in the shale is ignited. Products include oil vapor, condensed oil, hydrogen gases, and water that are collected from a sump at the base of the retort. The retorted shale remains in place after burning is complete.

Oil shale.--A sedimentary rock that contains organic material called kerogen, that may be extracted as liquid oil and gas by heating.

Oligotrophic.--A lake condition characterized by a lack of nutrients that can support only sparse plant and animal life, and a high oxygen content because of the low organic content.

Permeability.--A measure of the ability of an aquifer to transmit water under a hydraulic gradient.

Potentiometric surface.--A surface connecting points to which water would rise in tightly cased wells receiving water from given points in an aquifer. A map of the potentiometric surface is useful to indicate direction of ground-water movement.

Raw shale.--See unretorted shale.

Reaeration.--Physical absorption of oxygen from the atmosphere. The primary process by which a stream replaces oxygen consumed in the biodegradation of organic wastes.

Retorted shale.--Oil shale for which all or part of the kerogen has been converted to shale oil.

Room-and-pillar mining.--An underground mining method in which ore is mined in rooms that are separated by pillars. The roof of the mine is supported by the pillars as mining proceeds. Sometimes the pillars are mined as the mine is abandoned.

Saturated zone.--A subsurface zone in which all of the interstices are filled with water under pressure greater than that of the atmosphere.

Simulation.--Technique used to imitate and study the behavior of a system under existing or proposed conditions. Commonly used to predict the response of a system to proposed action. (See also Mathematical Model.)

Specific yield.--The volume of water that can be drained by gravity from a saturated rock or soil in relation to the bulk volume of the rock or soil.

Spent shale.--See retorted shale.

Spoil pile.--The disposal area for mine waste such as retorted shale.

Storage coefficient.--The volume of water released from storage or taken into storage in an aquifer, per unit surface area of the aquifer, per unit change in head.

Stream-aquifer system.--A stream and adjacent aquifer that are hydraulically connected, so that interchanges of water between the stream and aquifer will occur.

Stream depletion.--Reduction of streamflow in a stream-aquifer system due to withdrawals from wells that capture streamflow or intercept ground water that would have discharged to the stream.

Substrate.--The physical surface upon which an organism lives.

Surface runoff.--Overland flow or flow in rills that results from precipitation.

Suspended sediment.--Material maintained in the main body of streamflow by upward components of turbulence and kept in suspension for appreciable lengths of time.

Taxon (taxa, plural).--Any classification category of organisms.

Taxonomy.--The division of biology concerned with the classification and naming of organisms.

Time-trend analysis.--A statistical-analysis technique for studying the changes in constituents over time.

Total load.--The sum of suspended load and bedload transmitted by a stream through a cross section in an interval of time.

Transmissivity.--The rate at which ground water may be transmitted through a cross section of unit width over the entire thickness of an aquifer, under standardized conditions. Equal to hydraulic conductivity multiplied by the thickness of the aquifer.

Trophic relation.--Interaction of organisms with respect to each other and their environment.

Unconfined aquifer.--An aquifer that has a water table and contains ground water that is not confined under pressure by overlying impermeable or significantly less permeable material.

Underflow.--Downstream movement of ground water in a valley-fill aquifer; also used to describe water movement in an aquifer in general.

Unretorted oil shale.--Oil shale that has been mined and crushed in preparation for retorting.

Unsaturated zone.--A region of a porous medium that contains water in the gas phase under atmospheric pressure, water temporarily or permanently under less than atmospheric pressure, and air and other gases.

Wasteload-assimilative capacity.--A measure of the characteristic of natural water to incorporate natural waste.

Waste management.--Plans and operational procedures designed to eliminate or reduce any harmful effects related to waste effluent.

Wastewater.--Effluent from municipal treatment plants, or water flowing from mine workings, in-situ retorts, and retorted shale piles; water resulting from process plants and extraction facilities.

Water management.--Plans and operational procedures designed to allocate water supplies, reduce water shortages or surpluses, or achieve any specialized goal in natural or manmade water systems.

HYDROLOGIC-INFORMATION NEEDS FOR OIL-SHALE DEVELOPMENT, NORTHWESTERN COLORADO

Compiled by O. James Taylor

ABSTRACT

The Piceance basin of northwestern Colorado contains large reserves of oil shale. Expected development of oil shale will affect the regional hydrologic systems because most oil-shale mines will require drainage; industrial requirements for water may be large; and oil-shale mines, wastes, and retorts may affect the quantity and quality of surface water and ground water. In addition, the oil-shale industry may discharge particles and gases to the atmosphere that could alter the quality of high-altitude lakes and surface-water reservoirs.

Hydrologic data need to be collected in order to plan for oil-shale development and to estimate the effects of development. Test-well drilling and aquifer testing are needed to provide a better understanding of the local and regional flow system, to furnish additional data for a model that simulates mine drainage, and to explore for water supplies in aquifers of Paleozoic and Mesozoic age. Improved understanding of the hydrologic flow system also will result from additional studies of ground-water quality because major aquifers can be distinguished by certain dissolved constituents, and the solution of evaporate minerals affects water quality and permeability. Much of the ground water in the bedrock aquifers discharges through springs, and a systematic study of the springs will help to predict the effects of mine drainage on spring discharge and quality. Surface runoff, dissolved and suspended loads in streams, and the aquatic environment in streams would be highly susceptible to the disruptions in the land surface and will require additional study in order to estimate the effects of development. A water-quality assessment is proposed for the White River basin because it is a possible source of water and a region likely to be affected by development. The effects of emissions to the atmosphere from oil-shale plants require study because these emissions may affect the quality of water in lakes downwind. Spoil piles of retorted oil shale may be very large and require study to anticipate any problems caused by leaching and erosion. Processing wastes resulting from in-situ retorts and other waste materials need to be studied in greater detail in order to estimate their impacts on the hydrologic system.

INTRODUCTION

By O. James Taylor

Oil-shale development is likely in northwestern Colorado because of National demands for energy supplies. Estimated reserves in the Piceance basin are approximately 1.2 trillion bbl of oil from known oil-shale deposits with a minimum grade of 15 gal/ton of rock (Federal Energy Administration, 1974). The impact of large-scale oil-shale development on the hydrologic system in the Piceance basin and the entire region is of concern to local citizens, environmental groups, and State and local management agencies. Consequently, advanced technological strategies must be developed by involving the mining, retorting, geological, hydrological, and environmental sciences. This report discusses the needs for hydrologic information related to oil-shale development.

Purpose

Hydrologic data have been collected and interpreted for many years in the Piceance basin. Major reconnaissance investigations have been made by Federal and State agencies, universities, research laboratories, private companies, and consultants. However, hydrologic information is incomplete, is proprietary in some cases, and is in scattered publications and files. Hydrologic data gathered to date are not adequate for water-resource planning. A comprehensive hydrologic study plan is needed for the basin, in order to organize existing information and to formulate strategies for collection of additional data in an efficient manner.

The purpose of this report is to summarize existing hydrologic information in the Piceance basin, to describe types of needed information, to suggest methods of obtaining needed information, and to outline standards for collection. The report also will provide guidance for comprehensive integrated hydrologic studies that will be necessary for water-resource planning in oil-shale development. These studies should provide hydrologic understanding that will benefit all aspects of water-resource and oil-shale development in the region.

Design of Hydrologic Studies

The U.S. Geological Survey has a primary responsibility to assess the quantity and quality of the Nation's water resources. Hydrologic studies are required to provide the understanding of complex, interactive systems and the processes which govern the occurrence of water and its quality. Specialized, technical investigations can be conducted to determine the impact of proposed development or land use plans on the hydrologic system. Three specific guidelines are needed to design an investigation which will provide pertinent data and information in the most efficient manner. These are:

1. Goal identification: A clear definition of the objectives of the investigation is essential for success and will provide direction for decisions required in preliminary planning.

2. Approach: The areal and technical content of the investigation needs to be designated. Key elements to be considered in establishing the approach include types of measurements or samples to be collected; the measurement or sampling frequency as related to statistical design; and quality-assurance standards for unbiased interpretation of the hydrologic system.

3. Site selection: Site selection is guided by project objectives and approach. Some elements pertinent to site selection include geologic and hydrologic variations, prevailing weather patterns, land use, vegetation type, soil type, and other basin physical characteristics.

The impacts of oil-shale development on the hydrologic system are related to surface runoff, the present land use, soils, mineralogy, infiltration rates, and ground-water flow patterns. After development begins, changes in hydrologic conditions and mining must be monitored to permit assessment of the magnitude of any changes. As oil-shale development increases, the U.S. Geological Survey will be called upon to provide answers to the following questions:

1. Generally, what is the premining hydrology?

2. How do surface- and ground-water flow interact to produce existing hydrologic conditions?

3. What are current water-quality conditions in the basin in terms of dissolved-solids concentration, chemical-loading characteristics, suspended sediment, and aquatic biology?

4. What are the water-quantity and water-quality changes caused by mining?

5. What are the regional changes in hydrology, water quality, and air quality associated with mining operations?

Using the above questions as primary study objectives, approaches can be developed which will provide knowledge of current conditions and the hydrologic impacts of oil-shale development.

Previous Hydrologic Investigations

Published results of investigations are too numerous to list so only major reports are discussed in this section. Reports that describe the water resources of the Upper Colorado River Basin include those by Iorns and others (1965) and Price and Arnow (1974). Other hydrologic reports on the Piceance basin by the U.S. Geological Survey include a reconnaissance investigation by Coffin and others (1971); mathematical modeling of basin hydrology by Weeks and others (1974); an evaluation of hillslope and channel erosion by Frickel, Shown, and Patton (1975); results of test-hole drilling by Welder and Saulnier (1978); and solute transport modeling by Robson and Saulnier (1980). The U.S. Department of the Interior (1974) prepared a report on water supplies for energy in the Upper Colorado River Basin.

A regional analysis of water supply and demand for the region was prepared by the Colorado Department of Natural Resources (1979). Other reports that describe hydrologic information include environmental impact statements, environmental impact analyses, detailed development plans for oil-shale mines, industrial summary reports, and industrial progress reports. Copies of most of the available hydrologic reports for the Piceance basin may be examined in the Oil Shale Office of the U.S. Department of the Interior in Grand Junction, Colo.

Location and Extent of the Piceance Basin

The Piceance structural basin is in northwestern Colorado in Rio Blanco, Delta, Garfield, Gunnison, Pitkin, and Mesa Counties. The principal study area, called "Piceance basin" in this report, is a part of the structural basin that includes four major drainage basins, the Piceance Creek and Yellow Creek basins in the north and the Roan Creek and Parachute Creek basins in the south. The principal study area is shown in figure 1. The major drainage basins and their tributaries are shown in figure 2. The Federal Prototype Lease Tracts C-a and C-b that lie within the drainage basins of Yellow and Piceance Creeks also are shown in figure 2.

Geologic Setting of the Piceance Basin

Rocks exposed in and near the Piceance basin in northwestern Colorado range from Precambrian to Quaternary in age. Precambrian, Paleozoic, and Mesozoic rocks (fig. 3) crop out in the White River uplift immediately east of the Piceance basin and dip steeply westward into the basin where they occur at great depth, as shown in figure 4. The surficial features in figure 4 also are shown in figure 2. Rocks at the surface in the Piceance basin and along its edge range in age from Tertiary (Eocene) to Quaternary. This report is concerned primarily with the Eocene Green River and Uinta Formations and the Quaternary valley-fill alluvium, which contain the principal aquifers of the area (table 1).

Hydrologic Setting of the Piceance Basin

Normal annual precipitation in the basin ranges from about 12 to 20 in., as shown in figure 5 (Environmental Sciences Services Administration, 1968). Winter precipitation is stored as snowpack in the higher altitudes of the basin, and runoff from snowmelt is one of the main sources of streamflow. Areas of snowpack accumulation provide recharge to the ground-water system, as shown in figure 6. Recharge water moves downward through a series of upper aquifers above the Mahogany zone that consists of fractured oil shale and sandstone. Part of the ground water continues slowly downward through the Mahogany zone and into the lower series of aquifers. In some places in the Piceance Creek and Yellow Creek basins, the ground water discharges from the bedrock aquifers into the valley-fill alluvium,

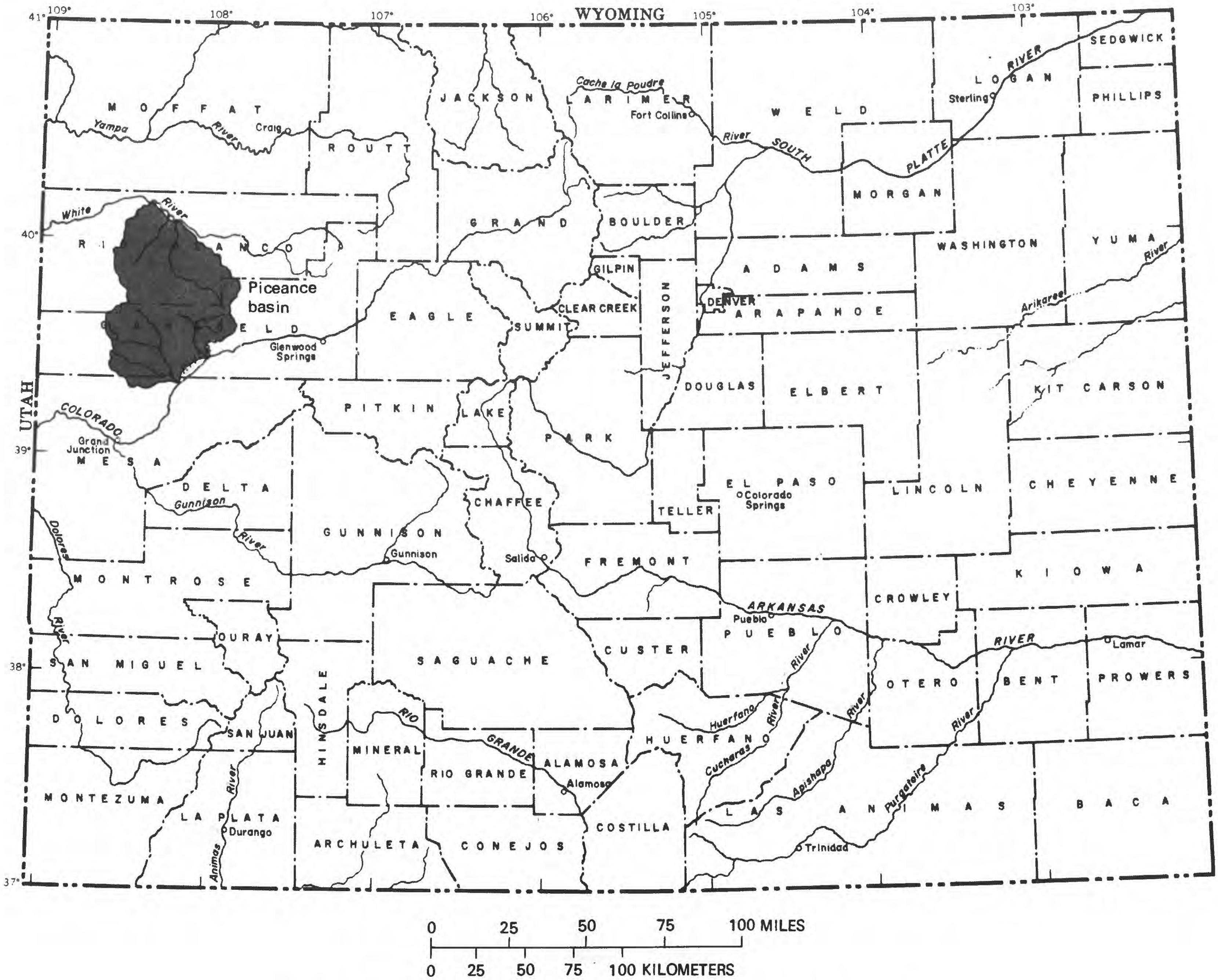
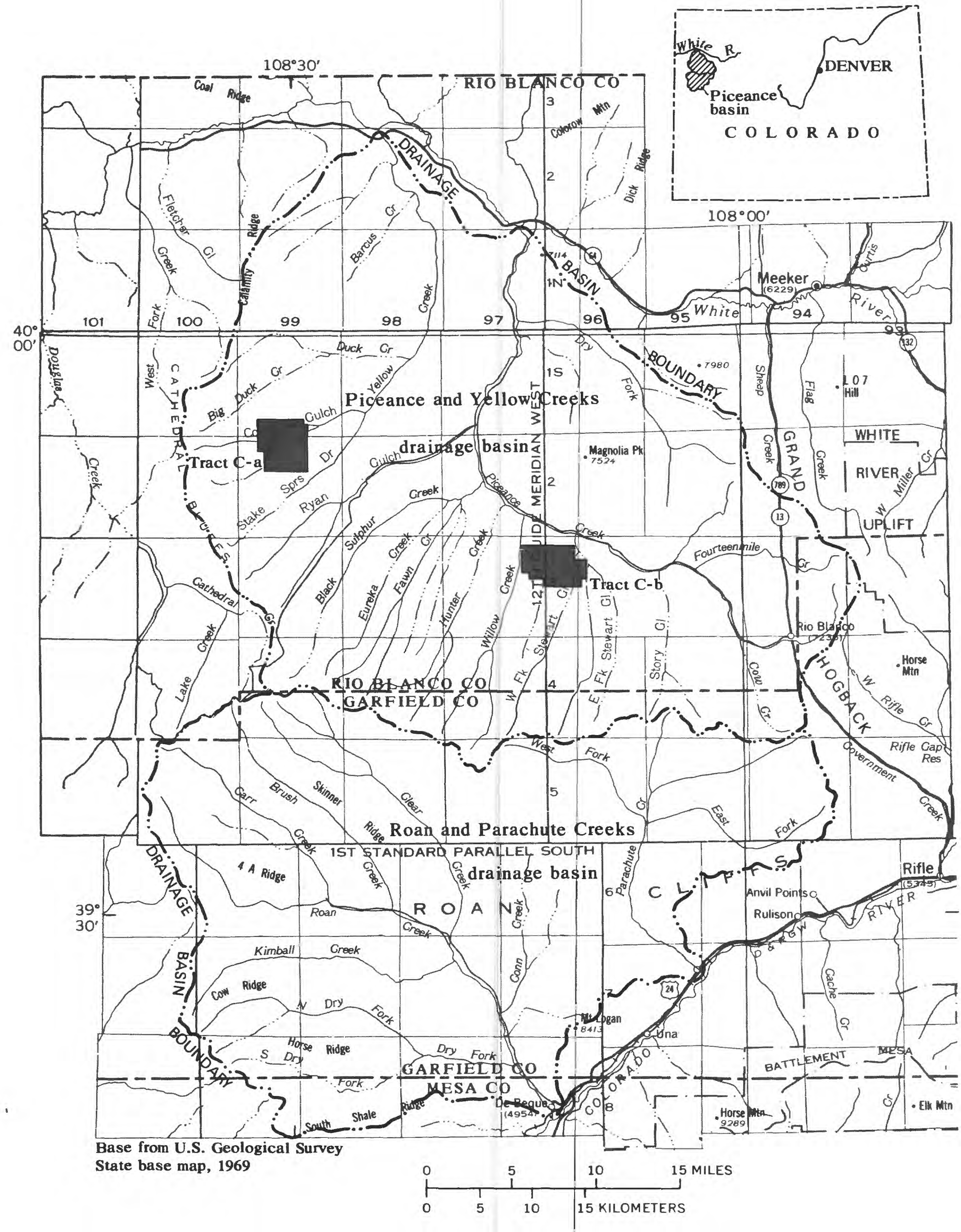


Figure 1.--Location of the Piceance basin, northwestern Colorado.



Base from U.S. Geological Survey
State base map, 1969

Figure 2.--Major drainage basins of the Piceance basin.

Erathem	System	Series	Unit South-North	General lithology (thickness in feet)
MESOZOIC	Cretaceous	Upper	Mesaverde Group: Williams Fork Formation	Brown/white sandstone, gray/black shale; coal (4,500)
			Mesaverde Group: Iles Formation	Brown/white sandstone; gray shale, coal (1,000 to 1,600)
		?	Mancos Shale	Gray shale; gray sandstone (5,000 to 6,000)
		?	Dakota Sandstone	Gray/tan sandstone (125 to 225)
		?[1] Lower	Cedar Mountain Formation	Yellow sandstone; green claystone (225)
	Jurassic	Upper	Morrison Formation	Variegated shale and mudstone; gray sandstone; local gray limestone (500)
		Middle	Curtis Formation	Gray/green, glauconitic sandstone; gray oolitic limestone (100)
			Entrada Sandstone	Gray/orange, crossbedded sandstone (75 to 100)
	?	?	Glen Canyon Sandstone[2]	Gray/orange, crossbedded sandstone (0 to 75)
	Triassic	Upper	Chinle Formation	Red/mottled sandstone, siltstone, shale; gray/brown conglomeratic sandstone (225 to 560)
		Lower	State Bridge Formation	Red-brown, brown-buff shale/siltstone; gray dolomite/limestone (100 to 480)
PALEOZOIC	Permian			
	Pennsylvanian	Upper	Weber Sandstone	Weber--Gray sandstone (20 to 250)
		Middle	Maroon Formation	Maroon--Maroon arkosic sandstone, shale, siltstone, conglomerate (1,600 to 1,700)
			Eagle Valley Formation	Eagle Valley--Gray siltstone, shale, sandstone, carbonate rocks, gypsum lenses
			Minturn Formation	Minturn--Gray-red sandstone, grit, conglomerate, shale, carbonate rocks (Eagle Valley + Minturn to 1,900)
			Belden Formation	Gray limestone/shale (550 to 700)
		Lower	Molas Formation	Red-brown shale/siltstone; gray chert (20 to 40)
	Mississippian	Upper		
		Lower	Leadville Limestone[3]	Gray limestone (100 to 260)
	?	?		
	Devonian	Upper	Chaffee Formation	Gray limestone, dolomitic limestone, and shale; white quartzite (120 to 260)
		Middle/Lower		
	Silurian			
	Ordovician	Upper	Fremont Limestone	Gray/white limestone and dolomitic limestone (60)
		Middle	Harding Sandstone	Gray/white sandstone, siltstone, or shale (5)
		Lower	Manitou Dolomite	Brown dolomite; gray shale; limestone pebble conglomerate (80 to 150)
	Cambrian	Upper	Dotsero Formation	Gray dolomite; limestone/dolomite conglomerate; gray shale (100)
			Peerless Formation	Gray shale; orange/brown sandstone and dolomite (67)
			Sawatch Sandstone	Brown sandstone (250 to 500)
		Middle/Lower		

NOTE: Slash indicates range in color or lithology

[1]The boundary between the upper and lower series of the Cretaceous System is uncertain. It may be within the lower part of the Mancos Shale, or at the top of the Cedar Mountain Formation

[2]The Glen Canyon Sandstone and Glen Canyon Group may be equivalent to the Wingate Sandstone (Poole and Stewart, 1964) or to the Navajo Sandstone (MacLachlan, 1972)

[3]The boundary between use of Madison Limestone and Leadville Limestone is uncertain

After Bass and Northrop, 1963; Bryant, 1979; Gaskill and Godwin, 1966; Imlay, 1980; Johnson and others, 1980; MacLachlan, 1972; Murray, 1966; Poole and Stewart, 1964. Compiled by M.E. MacLachlan, 1982

Figure 3.--Stratigraphic column of Paleozoic and Mesozoic rocks, White River uplift and Piceance basin.

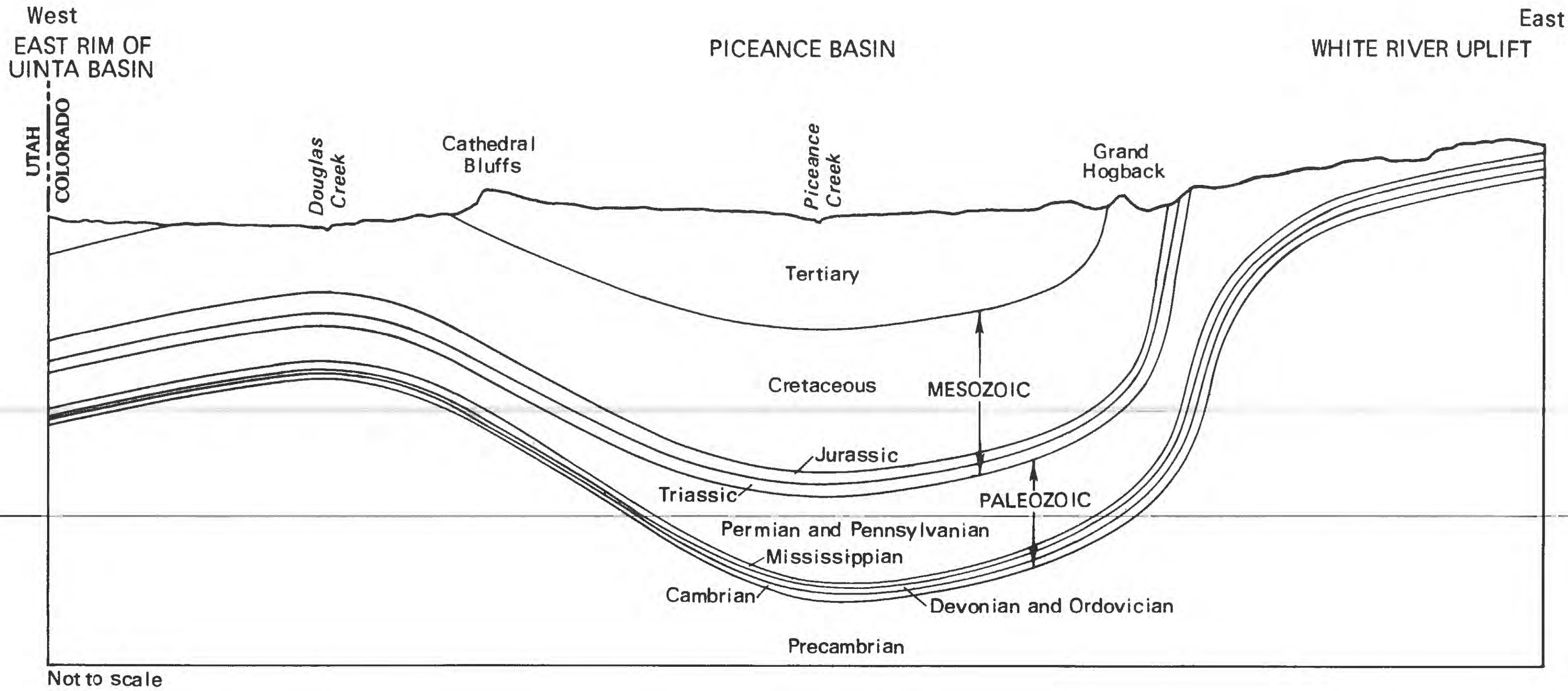
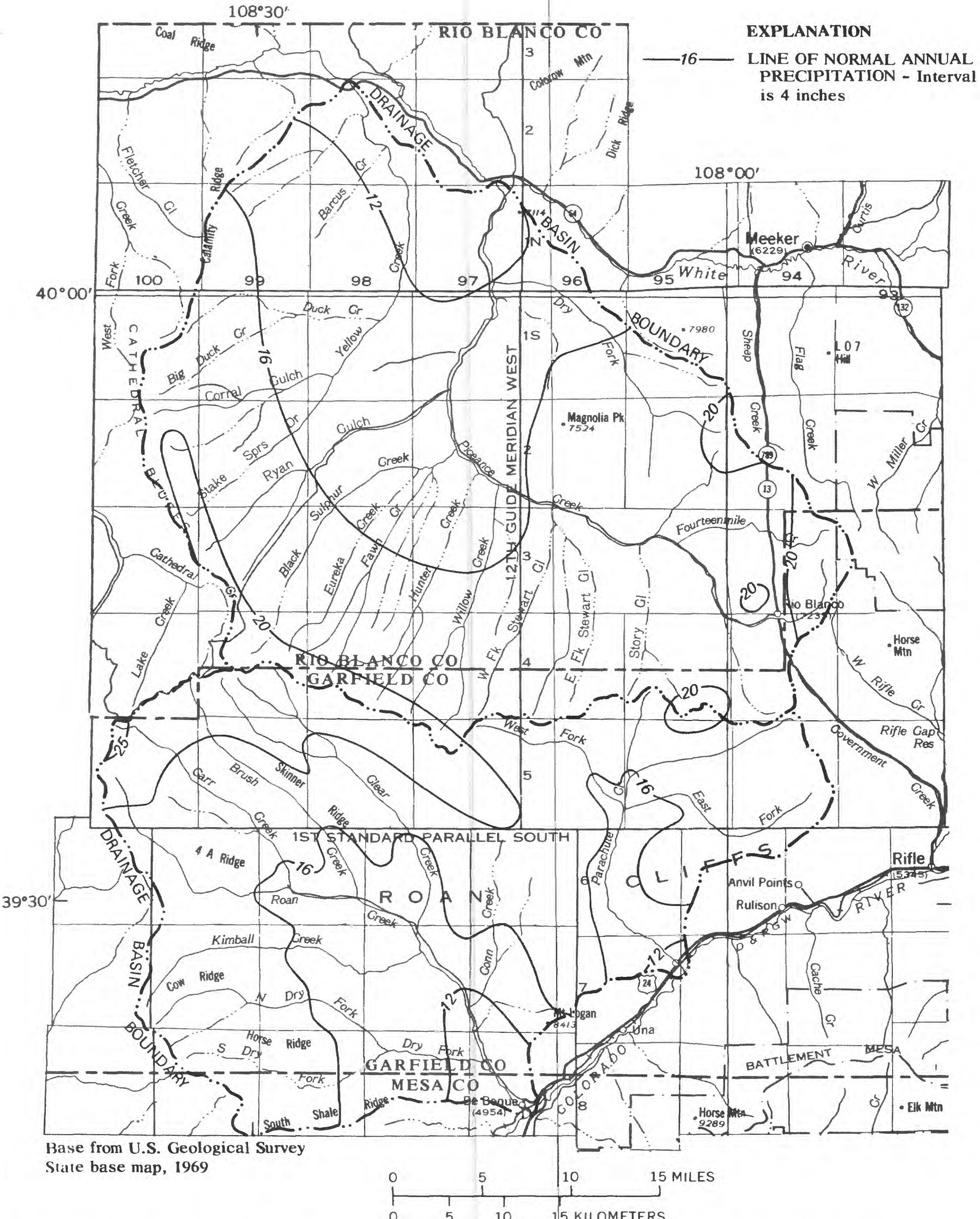


Figure 4.-- Generalized west-east geologic section of northwestern Colorado.

Table 1.--*Stratigraphic column of Tertiary (Eocene) and Quaternary rocks, Piceance basin*

[Modified from Coffin and others, 1971]

Geologic age	Formation	Geologic unit and thickness (feet)	Lithologic unit and thickness (feet)	
Quaternary		Alluvium and lake deposits (0-80)	Sand and gravel. Clay; generally organic.	
Tertiary (Eocene)		Uinta Formation (0-1,250)	Sandstone, silty, coarse to fine-grained; poorly sorted, and siltstone with some barren marlstone. Fractured in lower part. Little or no primary porosity.	
	Green River Formation	Parachute Creek Member (500-1,700)	Kerogenous dolomitic marlstone containing some thin ash beds. Can be divided into the following four zones:	
			Zone 4 (<500)	Marlstone containing little oil shale. Fractured.
			Zone 3 Mahogany zone (100-200)	Oil shale. Fractured except where deeply buried.
			Zone 2 Leached or low resistivity zone (<200-700)	Oil shale. Fractured; more porous and permeable than the underlying or overlying zones. Low resistivity on electric logs.
			Zone 1 High resistivity zone (1,100 or less)	Oil shale and sodium minerals. Slightly fractured. Thickest in north-central part of basin; thin elsewhere.
		Anvil Points Member (0-1,800)	Shale, sandstone, and barren marlstone with minor amounts of siltstone and algal and oolitic marlstone. A basin-edge facies which grades into the Garden Gulch and Douglas Creek Members.	
		Garden Gulch (0-900)	Shale and barren marlstone with local thin beds of sandstone and limestone. A basin-edge facies best developed in the southern part of the basin.	
		Douglas Creek Member (0-800)	Sandstone with some limestone and shale.	



Base from U.S. Geological Survey State base map, 1969

Figure 5.--Normal annual precipitation 1931-60. (Modified from Environmental Science Services Administration, 1968.)

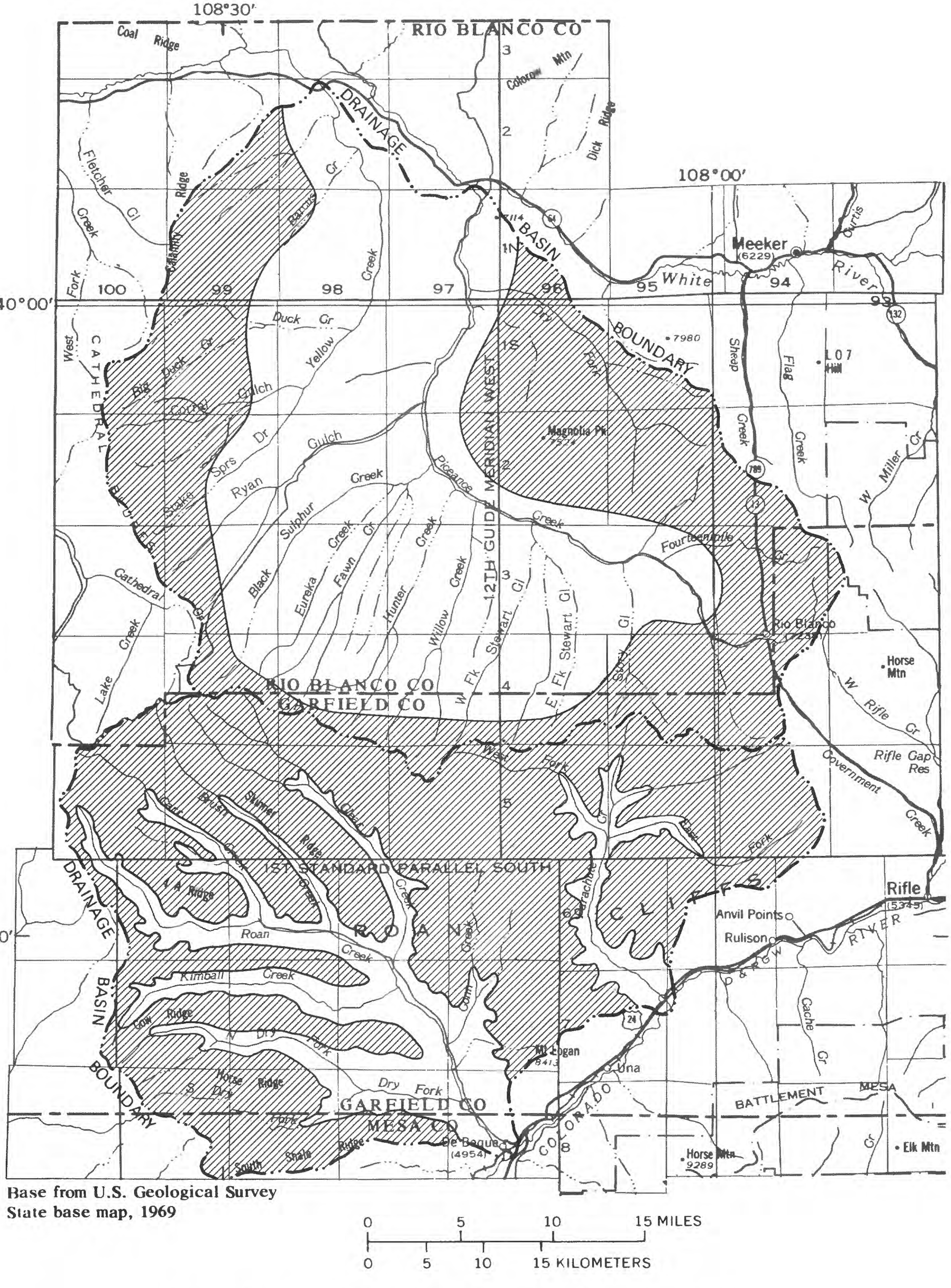


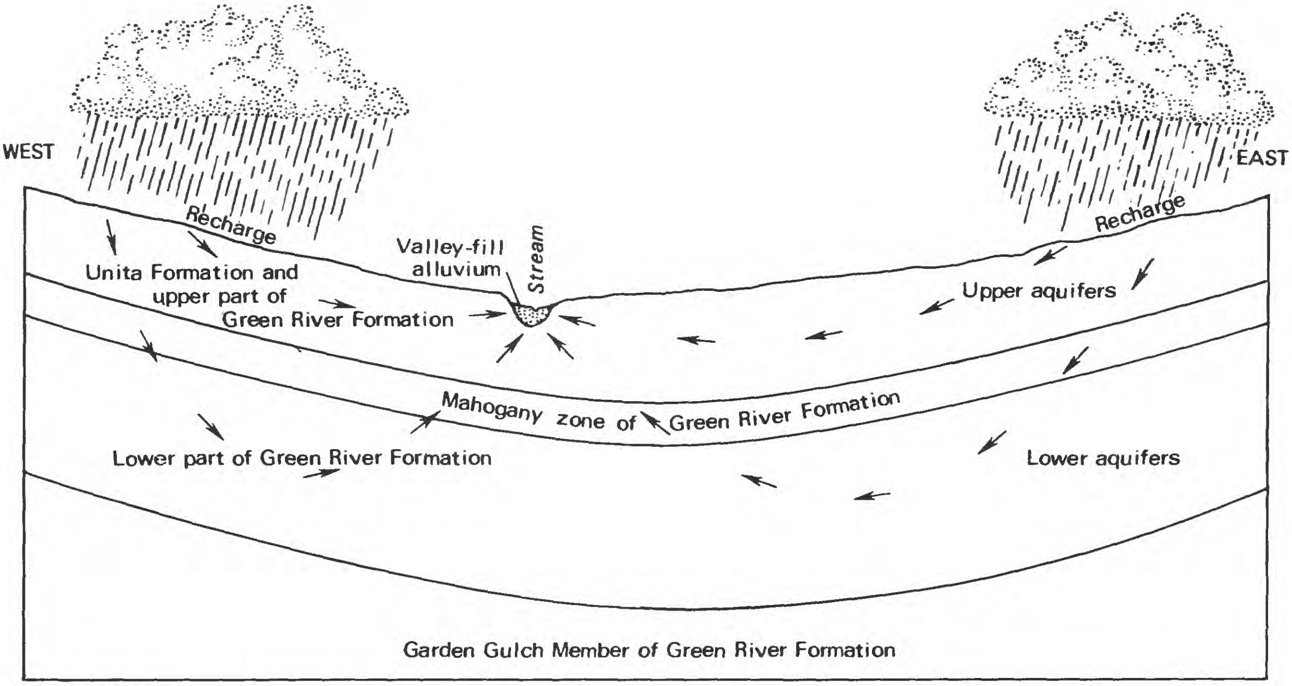
Figure 6.-- Approximate area of natural recharge (hachured).

which in turn yields water to springs. In other places in the basins, the ground water discharges directly from bedrock aquifers to springs near these creeks and their tributaries. The streams, alluvium, and bedrock in the Piceance Creek and Yellow Creek basins form a stream-aquifer system. In contrast, the oil-shale aquifers in the Roan Creek and Parachute Creek basins discharge to springs and seeps on the canyon walls above the streams and are not part of a stream-aquifer system, except possibly in the upper reaches of the streams where the valleys are not incised below the bedrock aquifers. Schematic diagrams of these ground-water flow systems are shown in figure 7.

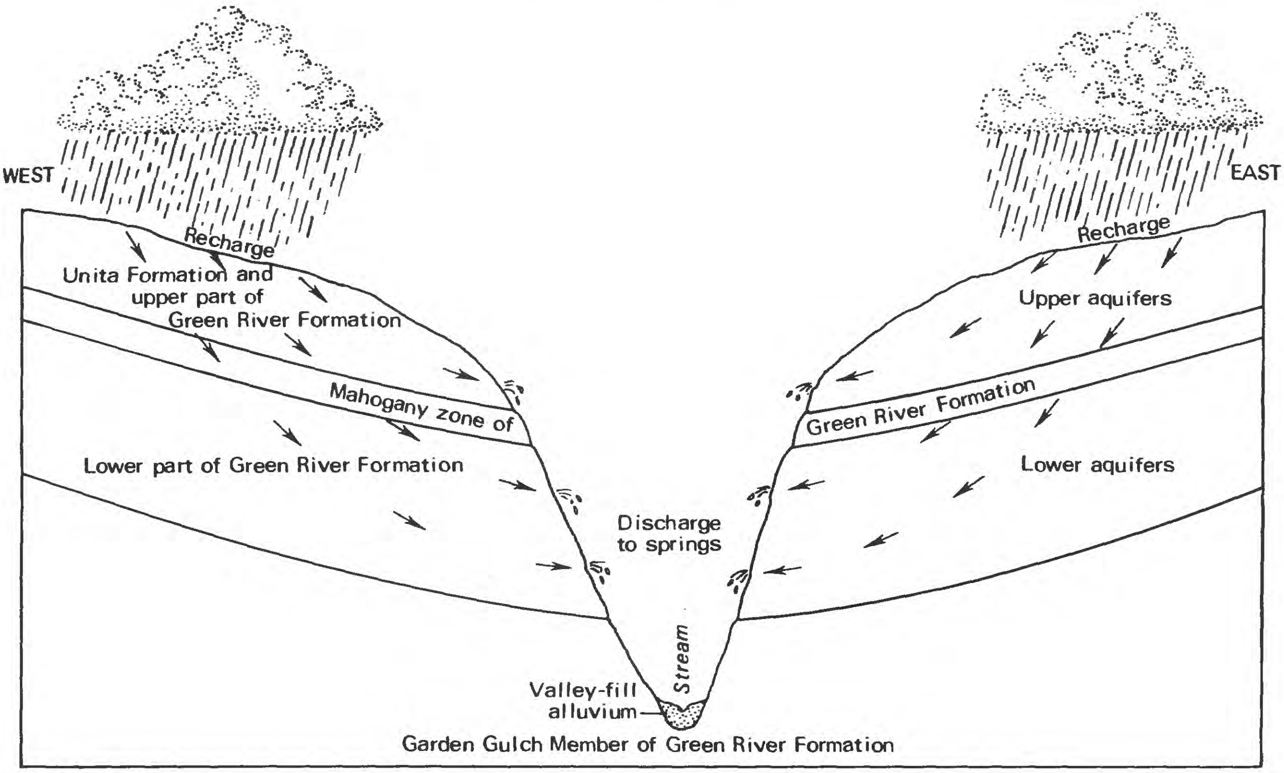
The hydraulic conductivities of the various formations in the Piceance basin differ greatly. The Douglas Creek, Garden Gulch, and Anvil Points Members of the Green River Formation all have relatively low hydraulic conductivities. The hydraulic conductivity of zones 2 and 4 in the Parachute Creek Member is relatively high. The other two zones and the Uinta Formation have relatively low hydraulic conductivities. The alluvium has the highest hydraulic conductivity of any formation in the basin.

Water quality in the basin is also highly variable. The dissolved-solids concentration in streams increases in the downstream direction. Hillside erosion contributes large amounts of suspended sediment and bedload to streams. Studies of benthic invertebrates in Piceance Creek indicate that stream quality is degraded in the downstream direction. The types of dissolved solids are similar in ground water and surface water but concentrations are greater in the lower aquifers. In the northern part of the Piceance basin, the solution of the minerals nahcolite and halite in the lower aquifers has resulted in dissolved-solids concentrations as high as 63,000 mg/L (milligrams per liter).

Much of the water required for oil-shale development may be obtained from local supplies of surface and ground water. A discussion of water use, supplies, and management follows.



A. Piceance and Yellow Creek drainage basins



B. Roan and Parachute Creek drainage basins

Figure 7.--Schematic diagram of ground-water flow systems.

WATER FOR OIL-SHALE DEVELOPMENT

By G. A. Miller and Vernon W. Norman

Current Use

Currently the majority of water used in the White River basin and in the Colorado River basin between Rifle and DeBeque comes from surface-water development for irrigated agriculture and livestock. Municipal water supplies are derived from surface-water sources, either directly from diversion or indirectly from wells adjacent to the rivers. Other uses of surface water are recreational purposes, such as swimming, fishing, boating, and rafting. In the past few years there has been an increase in the use of surface water for secondary crude-oil recovery at Rangely and for use in drilling exploratory holes for various resource evaluation and development. Surface water also is being used for construction needs, such as dust suppression and in soil compaction. The majority of ground-water use is for domestic and livestock purposes. Springs are often used for domestic, livestock, and limited irrigation needs.

Projected Use

A variety of needs for water are projected for oil-shale mines and plants. Estimates of water needs, the supplies available, and potential constraints on water availability indicate that prudent management of the water supply will be a necessity. Water uses for oil-shale development, as recognized today, may be classified into industrial uses at an oil-shale mine and plant and ancillary uses by the supporting population. The use by industry is assumed to be consumptive use; that for ancillary purposes is mostly for municipal systems, for which only a fraction is consumptively used.

Water use at an oil-shale mine and plant site may include water consumed for dust control, drilling, process steam, mine-ventilation exhaust, power generation, cooling, moistening retorted shale, reclaiming and revegetating retorted shale and other disturbed lands, stack scrubbers, and other minor uses, including domestic supplies. The amount of water use, based largely on projections rather than on operational data, may be in the range of 1 to 4 bbl of water per barrel of shale oil produced at a 50,000-bbl/d plant. Thus, water use by a 400,000-bbl/d industry may range from 19,000 to 75,000 acre-ft/yr. The wide range in projected use is in part related to different oil-shale mining and extraction processes and in part reflects the uncertainties of projecting uses based on only small-scale industrial experience. Estimated industrial water requirements are shown in figure 8. A large industry may have tremendous water requirements if the maximum water-use ratio is realized. Water requirements for a relatively small industry are shown in table 2 for greater detail.

Estimates of ancillary use by the increased population that will accompany large-scale development of oil shale are based on the projection of population growth. Published estimates suggest that a 50,000-bbl/d mine and plant will employ

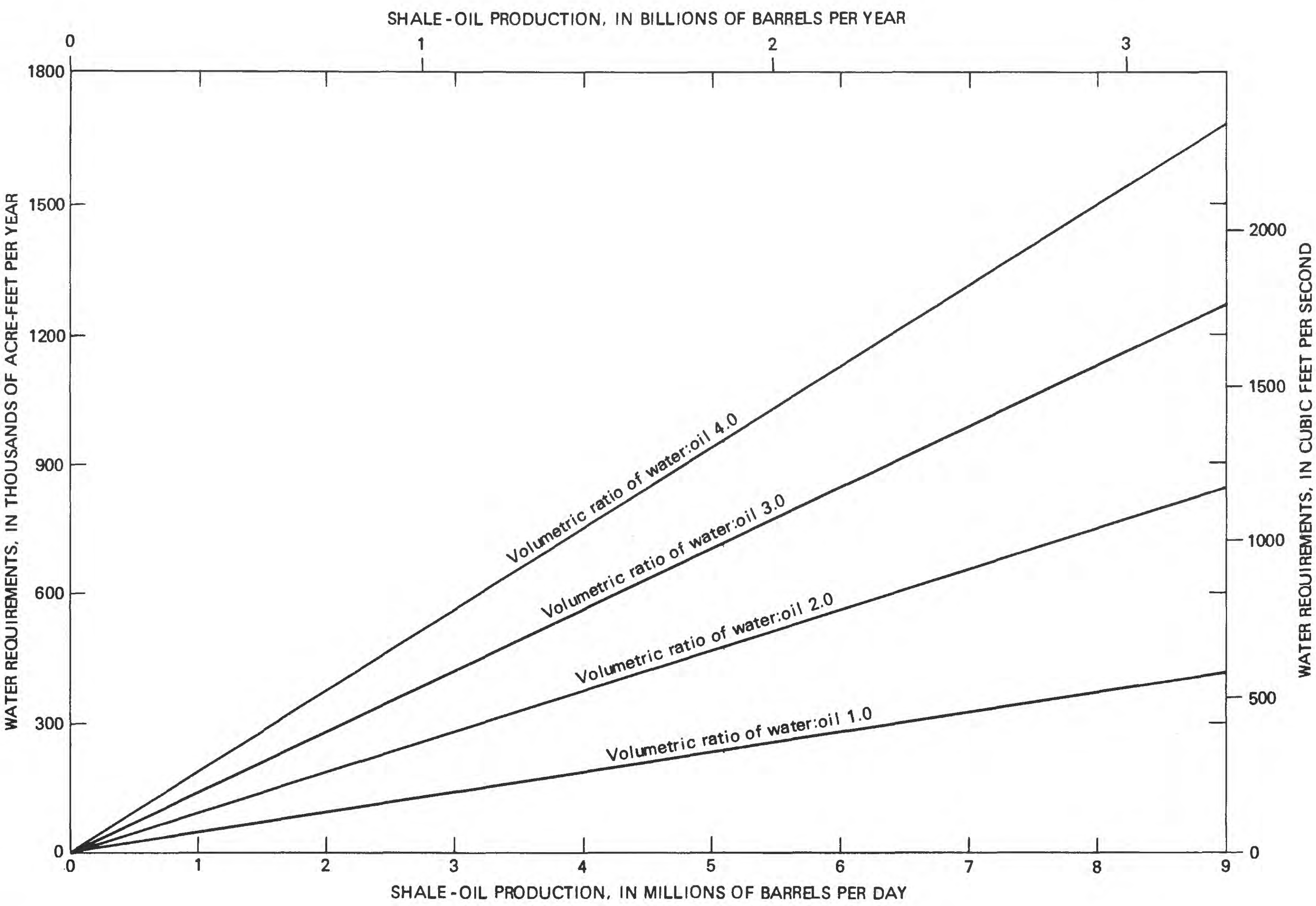


Figure 8.-- Industrial water requirements for shale-oil production.

Table 2.--*Industrial water requirements for shale-oil production 1 million barrels per day or less*

Shale-oil production (barrels per day)	Water requirements for indicated volumetric ratio of water to oil (acre-feet per year)			
	Water:oil 1.0	Water:oil 2.0	Water:oil 3.0	Water:oil 4.0
50,000	2,400	4,700	7,100	9,400
100,000	4,700	9,400	14,000	19,000
200,000	9,400	19,000	28,000	38,000
300,000	14,000	28,000	42,000	56,000
400,000	19,000	38,000	56,000	75,000
500,000	24,000	47,000	71,000	94,000
600,000	28,000	56,000	85,000	113,000
700,000	33,000	66,000	99,000	132,000
800,000	38,000	75,000	113,000	151,000
900,000	42,000	85,000	127,000	169,000
1,000,000	47,000	94,000	141,000	188,000

Table 3.--*Ancillary water requirements for shale-oil production 1 million barrels per day or less*

Shale-oil production (barrels per day)	Water requirements (acre-feet per year)		
	Population per plant[1]		
	9,000	12,000	15,000
50,000	1,000	1,300	1,700
100,000	2,000	2,700	3,400
200,000	4,000	5,400	6,700
300,000	6,000	8,000	10,000
400,000	7,600	11,000	13,000
500,000	10,000	13,000	17,000
600,000	12,000	16,000	20,000
700,000	14,000	19,000	23,000
800,000	16,000	21,000	27,000
900,000	18,000	24,000	30,000
1,000,000	20,000	27,000	34,000

[1]Plant size assumed 50,000 barrels per day.

about 3,000 people. Multiplier factors to convert work force to total population vary, but many are in the range of 3 to 5. The factor may decrease as the size of industry increases. Using a factor of 4 would result in an estimated population of about 100,000 people for a 400,000-bbl/d industry. Estimates of use per capita vary over a wide range (perhaps 50 to 200 gal/d per person). Assuming 100 gal/d per person is the required water-system intake, then 100,000 people would need about 11,000 acre-ft/yr. An open-pit or surface mine would require perhaps one-fourth as many miners as a similar-sized underground mine with a smaller ancillary use. Ancillary use of water may increase the total use substantially for various population-growth rates, as shown in figure 9. Requirements for a relatively small industry are listed in table 3 in greater detail.

The production of electricity for oil-shale mining and processing also may consume large quantities of water for steam generation. The need is not certain, because some or all of the electricity may be produced at a few selected oil-shale sites rather than at each site. Whether the electricity is produced within or outside the oil-shale region, water probably will be consumed at powerplants. Onsite generation using low-to-medium Btu off-gas may be produced by gas turbine, which would greatly reduce the water needs.

Water Supplies

Sources of water that may be used by an oil-shale industry include the White and the Colorado Rivers adjacent to the Piceance basin, streams within the basin, aquifers within the oil-shale deposits or deeper aquifers, and water imported from other areas. Because the effort in gathering water information in the past 70 years has concentrated on the surface waters for water-rights designations and planning purposes, much more is known about the quantity and quality of surface water than is known about ground water. Local water supplies probably will be utilized first; these potentially could supply the needs of an oil-shale industry of considerable size.

The two river systems most likely to supply water for oil-shale development are the White and the Colorado Rivers because of their proximity and because they receive the waters draining the oil-shale region. Of these two river systems, the White River will probably supply the majority of water for the initial years of oil-shale development. Many water rights are owned by oil-shale companies in the White River basin, and main-stem and tributary reservoirs may be constructed to serve individual oil-shale sites. However, the owners of water rights also must conform to water compacts and treaties.

Almost all of the local runoff from the Piceance basin results from four streams: Piceance and Yellow Creeks flow northward into the White River; Parachute and Roan Creeks flow south into the Colorado River. The average combined annual outflow in these streams is about 72,450 acre-ft. Most of this flow is measured at gages that are downstream from the present irrigated areas in the basin. Thus, there is a potential to utilize much of this water for oil shale. Referring back to the discussion of water uses by industry, this locally derived streamflow, assuming continued present irrigation use, potentially could supply most or all water needs for a 400,000-bbl/d industry.

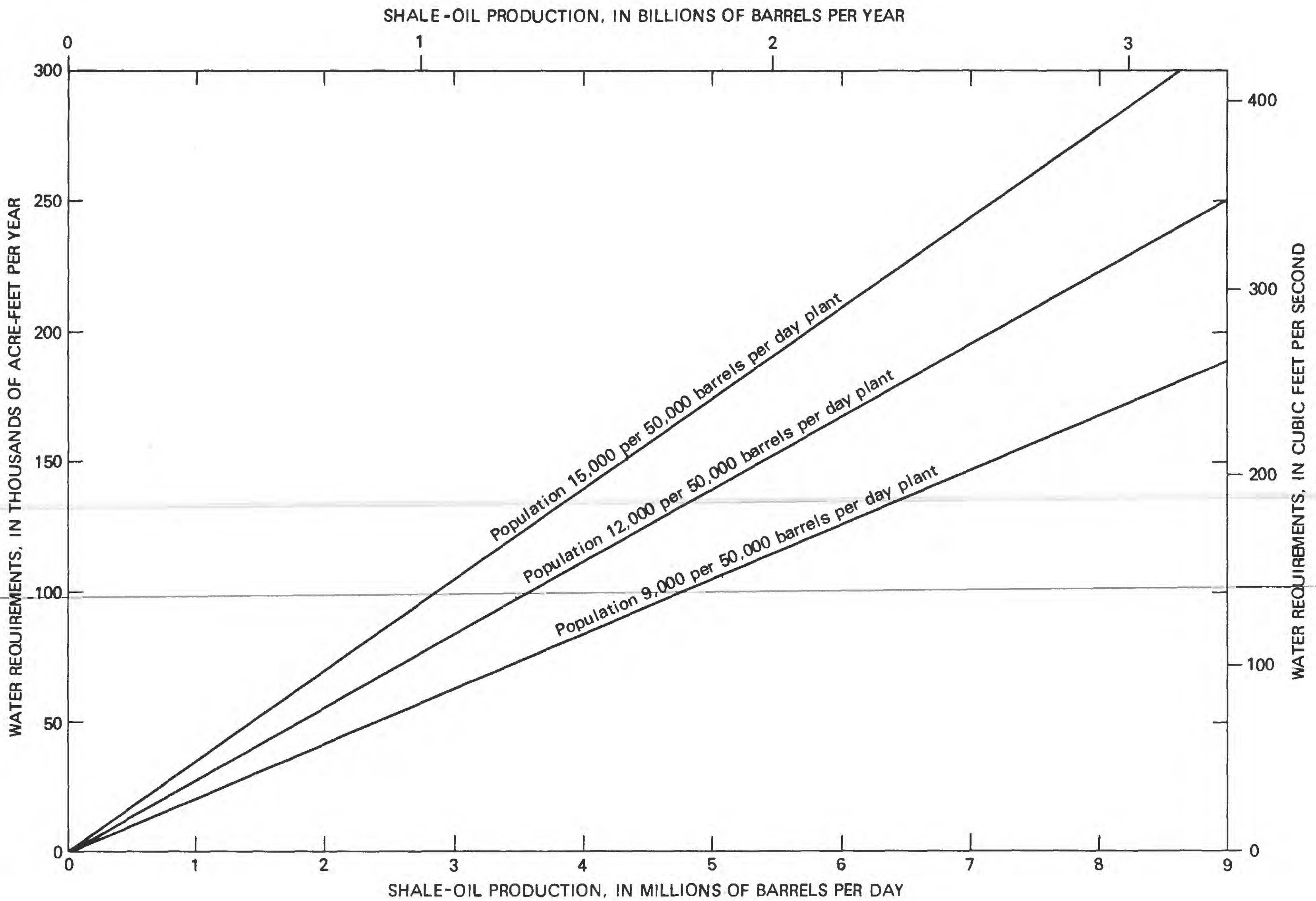


Figure 9.-- Ancillary water requirements for shale-oil production.

Potential ground-water supplies occur in the alluvial deposits along stream courses, in the Uinta Formation, and in the underlying Green River Formation. The stored volume of water in these aquifers is unknown, but if the average porosity of fractures and solution cavities is assumed to be only 2.5 percent, these aquifers contain 40 million acre-ft of water. The quality of most ground water is such that it can be used by an oil-shale industry. Drainage of oil-shale mines in much of the basin will draw on stored water, making it available as a part of the mining operation. However, in many regions of the basin the mine-drainage process will also cause reduction in the discharge of nearby springs and streams. Drainage rates for mines have been estimated to range from several hundred gallons per minute to as much as 20,000 gal/min. At the Federal Prototype Lease Tract C-a (fig. 2), drainage rates for a small-scale experimental mining operation typically ranged from 1,500 to 2,000 gal/min during 1978-80. Much of this water has been returned to the aquifer through injection wells and thus potentially is available for future use. This rate of drainage, about 3,000 acre-ft/yr, probably would be adequate to support a mine and plant producing from 15,000 to 60,000 bbl/d of shale oil. Extrapolating further, if only 1 million acre-ft of the water stored in the aquifer system were available for oil-shale uses, it would support a 400,000-bbl/d industry for about 10 to perhaps 50 years.

Several stratigraphic units beneath the Green River Formation may constitute a deep aquifer system. The lack of drill hole and test data on these units limits any discussion of their water-bearing characteristics to inferences and the extrapolation of geologic data from areas where their water-bearing characteristics are better known. These units aggregate a thickness of several hundred feet and potentially could be an additional significant source of ground water for an oil-shale industry. They are utilized as aquifers in several areas where they lie at shallow depths, and well yields from each unit typically are 10 to 100 gal/min, although much larger yields are possible. Definitive data are not available on the water quality in these units beneath the Piceance basin, but they contain water of usable quality in other areas.

Water Management

Potential constraints on the use of water by an oil-shale industry in Colorado are made up of a broad spectrum of legal, institutional, and economic factors. Included are international treaties and agreements with Mexico, the Colorado River Compact between the Upper Basin and Lower Basin, salinity goals or limits on the Colorado River system, State and Federal water-quality standards and rules, and State laws pertaining to water rights. The existence of these potential constraints is only mentioned here; the degree to which they operate will greatly affect the approach taken to manage water supplies for an oil-shale industry.

The Colorado River Compact requires the Upper Basin States to pass 750,000 acre-ft of surface water to Mexico, half of the surface flow required by the Mexican Water Treaty. The other half of the required surface flow will originate in the Lower Colorado River Basin. Currently there is no compact for the White River between Colorado and Utah which would constrain development in Colorado. For large-scale operations using surface-water supplies, reservoirs definitely would be needed to store water during the spring snowmelt period.

In a recent report (13A assessment) to the Water Resources Council, the Colorado Department of Natural Resources (1979) concluded that a 1.3 million-bbl/d oil-shale industry could be supported from surface-water supplies in the Upper Colorado River Basin without significantly reducing other projected consumptive uses. The following major qualifiers were used to explain the above conclusion:

1. Reservoirs, pipelines, and pumping facilities will have to be constructed in order to store and transport the water in addition to purchasing any water available from existing reservoirs.

2. Projections of other consumptive uses into the future were used, and further investigation is needed to improve the accuracy of these projections.

3. Only the institutional factors of the State's water-rights system and compacts, treaties, congressional acts, and U.S. Supreme Court decrees were taken into account.

4. Interstate compacts could limit amount of development in any one State.

Future effects of an oil-shale industry on the hydrologic system can be described in a qualitative way. The water-management practices that are used, along with oil-shale extraction methods and land-reclamation techniques, will have a great influence on the magnitude and timing of these effects. Hydrologic information is generally inadequate for making quantitative, site-specific predictions. The estimated potential effects of an oil-shale industry on the hydrologic system are described below:

1. Mine drainage and use of local water supplies will decrease ground water in storage and diminish flows in many local streams, springs, and seeps, and in the White and the Colorado Rivers.

2. Changes are likely in the water quality of many streams, springs, and seeps. Such changes can either degrade or enhance the water quality, depending in large part on how water-management practices are applied. For example, the stream discharge to the White River from Piceance and Yellow Creeks averages about 18,500 acre-ft annually. The average dissolved-solids concentration of this stream discharge is about 1,850 mg/L, which is about 47,000 ton/yr of salts. These salts mostly are derived from small amounts of brackish to saline baseflow that discharges from the aquifers to the lower reaches of the streams. Diverting these streamflows for utilization by an oil-shale industry would diminish the flow in the White River by about 5 percent or less but would reduce the salt load in the river by more than 20 percent.

Water quality and the quantity of runoff and ground-water recharge in mined-out areas may be dramatically influenced for a long period by the extraction methods used and, in particular, by the land-reclamation techniques. Aboveground retorting of oil shale and subsequent surface disposal of the retorted shale is most likely to affect the surface-water flows and quality; in-situ methods are likely to affect ground water because the in-situ retorts will be located within the bedrock aquifers. Reclamation practices for mine areas can be designed to have specific effects on local runoff, recharge, evapotranspiration, and water quality.

3. The influx of large numbers of people certainly will affect the hydrologic systems of a rural region such as the Piceance basin. However, a study of the impact of these population increases is beyond the scope of this report.

4. Emissions from the oil-shale industry to the atmosphere may contain potentially harmful oxides of sulfur and nitrogen. These elements may cause acid rain that is suspected to be a cause of corrosion and the destruction of fisheries.

Ground water, surface water, and water quality are closely related in the Piceance basin. However, for purposes of discussion, the needed hydrologic data and information have been separated into major subdivisions. Proposed study plans for each major subdivision follow.

TEST-WELL DRILLING AND LOGGING

By Frank A. Welder

Wells provide access to the ground-water reservoir and permit a variety of geophysical and hydrologic measurements that help to define the aquifer characteristics. Wells also permit collection of water samples for determination of water quality. The number of wells available for testing and sampling is insufficient for appraisal of ground-water conditions throughout the basin. Therefore, a test-well drilling program is needed to provide information on the existence and characteristics of aquifers in the area and to provide an adequate observation-well network.

Valley-Fill Alluvium

A program for drilling shallow test wells in valley-fill alluvium is needed. The alluvium is very permeable in some reaches and relatively impermeable in others. A drilling program would provide information on the lithology, water-bearing properties, and saturated thickness of alluvial aquifers. If clay layers divide the alluvium into different water-bearing zones, closely spaced observation wells completed in each of the zones would be helpful.

Observation and pumpable wells completed in the alluvium are needed in all major valleys of Yellow, Piceance, Roan, and Parachute Creeks. Wells will permit (1) Aquifer testing of the alluvium to determine aquifer characteristics, (2) the preparation of potentiometric maps, (3) calculation of underflow in valley-fill alluvium and stream-aquifer interrelations, (4) evaluation of the degree of hydrologic connection between alluvial aquifers and bedrock aquifers, and (5) a better understanding of water quality in alluvial aquifers. Interpretation of these data will permit a better appraisal of the behavior of hydrologic systems.

Uinta and Green River Formations

A large volume of ground water is present in the Uinta and Green River Formations in the Piceance basin, and the ground water occurs in fractures and solution cavities in strata that contain oil shale. Because this ground water must be drained prior to mining or retorting but may be used for industrial supplies, ground water and oil-shale development are inextricably linked. Adequate ground-water information is needed for the aquifers within the Uinta and Green River Formations so that sound decisions can be made regarding mine drainage, water supply, water use, and water management.

The lack of test holes and wells in the Uinta and Green River Formations greatly reduces the opportunities for hydrologic measurements and interpretive testing. In particular, aquifer testing at numerous sites will permit the calculation of (1) The behavior of the aquifers during mine drainage and (2) the volume of water in storage that is available for use. Needed aquifer testing cannot proceed until exploratory drilling provides the necessary number, types, and arrangements of suitably constructed wells. A pumpable central well and at least three observation wells are required to test for the directional transmissivity that is believed to be present in some aquifers. Multiple-well aquifer tests are needed for the upper and lower series of aquifers. Drilled wells must penetrate the aquifer completely to ensure that the entire aquifer is being tested. Wells in the lower aquifers need to be tightly cemented through the upper aquifers to prevent leakage around well casings during testing. The aquifer tests are described in greater detail in the following chapter.

The Mahogany zone of the Parachute Creek Member impairs the hydraulic connection between the upper and lower aquifers and therefore influences the flow field greatly under natural or pumping conditions. Leakage between the upper and lower aquifers is partly controlled by the vertical hydraulic conductivity of the Mahogany zone. The hydraulic conductivity of a confining bed is not easily determined because the bed cannot be pumped. The use of a thermal test to indirectly determine vertical hydraulic conductivity is discussed in the section entitled "Aquifer Testing." If some of the drilled wells were cemented tightly enough, temperature logs might be used to estimate the vertical hydraulic conductivity of the Mahogany zone.

During the exploratory drilling program, cores should be taken in selected intervals in selected holes. The cores should be subjected to mechanical tests, the results of which will be used in research related to subsidence of the land surface, compressibility of confined aquifers, and interrelations between stress fields and aquifer hydraulic conductivity. The mechanical tests should provide information on:

Young's Modulus,
Poisson's Ratio,
Shear strength and angle of internal friction, and
Specific gravity.

Results from tests should be correlated with other geologic, geophysical, geochemical, and hydrologic measurements in order to improve understanding of rock mechanics and aquifer characteristics. All cores, including cores subject to mechanical testing, will be assayed for kerogen concentration to augment existing data on oil-shale resources at various locations and depths.

Geophysical logging should be conducted during drilling and coring. Logs of uncased holes permit more accurate testing of the formation because the effects of casing and cement are not present. Logs needed are:

Natural gamma,
Gamma-gamma density,
Resistivity,
Neutron-neutron,
Sonic,
Caliper,
Dip and inclination, and
Spinner (flow velocity).

Approximately 1 year after well drilling and cementing, temperature logs should be run throughout the entire depth of all wells completed in the lower aquifers for use in estimating the vertical hydraulic conductivity of the Mahogany zone. The delay of 1 year is necessary to avoid distortions of the natural temperature profile caused by heat given off by the well cement during casing. Because aquifer testing also may disturb the temperature profile, temperature logs should not be run until the hydrologic and thermal characteristics of the aquifers and confining beds have recovered to their natural state.

After drilling and coring, a dip-and-inclination survey should be made for each well to determine if the well is plumb. Wells that are not plumb may be spaced differently at depth than they are at the land surface.

Paleozoic and Mesozoic Formations

A drilling program also is needed to explore for deep aquifers of Paleozoic and Mesozoic age beneath the Green River and Uinta Formations. Deep aquifers may constitute a valuable and alternative source of water. Alternatively, deep aquifers may serve as a reservoir for wastewater injection. Exploratory drilling to the top of the Precambrian rocks is desirable because the hydrologic characteristics of all of the overlying formations are poorly understood (fig. 4). However, the drilling depths from the land surface to the top of Precambrian rocks range from about 10,000 ft on the western flank of Piceance basin to about 25,000 ft at the center of Piceance basin. Precambrian rocks are exposed along the South Fork of the White River in the White River uplift. Any site selected for drilling should be near the Piceance basin so that the properties of the penetrated and tested units are representative of the region in which the information is needed. However, the cost of deep drilling limits selected sites to the flanks of Piceance basin or adjacent uplift regions. A brief description of possible aquifers in the stratigraphic sequence follows.

Rocks of Paleozoic age include many formations that may be fractured, porous, permeable, and water saturated (fig. 3). These rocks include the Weber Sandstone of Pennsylvanian and Permian age and the Leadville Limestone (or Madison Limestone) of Mississippian age. This limestone formation is known to be permeable in other areas. An overlying evaporite sequence of Pennsylvanian age, which contains saline water and which thins and disappears north and west of Meeker, would have to be carefully investigated in any study of the Leadville Limestone. Mallory (1971) has a regional study of these evaporate deposits in northwest Colorado. Permeable limestone and quartzite formations of early Paleozoic age also may lie stratigraphically below the Leadville Limestone (or Madison Limestone).

Many formations of Mesozoic age are potential aquifers. The Mesaverde Group, Mancos Shale, Dakota Sandstone, and Cedar Mountain Formation of Cretaceous age all contain sandstone beds. The Morrison Formation, Curtis Formation, and Entrada Sandstone of Jurassic age are known to be aquifers in other areas. The Glen Canyon Sandstone of Triassic and Jurassic age and the Chinle Formation of Triassic age are mostly sandstone. The maximum thickness of the formations of Mesozoic age is nearly 14,000 ft.

In summary, the formations that may include aquifers are listed below in stratigraphic sequence:

Mesaverde Group
Mancos Shale
Dakota Sandstone
Cedar Mountain Formation
Morrison Formation
Curtis Formation
Entrada Sandstone
Glen Canyon Sandstone
Chinle Formation
Weber Sandstone
Leadville Limestone or Madison Limestone
Limestone and quartzite in formations of early Paleozoic age

Investigators need to obtain, integrate, and interpret geologic and hydrologic data for potential aquifers of Palezoic and Mesozoic age with the view of ultimately selecting sites for exploratory test drilling. First priority should be given to selecting a site for drilling a deep exploratory well, perhaps as deep as 15,000 ft, to Precambrian rocks. The site should be in or reasonably near the Piceance basin, so that potential supplies of ground water might be shown to be available for oil-shale processes. The test hole would provide a driller's log, and access for geophysical logs, aquifer tests, and water-quality analysis.

Second priority should be given to a general study of northwestern Colorado with emphasis on all possible aquifers in the entire area. Both priorities would require exhaustive research of information from well-log service companies, published reports, and field-reconnaissance studies. The types of information sought would include:

1. Location, depth, and history of oil and gas wells;
2. Drill-stem test data such as potentiometric head, permeability, and quality of water;
3. Mud-circulation records;
4. Well-completion records;
5. Lithology;
6. Stratigraphic tops;
7. Geophysical logs;
8. Maps; and
9. Water quality.

This information would be integrated into maps showing geologic structure, lithology, aquifer thickness, potentiometric heads, and aquifer characteristics. These maps would be used to prepare an intensive regional analysis of ground-water behavior and potential.

AQUIFER TESTING

By O. James Taylor

The hydrologic characteristics of the bedrock and alluvial aquifers are major controls on the ground-water flow system under natural conditions and the hydrologic response to pumping or injection wells. These important characteristics, aquifer transmissivity and storage, are normally determined by field tests that use wells completed in the aquifers selected for testing. An ideal test involves pumping a single well at a steady rate while measuring water-level declines in the pumped well and other nearby observation wells. After cessation of pumping, the measurement of recovery of water levels in all wells completes the aquifer test. A simplified test involves measurements in the pumped well only, but does not permit accurate calculation of the aquifer storage coefficient. Resulting test data are analyzed using a variety of methods to determine the local hydraulic characteristics of the aquifer. Needed tests for alluvial aquifers will be discussed first, followed by tests of the Uinta and Green River Formations.

Valley-Fill Alluvial Aquifers

Aquifer testing is proposed for the valley-fill alluvial aquifers along major streams. Alluvial aquifers separate the bedrock aquifers from the streams along Piceance and Yellow Creeks. The presence of beds of low permeability in these alluvial aquifers will delay interchange of water between the bedrock aquifers and the stream. Understanding of the hydrologic connection between the alluvial aquifers and Roan and Parachute Creeks can be improved by aquifer testing. Using existing or newly drilled wells, several types of aquifer tests at numerous sites are proposed according to the availability of suitable wells:

1. Pumping a single well completed in the alluvial aquifers and measuring drawdown in the pumped well. The drawdown measurements will permit calculation of transmissivity and provide limited information on the degree of hydraulic connection between the stream and aquifer.

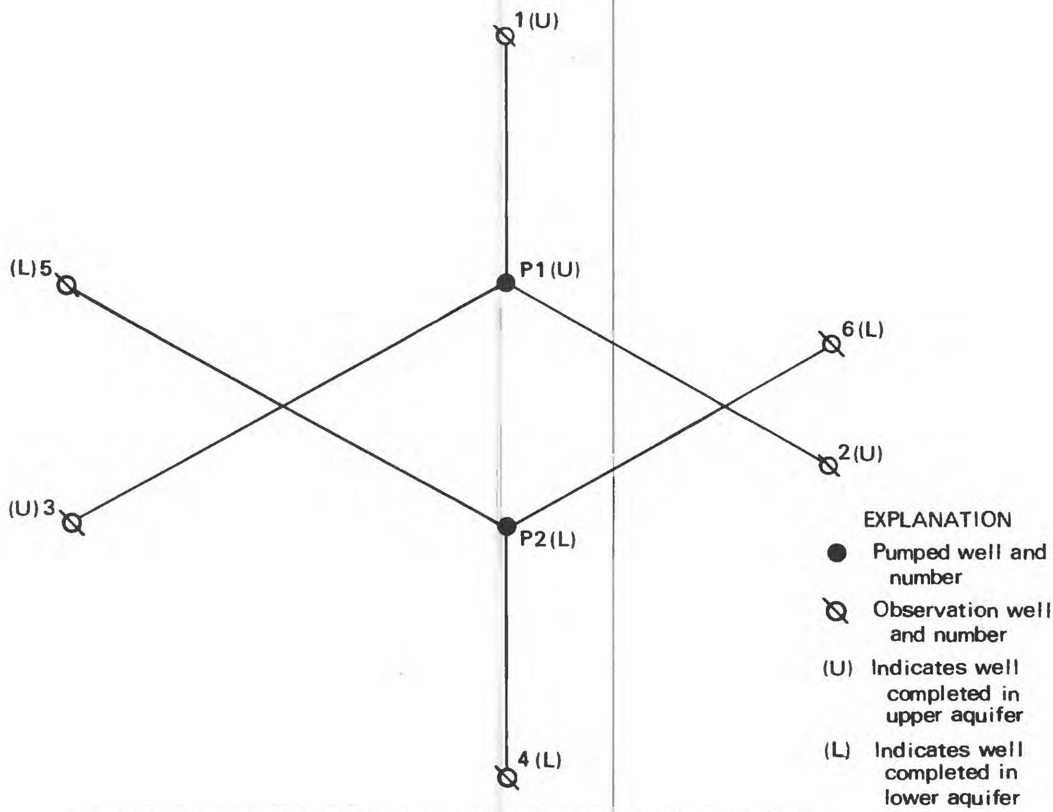
2. Pumping one well and measuring drawdown in observation wells, all completed in alluvial aquifers. The drawdown measurements will permit calculation of transmissivity and storage characteristics, indicate whether the aquifer is confined or unconfined, and provide information on the degree of hydraulic connection between the stream and aquifer. The type and location of aquifer boundaries also may be determined by aquifer testing.

3. Pumping a well completed in the shallow bedrock aquifers and measuring drawdown in observation wells completed in the alluvial aquifers. Alternatively a well in the alluvium could be pumped and measurements made in observation wells in the bedrock. The measurements will provide information on the degree of hydraulic connection between the shallow bedrock and valley-fill aquifers. If drillers' logs indicate the presence of clay beds in the alluvial aquifers, the tests could be performed using wells completed at various depths in the alluvium to determine the degree of hydraulic connection among the various aquifers in the alluvium and the shallow bedrock.

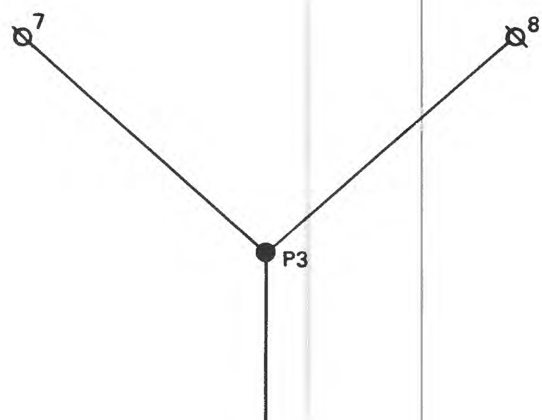
Aquifers of Uinta and Green River Formations

Several multiple-well aquifer tests of the fractured bedrock aquifers in the Piceance basin are reported by Coffin and others (1968), Weeks and others (1974), and Dale and Weeks (1978). Data on water levels and industrial withdrawals for mine drainage and well testing on lease tracts C-a and C-b were used by the U.S. Geological Survey to represent large-scale aquifer tests. These tests indicate that the aquifers in the upper part of the Parachute Creek Member of the Green River Formation may be anisotropic--that is, they display directional lateral hydraulic conductivity and transmissivity. The areal extent of the directional transmissivity is not known because of the paucity of aquifer tests.

An analysis of the hydraulics of anisotropic aquifers by Papadopulos (1965) indicates that a pumpable central well and a minimum of three properly located observation wells are required to obtain the directional transmissivity and a valid storage coefficient in an aquifer test. Therefore, some previous bedrock aquifer tests in the Piceance basin utilizing fewer than three observation wells may have given inaccurate results. At each of the aquifer-test sites two pumpable wells will be needed--one in the upper aquifers and the other in the lower aquifers. The two pumpable wells should be drilled within several hundred feet of each other so that (1) Well-interference measurements can be made and interpreted during aquifer testing, and (2) the hydraulic gradient across the Mahogany zone can be determined at each site. Three observation wells will be needed in the upper aquifers and three other observation wells in the lower aquifers. The companion observation wells should be drilled within 100 ft of and located at different directions and distances from each pumpable well. The close spacing of observation wells is suggested to minimize the effects of aquifer heterogeneity that were observed in an aquifer test at tract C-b. Test results using observation wells approximately 100 ft from the pumped well yielded a feasible solution; test results using more distant observation wells yielded an infeasible solution, presumably because of aquifer heterogeneity that is not considered in the test for aquifer anisotropy. The required well pattern is shown in figure 10*A*. The pumped well P1 and observation wells 1, 2, and 3 are completed in the upper aquifers. Pumped well P2 and observation wells 4, 5, and 6 are completed in the lower aquifers. This pattern permits a relatively small drilling pad. Dually completed wells also can be used, as illustrated in figure 10*B*. If packers are used to isolate aquifers from each other in each well, either aquifer can be pumped through well P3, and observations of both aquifers can be made at each of the three observation wells numbered 7, 8, and 9. The pumped well for each aquifer test should be pumped at least 3,000 minutes (about 2 days), based on estimated hydraulic properties. Measurements need to be made in all observation wells and the pumped well during and after the cessation of pumping. If numerous multiple observation-well tests indicate that the upper or lower aquifers do not exhibit directional transmissivity extensively, additional aquifer testing can be run more cheaply using only one pumped well and one observation well.



A. Singly completed wells that tap either the upper or lower aquifers



B. Dually completed wells that tap the upper and lower aquifers

Figure 10.--Proposed well patterns for exploratory drilling and aquifer testing.

Prediction of the effects of mine drainage on the hydrologic system also requires values of the specific yield of the aquifers. If the aquifers at some sites undergo conversion from confined to unconfined conditions during the tests, both the storage coefficient and the specific yield of the aquifers can be determined using methods proposed by Moench and Prickett (1972). The specific yield of the aquifers also can be calculated by comparing the pumped volume and drained aquifer volume at a mine-drainage site. Various geophysical logging techniques can be used to estimate the fracture porosity of the aquifers, which represents a maximum value for the specific yield.

After aquifer testing to determine the transmissivity and storage characteristics of the aquifers, other aquifer tests may be conducted using the same wells. Weeks (1969) has designed tests to determine the ratio of horizontal to vertical hydraulic conductivity using partially penetrating pumping and observation wells. These tests could be conducted by using packers to isolate parts of the completely penetrating wells. Robson and Saulnier (1980) and Taylor (1982) reported that the vertical hydraulic conductivity of some aquifers in the Piceance basin is substantially lower than the horizontal hydraulic conductivity. Impaired vertical hydraulic conductivity tends to stratify the aquifers and influences the response of the aquifers to pumping.

Mahogany Zone of the Parachute Creek Member of the Green River Formation

The areal distribution of the vertical hydraulic conductivity of the Mahogany zone, a confining layer, is also needed. The Mahogany zone of the Parachute Creek Member of the Green River Formation impairs the hydraulic connection between the upper and lower aquifers and therefore greatly influences the flow field during natural and pumping conditions. The hydraulic conductivity of a confining bed is not tested easily. A thermal test to indirectly determine vertical hydraulic conductivity was proposed by Stallman (1960) and developed by Bredehoeft and Papadopulos (1965) and Sorey (1971). The technique utilizes a temperature log from a tightly cemented well in which there is no vertical flow within the casing, as shown in figure 11. The downward curvature of the temperature within the confining beds of the Mahogany zone presumably is due to downward movement of ground water across the zone. The vertical hydraulic conductivity of the zone is calculated using values of the curvature of temperature profile, the thermal conductivity of the zone, and the hydraulic gradient across the zone. Paired wells, one completed in the upper aquifer and one in the lower aquifer, are needed for this technique. A series of paired wells in the Piceance basin is described by Welder and Saulnier (1978), and others are needed. These wells also can be used for aquifer testing, provided they are close enough to permit accurate measurement of the natural vertical hydraulic gradient.

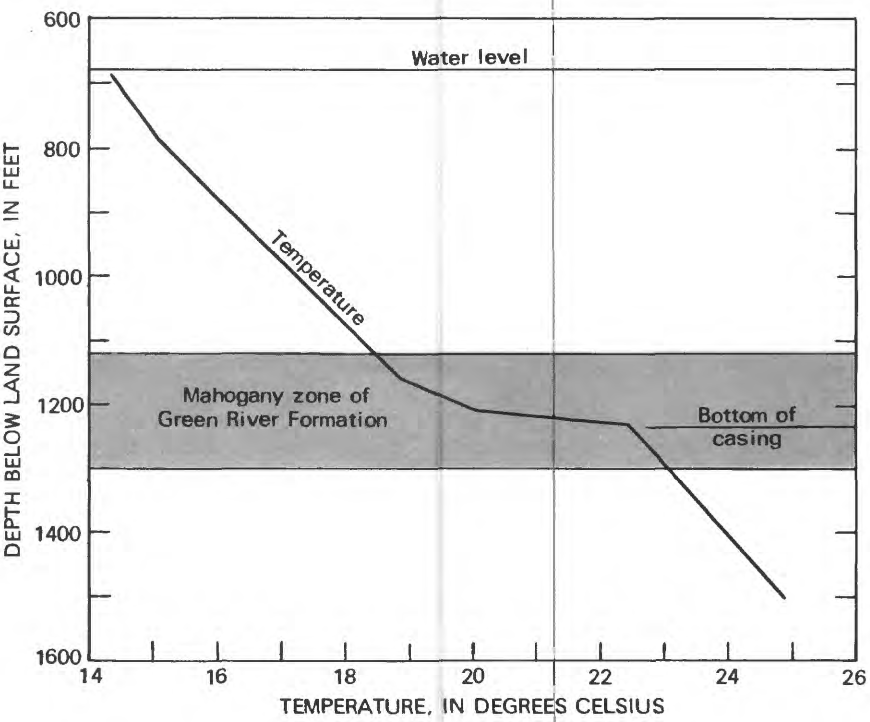


Figure 11.-- Fluid temperature in test hole in sec. 20, T. 1 N., R. 98 W., May 6, 1976 (Welder and Saulnier, 1978).

MATHEMATICAL MODELING OF THE GROUND-WATER FLOW SYSTEM

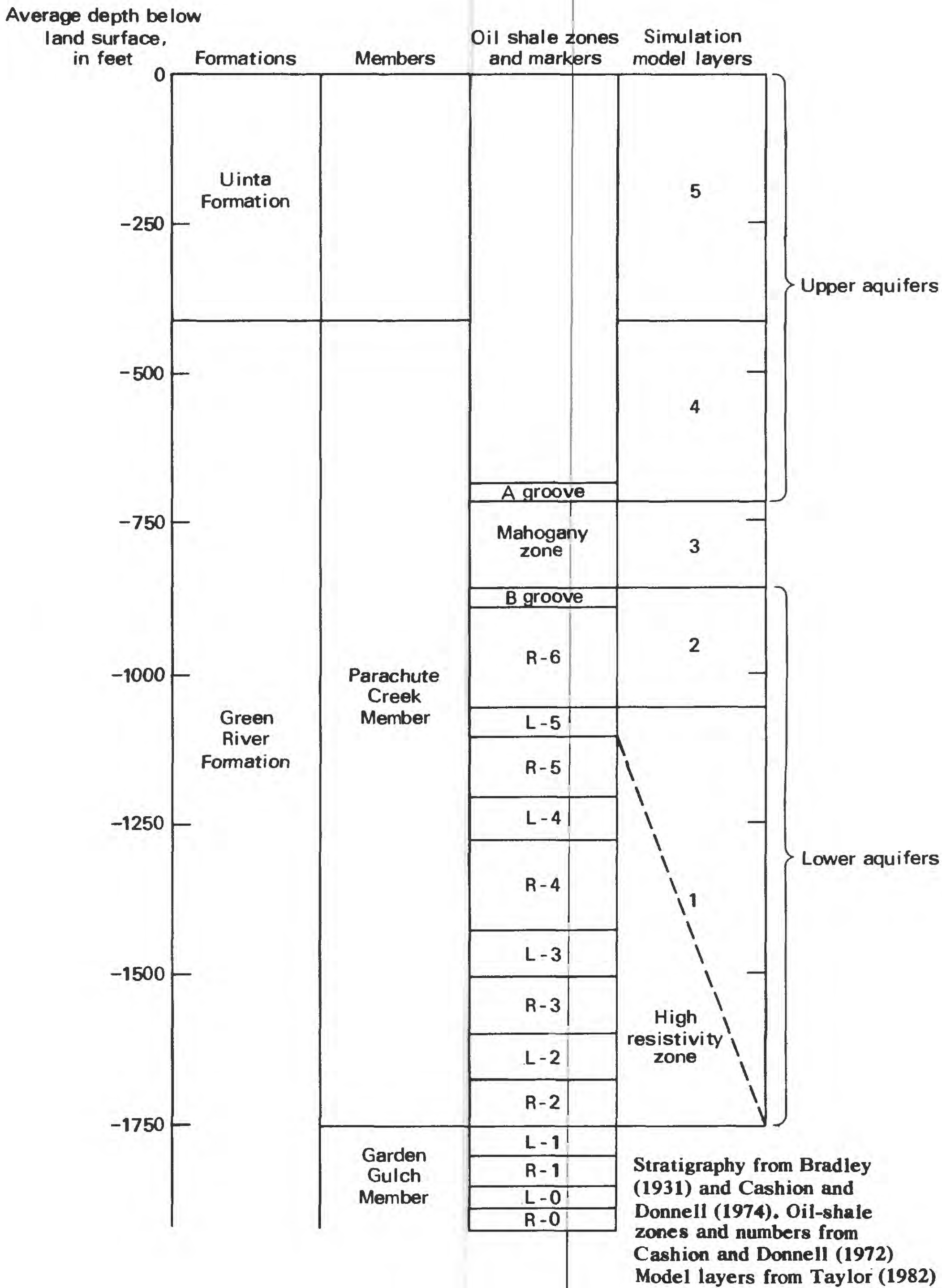
By O. James Taylor

Two mathematical models have been prepared for the northern part of the Piceance basin. Weeks and others (1974) prepared a quasi-three-dimensional model that was used to predict the hydrologic effects of mine drainage at tracts C-a and C-b (see fig. 2). Robson and Saulnier (1980) described the predicted hydrologic and solute-transport effects of mine drainage, also at lease tracts C-a and C-b.

A new five-layer three-dimensional mathematical model has been prepared for the entire Piceance basin (Taylor, 1982). The model contains 9,200 nodes and simulates major aquifers, streams, and springs. Directional aquifer characteristics are incorporated in the model for greater accuracy. Relations among geologic, oil-shale, and hydrologic layers are shown in figure 12. Model layers 1 and 2 represent the lower aquifers, layer 3 represents the Mahogany zone, and layers 4 and 5 represent the upper aquifers. Additional hydrologic data are currently (1982) being collected to improve the accuracy of the model. Several test drilling and gain-and-loss studies along Piceance and Yellow Creeks will help to determine the degree of hydraulic connection between the bedrock aquifers and creeks and will fulfill the need to incorporate the valley-fill alluvium as an additional layer in the model. Streamflow and water-quality measurements in Roan and Parachute Creek basins will improve the understanding of the normal discharge of springs and the chemical characteristics of water in major aquifers. Data from wells completed in the bedrock aquifers are being analyzed to improve the definition of potentiometric maps and to define the most permeable zones within the aquifers. Radiometric dating using water from the bedrock aquifers will be attempted, in order to determine residence time in the bedrock and its relation to the hydrologic description of the flow system.

If knowledge of the aquifer characteristics can be sufficiently improved, the model could be used to predict:

1. The hydrologic effects of mine dewatering.
2. The best way to dewater the mines.
3. The suitability of oil-shale aquifers for storage reservoirs if temporary surplus supplies are injected into wells distant from dewatering mines.
4. The overall water supply available from the oil-shale aquifers of the basin.



Stratigraphy from Bradley (1931) and Cashion and Donnell (1974). Oil-shale zones and numbers from Cashion and Donnell (1972) Model layers from Taylor (1982)

Figure 12.-- Generalized correlation of stratigraphic, oil-shale, and mathematical-model layers, Piceance basin.

GROUND-WATER QUALITY

By R. L. Tobin and D. Briane Adams

Regional Quality

An appraisal of water quality in the aquifers of the Piceance basin is desirable for several reasons. The study of water quality helps to understand the natural flow systems, especially in conjunction with other geologic and hydrologic information. Water-quality analyses also help to determine the suitability of the ground water for various uses, including disposal of water drained from mines.

Water-quality analyses indicate that water in the alluvium and the Uinta Formation is generally a mixed cation bicarbonate or bicarbonate sulfate type and that most of the water in aquifers of the Green River Formation is a sodium bicarbonate type. The concentrations of major and minor constituents, however, vary within and between the aquifers. Concentrations of dissolved solids range from 400 to greater than 10,000 mg/L and generally increase with depth and with distance from the major recharge areas. Dissolved solids are greatest in the north-central section of the basin where ground water dissolves extensive deposits of nahcolite and related salts within the lower aquifers as shown in figure 13.

The differences in the chemical types and concentrations of ground water in the Piceance basin result from the dissolution, precipitation, ion exchange, and oxidation of minerals in the rocks of the Piceance basin (Robson and Saulnier, 1980). The alluvium consists of gravel, sand, and clay; the Uinta Formation is composed of silty sandstone; the Green River Formation is composed of dolomitic marlstone, oil shale, and saline deposits. Water in these rocks generally moves slowly because their permeability and the hydraulic gradient are low. Most ground water in the bedrock aquifers moves along fractures, solution channels, and collapse structures which are common in the basin. Because the strata have little or no primary porosity, most of the chemical constituents in water are derived from minerals along fracture planes. An exception is those salts which are leached from the extensive saline deposits near the center of the basin.

Many of the samples analyzed to date probably represent water that was either sampled from wells open to several contributing zones or water that has moved through several aquifers. For example, some of the dissolved constituents in the water of the valley-fill alluvium may have been derived from sources within the bedrock aquifers of the Uinta and the Green River Formations. Springs are common throughout the basin and fractures have provided localized conduits for hydrologic connections between aquifers.

Despite sampling difficulties and the stratigraphic and structural complexities of the basin, significant chemical differences can be distinguished among major aquifers. A reduced environment is common within the aquifers of the Green River Formation. Hydrogen sulfide and methane gases are reported from many wells which penetrate the lower bedrock aquifers below the Mahogany zone. Saulnier (1978) suggested that certain water-quality constituents and their ratios may be characteristic for each major aquifer. For example, concentrations of arsenic,

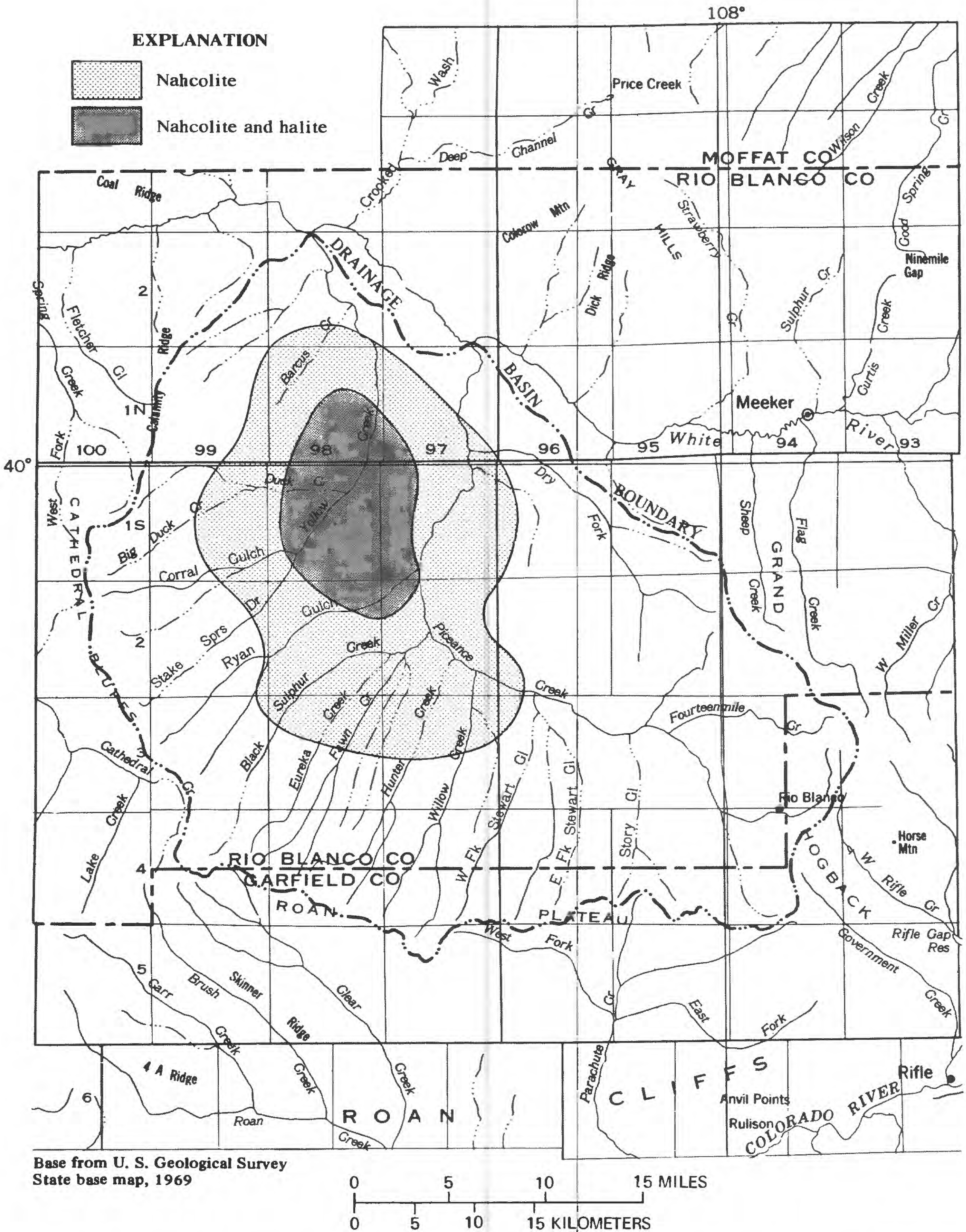


Figure 13.--Location of principal nahcolite and halite deposits in the Piceance basin. (From Dyni, 1974.)

barium, boron, fluoride, lithium, and molybdenum generally are higher in the lower bedrock aquifers than in the upper bedrock aquifers. Strontium concentrations of several milligrams per liter and mixed water types are characteristic of the valley-fill alluvium and upper bedrock aquifers. Such characteristics, if found to be consistent throughout the basin, could be useful as water-source indicators for assessments of the hydrology of the Piceance basin.

Water-Quality Network

The collection of water samples in the basin for water-quality analyses has been limited in scope. Wells and springs have been sampled only once or twice since 1974. In addition, most of the water samples from wells probably represent a mixture of water from several aquifers, or water affected by in-hole solution. A comprehensive water-quality network is needed to improve understanding of the natural flow system and the effects of resource development on ground-water quality. Possible water-quality changes may result from several or all of the following planned activities that alter hydrologic flow paths, residence times, and solution chemistry:

1. Mine drainage for aboveground or in-situ retorting.
2. Reinjection of water for streamflow augmentation or temporary storage.
3. Backfilling of mined material.
4. Leaching from in-situ retorts after retort abandonment.
5. Disposal of retorted shale aboveground.
6. Development of water supplies.
7. Changes in land use.

Sampling sites for the proposed network would consist of existing wells, new wells, and springs. An adequate water-quality network is not possible without a test-well drilling and well-completion program. In many instances, the water-quality network could be established and monitored in coordination with the gathering of other hydrologic information. Water-quality monitoring during exploratory drilling would provide important information on the changes of ground-water quality with depth. Packers need to be installed in wells, and major water-producing zones need to be tested and sampled. Samples of spring water discharging above the Mahogany zone in Roan and Parachute Creek basins should represent water that has been transported only through the upper aquifers (see fig. 7). The injection of tracers could be coordinated with hydrologic studies using hydrologic models. Residence times obtained from tracer studies should help to calibrate the hydrologic models, but the interpretation of tracer movement in the heterogeneous aquifers may be difficult.

The chemical constituents that need to be analyzed in the network cannot be predicted accurately because of uncertainties in the operation of the geochemical system. However, a general list of constituents that should be considered for analysis is included in table 4. Current data collection and interpretation should improve understanding of those constituents that will prove valuable as indicators of changes in ground-water quality related to oil-shale development. As the understanding of the geochemical flow system improves, many of these chemical constituents can be eliminated from further study.

Table 4.--*Chemical constituents for consideration in network to monitor ground-water quality in the Piceance basin*

Aluminum	Copper	Phenols
Ammonia	Cyanide	Phosphorus
Arsenic	Fluoride	Potassium
Barium	Iron	Selenium
Bicarbonate	Lead	Silica
Boron	Lithium	Sodium
Calcium	Magnesium	Strontium
Carbon, organic	Manganese	Sulfate
Carbonate	Mercury	Thiocyanate
Chloride	Molybdenum	Thiosulfate
Chromium	Nickel	Vanadium
Cobalt	Nitrogen	Zinc

SPRINGS

By Kimball E. Goddard

Bedrock aquifers in the Piceance basin may discharge to streams as springs and seeps. Piceance, Yellow, Parachute, and Roan Creeks are maintained during low-flow conditions partly by some of the hundreds of springs in the basin. Data on the springs have been collected during past hydrologic investigations conducted by the U.S. Geological Survey (Colorado State Engineer, Division of Water Resources, 1978), and data collection is continuing. However, data were collected in the past as part of other activities, sampling was nonsystematic, and the period of collection was so short that a trend analysis is not possible.

Further study of the distribution and annual discharge of the springs also would contribute more accurate hydrologic data that could be used in ground-water and surface-water models currently being developed. Becuase major oil-shale development probably will affect the aquifer system and, hence, the springs, longer studies need to be undertaken that would document these changes. To meet these general objectives, four studies are proposed and briefly described in this section. The studies are: (1) An inventory and sampling program based on statistical design, (2) a multiyear hydrologic-monitoring program, (3) a multiyear geochemical-monitoring program, and (4) a spring-modeling program. Although various phases of these proposed studies may be combined into a single project, the rationale and design of each study are described separately in the following sections.

Inventory and Sampling

The inventory and sampling of springs requires field visits for data collection. Generally, data collected on springs during previous studies were obtained at locations and times convenient to field personnel rather than according to unbiased design. For example, most of the data previously collected were on springs close to roads, and 90 percent of the information was collected during a few summer months. These data are biased, and therefore interpretation is difficult.

For definition of the current hydrologic system in the Piceance basin, a new inventory and sampling study is necessary that would eliminate bias due to location and time of year. The goals of the study must be specified, in order to design an inventory and sampling program that will provide the desired level of accuracy. Considerations in the sampling program include the scatter in the properties of the springs, incorporation of data from the previous sampling programs, and the feasibility of reaching specified goals. Reasonable goals for the inventory and sampling program are:

1. To provide estimates of the natural discharge from springs issuing from each major bedrock aquifer in specified areas of the basin.

2. To define the dissolved constituents in spring water so that water from the upper and lower bedrock aquifers of the Green River Formation (fig. 7) can be distinguished.

Springs are numerous in the Piceance basin, so every spring cannot be visited and sampled. Therefore, samples need to be taken from representative subsets of springs. The locations of springs in the basin are not random but are controlled by topography, geology, and hydrology. The first phase of the inventory and sampling study would be to divide the springs into groups based on general location and topography and on geologic and hydrologic controls. The number of groups based on general location and topography can vary according to the amount of detail desired. A convenient method would be to subdivide the Piceance basin into drainage basins. For example, the springs may be divided into four major groups corresponding to the drainage basins of Piceance, Yellow, Roan, and Parachute Creeks. Other groups may be formed of smaller drainage basins, such as the deeply incised tributary valleys of Roan and Parachute Creeks. The geologic and hydrologic controls on springs in the Piceance basin permit further subdivision. Along the valleys of Piceance and Yellow Creeks and their tributaries, many of the springs discharge along faults and fractures. Where the bedrock aquifers are dissected by incised stream valleys in Roan and Parachute Creek drainage basins, the springs are controlled by the hydrologic characteristics of the aquifers. These springs discharge water from the upper aquifers and probably from the lower aquifers. Springs also may be subdivided into groups based on the stratigraphic interval from which they discharge, or the source aquifer. The map in figure 14 shows regions resulting from a possible subdivision of springs in the Piceance basin. The regions include groups of springs that are subdivided on the basis of probable source aquifers. Springs that discharge water that has moved only through the upper bedrock aquifers are found in areas of natural recharge (see fig. 6); springs that discharge water that may have moved through the upper and lower bedrock aquifers are found in areas of natural discharge (see fig. 7).

Due to natural heterogeneity, springs in the same group may vary in discharge and water quality. Therefore, it will be necessary to choose several springs from each group for analysis. Within the spring groups, a specific sampling area should be chosen by random selection. A selection scheme based on a grid or quadrant could be developed that would allow sampling areas to be chosen without bias based on access. This method of stratified random selection is particularly useful when an individual group is more homogeneous than the population as a whole. Ideally, after the spring groups have been determined, a data-collection schedule should be arranged that is not biased with respect to the time of year. This schedule may call for monthly or quarterly visits to each site or rotation of visits to sites within a group.

Hydrologic Monitoring

The hydrologic system in the Piceance basin is approximately in a state of natural equilibrium because water use is small. The quantity and quality of spring discharge is a result of recharge to, flow through, and discharge from undisturbed aquifers. However, as oil-shale development increases, the hydrologic system probably will be altered. Ground-water flow paths may be changed and springs near the developed areas affected. Many of the springs in the Piceance basin are presently used as water sources for wildlife and domestic livestock. Also, as previously stated, spring discharge contributes part of the discharge to the streams during low-flow conditions. These streams are used as sources of irrigation and stock water in the Piceance, Yellow, Roan, and Parachute Creek valleys.

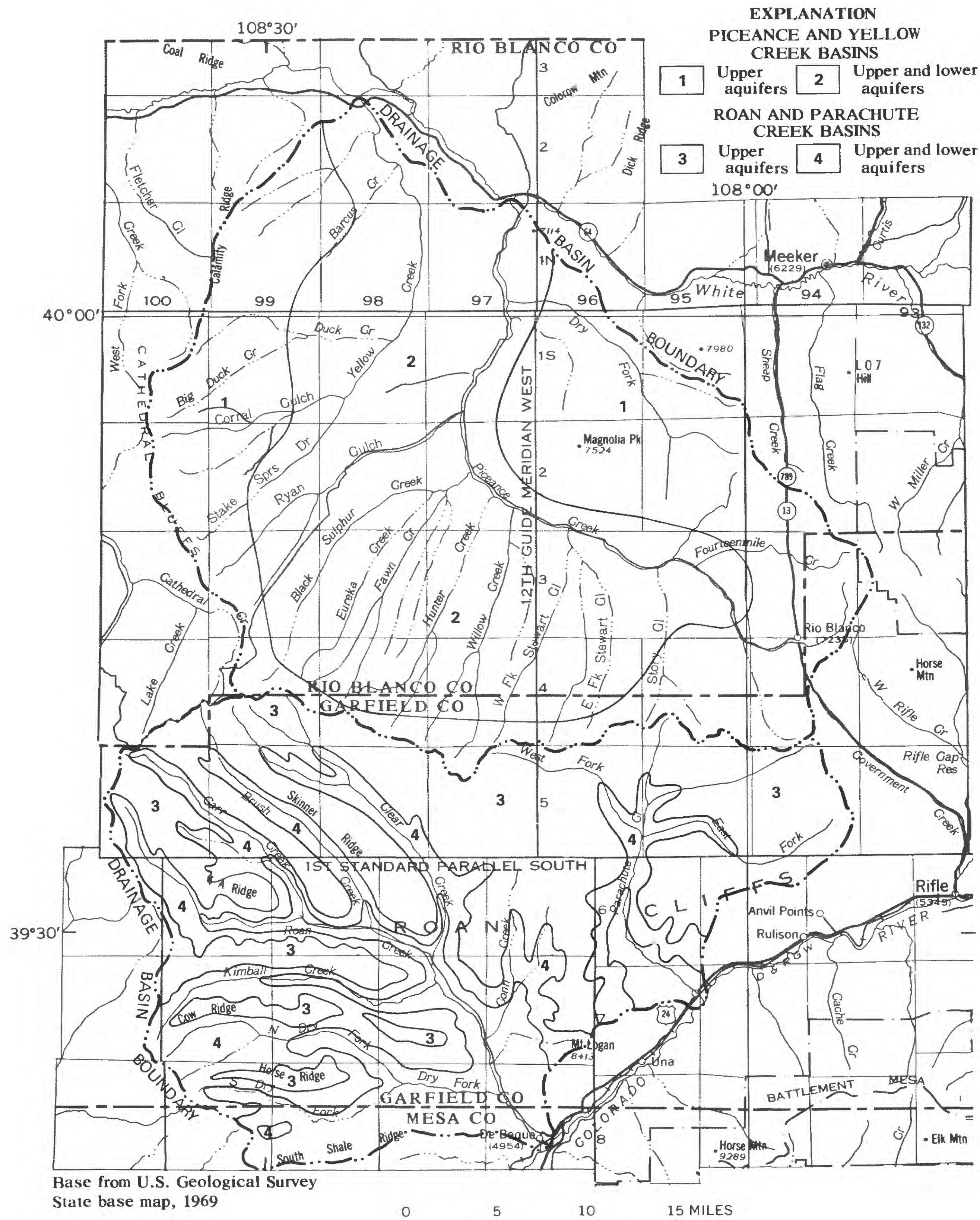


Figure 14.--Possible regions for investigations of springs, based on aquifer sources.

In order to document changes in spring discharge, a long-term spring-monitoring program is necessary. The program needs to be started soon because mine drainage is now underway and has begun to alter the natural flow system. Any hydrologic spring-monitoring program needs to continue throughout oil-shale development and the reclamation period. A spring-monitoring program is needed that is based on the premise that large-scale oil-shale development eventually may cover most areas of the Piceance basin and that this development probably will affect the various aquifers at different rates and by different amounts. Spring discharge also is affected by long-term variations in precipitation. For this reason it is important to select some springs that currently are distant from developmental effects to serve as control sites. Springs selected should be perennial and have easy access. In addition, the spring should discharge from a small area or orifice in bedrock, if possible, and be developable. Small concrete structures placed over the springs are needed, as well as discharge pipes or small flumes for measurement of flow. This improvement would help to assure a constant measuring point over the life of the project. The monitored springs need to be equipped with continuous recorders or visited at least four times a year, and a few key springs will need to be visited monthly. Required periodic data include discharge, water temperature, specific conductance, and pH.

Geochemical Monitoring

The hydrologic changes that will occur as mine dewatering proceeds are likely to create changes in the quality of the ground water. In addition, the mining, aboveground retorting, and in-situ retorting of oil shale will create an unknown quantity of soluble inorganic and organic compounds. Unknown amounts of these compounds could be leached from spoil piles or in-situ retorts and contaminate the ground-water reservoir unless proper procedures are followed. Therefore, a geochemical-monitoring program for springs in the Piceance basin is needed as soon as possible to document probable changes. The geochemical program could easily be added to the hydrologic-monitoring program. The sampled springs should be in an area expected to show water-quality changes due to mine dewatering or leaching. Several of the large springs along Piceance and Yellow Creeks need to be included in the geochemical-monitoring program because these springs may indicate changes in the solution rate of the nahcolite and halite deposits near the center of the basin.

The springs need to be visited quarterly or semiannually and samples collected at least semiannually, possibly during the highest and lowest discharge periods. As is the case of the hydrologic-monitoring program, improvements in the selected springs are needed so that the sampling point remains stable throughout the program period. It is necessary to collect samples in accordance with standard procedures in which temperature, specific conductance, pH, and alkalinity are tested onsite. Laboratory analyses are needed that include all major ions, selected inorganic and organic constituents which are found in the basin, and constituents that may be leached from spoil piles or abandoned in-situ retorts (see table 4).

Spring Modeling

A hydrologic or chemical-transport model could be used to improve the understanding of the hydrology and geochemistry of springs. The model could be constructed by using hydrologic and geochemical data collected in other studies of mine drainage and chemical transport during oil-shale development. A schematic grid for a cross-sectional finite-difference model is shown in figure 15. This grid might be used to analyze a thin vertical slice of the flow system between tributaries of Roan Creek. The flow system is subdivided into many layers to provide vertical detail. The layers above the current potentiometric surface of the upper aquifers would permit simulation of a rise in the potentiometric surface as a result of simulated changes in recharge and discharge. The relatively thin Mahogany zone is subdivided into three layers to permit simulation of nonlinear hydrologic gradients across the zone. Layers that represent the lower bedrock aquifers would help to determine the plausibility of discharge into talus slopes that is suspected but not proven. This model would help to coordinate field data on natural recharge, water-level fluctuations in wells, spring discharges, water quality of spring water, and age determinations of spring water.

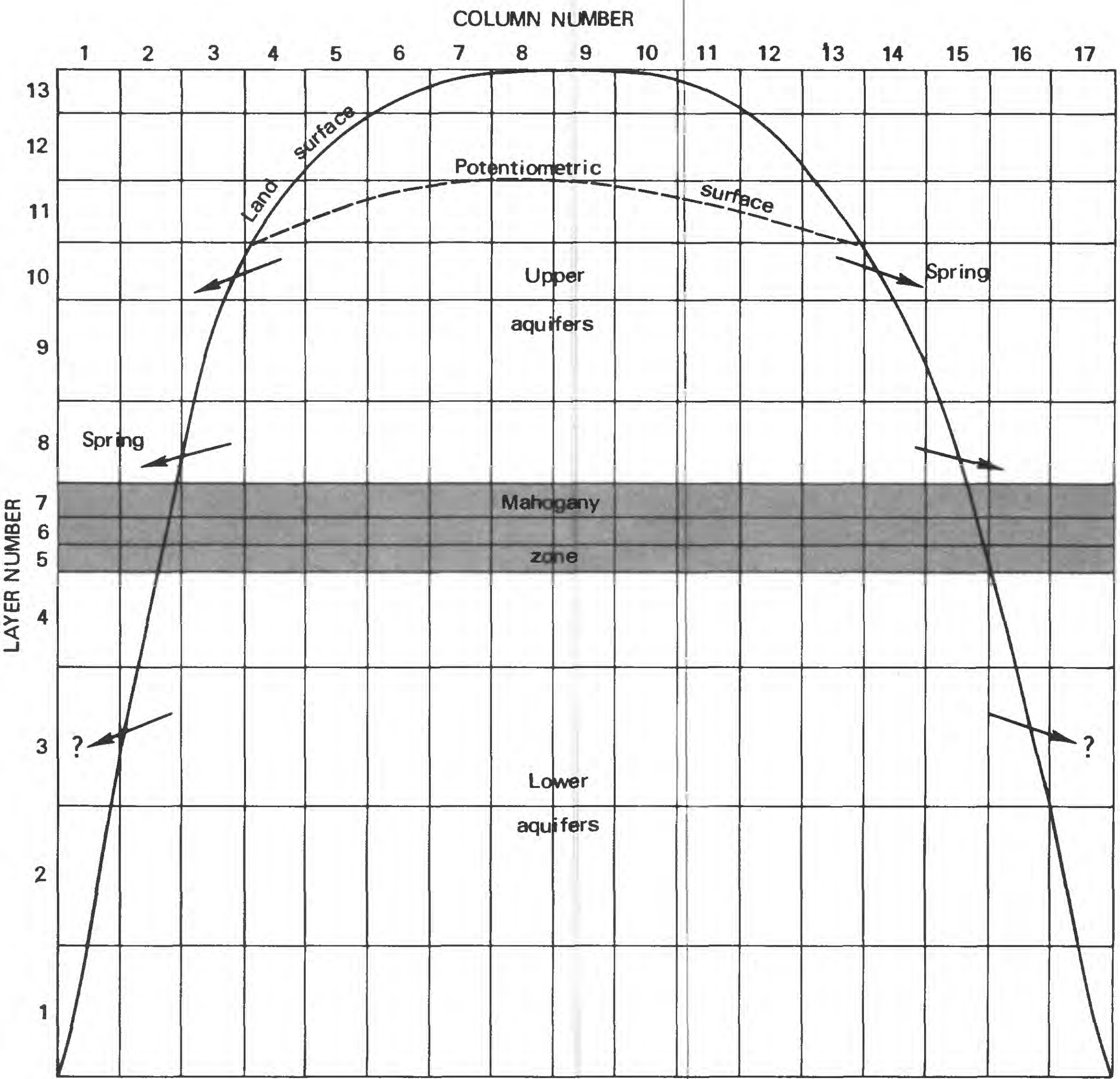


Figure 15.-- Schematic diagram showing vertical grid for model analysis of flow system between major tributaries of Roan Creek.

STREAMFLOW ANALYSIS

By R. S. Parker

Streams form an integral part of the hydrologic cycle in the Piceance basin. Streamflow is derived from surface runoff, discharge from springs, and discharge from bedrock aquifers. Streamflow interchanges with underflow in valley-fill alluvial aquifers, at least in some valley reaches. Oil-shale development is likely to affect streamflow, suspended and dissolved loads in streams, and the aquatic environment.

Water Budget

Streams in the Piceance basin are part of the stream-aquifer system depicted in figure 16. The stream-aquifer system includes bedrock aquifers, valley-fill alluvial aquifers, and stream channels. Precipitation, shown in figure 16, includes snow and rain that fall on the uplands and flood plain. Snowmelt and rain are disposed of partly by evapotranspiration. Part of the precipitation becomes surface runoff to the streams and subsurface flow in the unsaturated zones of the bedrock or alluvial aquifers. Part of the subsurface flow recharges the bedrock aquifers and discharges to the valley-fill aquifer. In some reaches of the valleys, the valley-fill alluvium is clay that is poorly permeable. In those reaches, the subsurface flow in the bedrock probably flows downstream beneath the alluvium and eventually discharges to the alluvium in a reach where the alluvium is permeable.

Water moves downstream as streamflow in the channel and as underflow in the alluvial and bedrock aquifers. Interchange of water between the stream channel and the alluvial aquifer in some reaches may be impeded by clay beds in the alluvium, as reported by Coffin and others (1968). Water-budget studies are needed for selected reaches of major streams to identify these interchanges. Furthermore, a water budget of the components of the hydrologic cycle is needed because alteration by man of any component could change other components greatly. The budget studies described by Wymore (1974) could be extended and used to estimate precipitation, soil moisture, and evapotranspiration. Combined surface runoff and subsurface flow can be predicted using a calibrated watershed model if adequate precipitation and streamflow data are available. The watershed model is discussed later in this section. Discharge from the bedrock aquifer is being evaluated by simulation-model studies described by Taylor (1982). The relation between streamflow and underflow in the alluvial aquifer can be estimated by means of carefully planned gain-and-loss studies. Reaches of a stream that are gaining or losing indicate a good hydraulic connection between the stream and alluvial or bedrock aquifers; reaches of a stream that do not gain or lose flow are probably adjacent to reaches of the aquifers that are poorly permeable. The results of gain-and-loss studies need to be interpreted in conjunction with drillers' logs and hydrographs of wells and test holes completed in the alluvium near study sites. These studies need to be repeated in the same reaches of the streams at various times of the year in order to determine the interchange under conditions of spring runoff, low runoff, and active irrigation.

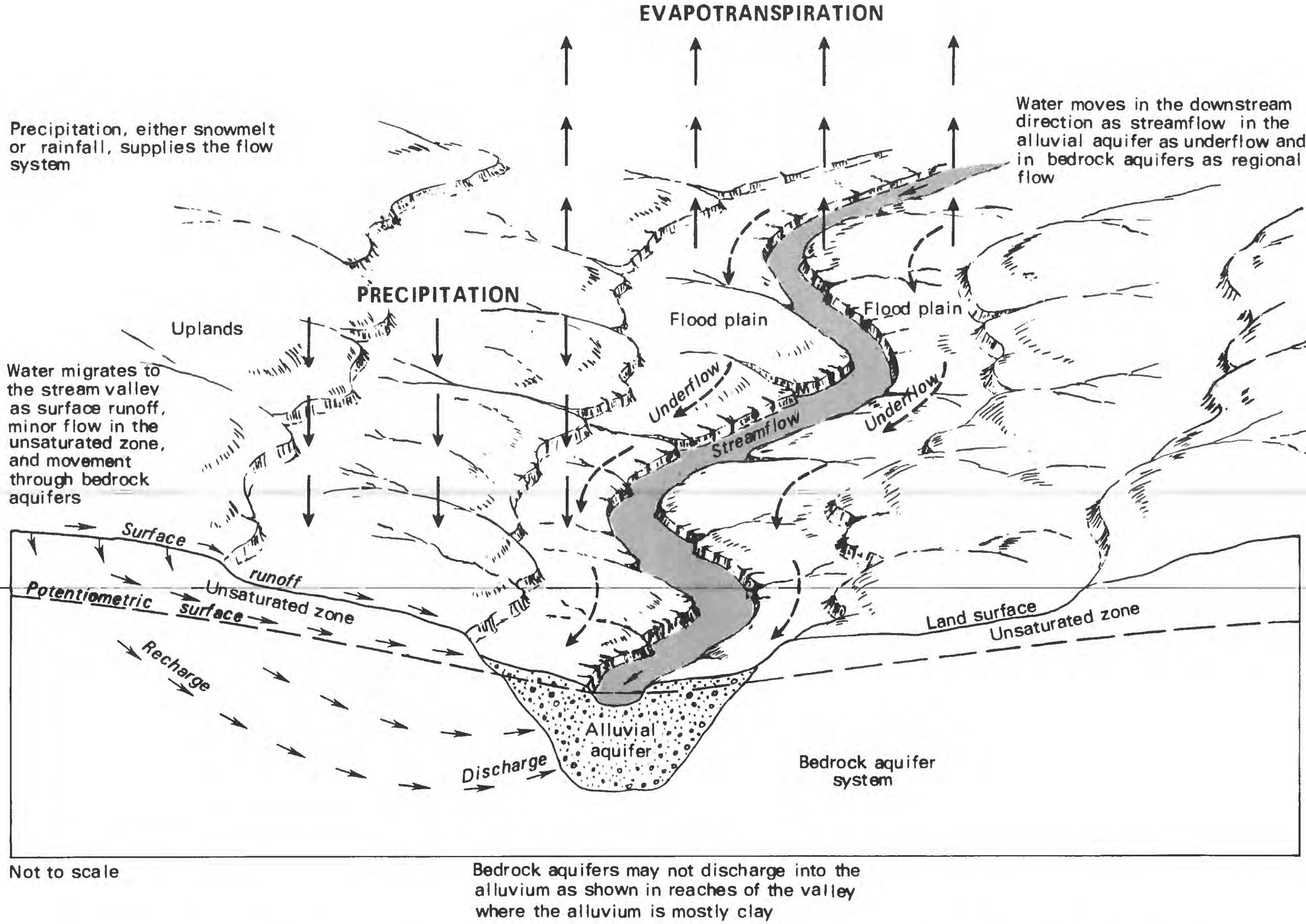


Figure 16.-- Schematic diagram depicting principal hydrologic flow components in the stream-aquifer system.

Watershed Modeling

Watershed modeling is needed in the Piceance basin in order to improve understanding of water budgets, to extend flow records using simulation, and to estimate the effects of land use changes. Possible changes include open-pit mining, aboveground storage of unretorted shale, and spoil piles of retorted shale. Thirty-three streamflow gages currently (1982) are being operated in the basin by the U.S. Geological Survey, as shown in figure 17. Twenty-four gages are in the Piceance and Yellow Creek drainages which flow to the White River, and nine gages are in the Roan and Parachute Creek drainages which flow to the Colorado River. Most of these stations have been operated since 1974, but little analysis has been done on the data collected. A study is needed to analyze the data collected at many of these gaging sites by using a watershed model. The U.S. Geological Survey precipitation-runoff modeling system (PRIMS) (G. H. Leavesley and others, U.S. Geological Survey, written commun., 1982) is particularly suited for use in the Piceance basin because the model contains snow-accumulation and snowmelt routines, which are predominant components of the hydrologic cycle in this area (Weeks and others, 1974). The successful calibration of this model provides a water balance of each gaged basin. This water balance provides estimates of ground-water recharge and discharge for the basin and estimates of ground-water storage and losses from the alluvial aquifer.

When this model is used, the basin is partitioned into hydrologic-response units, such as the five units shown in figure 18. Within each unit, it is presumed that the hydrologic response is uniform and need not be described with distributed hydrologic parameters. Each unit is subdivided on the basis of soils, vegetation type, elevation, slope, and aspect. It is, therefore, important that the network of small gaged watersheds represents the response units identified in the Piceance basin. Analysis of response units in the existing gaged watersheds and in the entire Piceance basin would provide one way in which to evaluate the streamflow-gaging network. For example, if several response units are determined to be similar, the watershed might be monitored with fewer gages because of its uniformity. If the basin is subdivided into a greater number of response units and the hydrologic response is less uniform than originally presumed, more gages may be needed. It may be necessary after such analysis to discontinue or move some streamflow-gaging stations or to build additional gages. The process of calibrating the model helps to direct additional data-collection activities by identifying important aspects and interactions of the hydrologic cycle within the Piceance basin. For example, additional information needed on the ground-water system can be collected by appropriate low-flow investigations of the streams. It is also essential to define the annual water equivalent of the snowpack at the beginning of snowmelt. These are important data because most of the streamflow is derived from snowmelt. The available snow-course data are very sparse and need to be expanded to support a modeling study of watersheds in the Piceance basin.

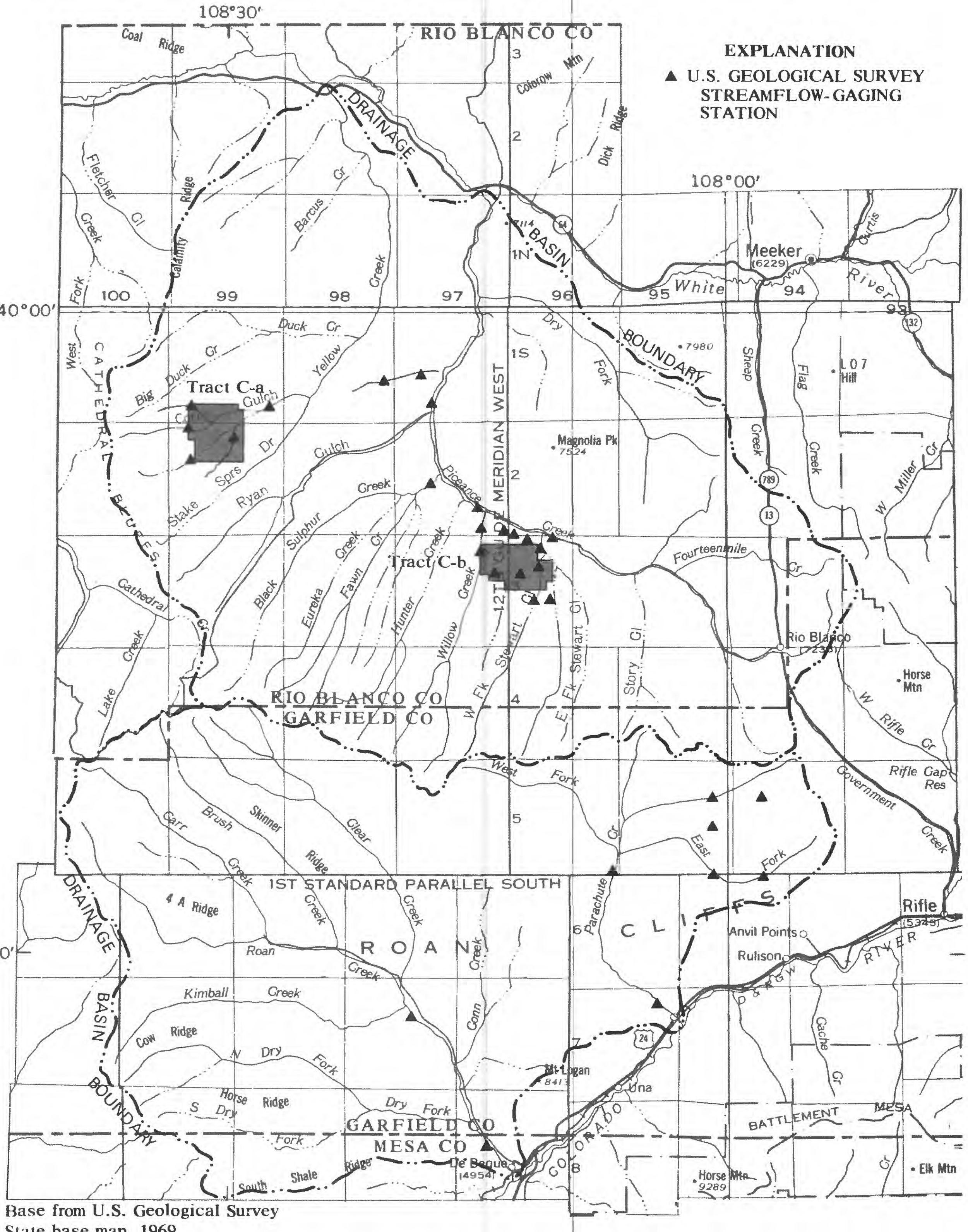


Figure 17.--Location of streamflow-gaging stations.

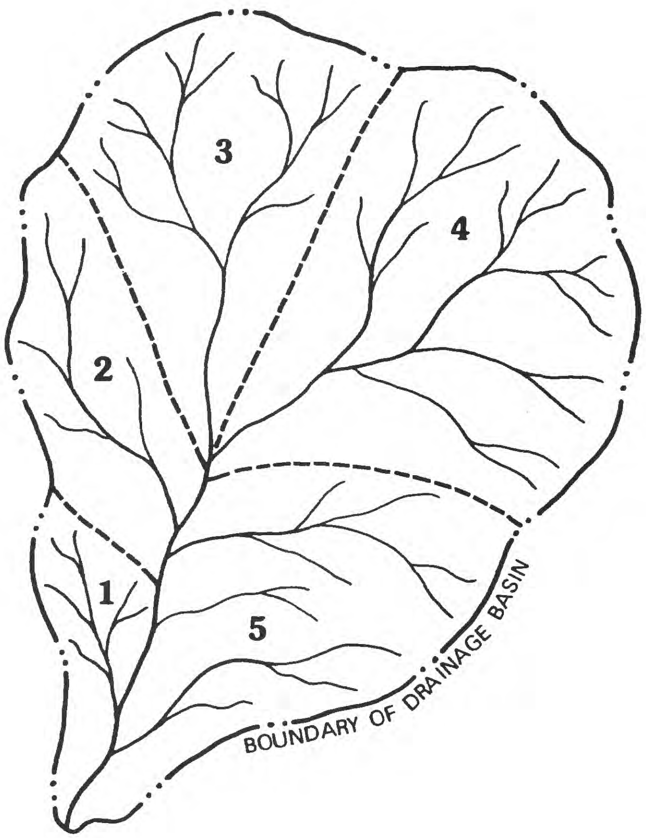


Figure 18.--Schematic diagram showing subdivision of drainage basin into five hydrologic-response units.

The watershed model of the U.S. Geological Survey can be used to simulate records of mean daily discharge data based on long-term records of snow course and climatic records. Statistical analysis of the gaged and simulated values provides flow-duration curves and low-flow statistics which describe the flow characteristics of any particular basin. The model also can be used to estimate the effects of land use changes by altering the hydrologic-response units in the model. Also, to properly evaluate the water quality of streams in the Piceance basin, predicted mean daily discharge values may be used to calculate dissolved and suspended chemical loads from field measurements of constituent concentrations.

Flood-Frequency Analysis

Flood-frequency analysis describes the magnitude and frequency of flood events that may be expected for a given stream. This information is needed to appraise the advisability of storing retorted oil shale in stream valleys (U.S. Environmental Protection Agency, 1977). Dams or retention structures proposed for construction upstream and downstream from retorted shale piles cannot be designed properly without information describing the probability of flood events. Because only a few years of streamflow data are available for most streams in the Piceance basin, a watershed model is needed to simulate flows for longer periods of time.

Unfortunately, the model previously described cannot provide an accurate assessment of the peak-flow conditions because it can only simulate mean daily discharges resulting from snowmelt. Analyzing high flows in this region is complicated by two different types of interacting hydrologic regimes. Much of the water derived from a basin in a particular year results from snowmelt. In some years the peak discharge is the peak from the snowmelt hydrograph. However, there are years in which the annual peak discharge results from a high-intensity rainstorm. The resulting hypothetical flood-frequency curve from mixing these two hydrologic regimes is shown in figure 19. The lower, more frequent floods result primarily from snowmelt. The larger floods, although less frequent, are shown on a separate frequency curve which represents the effect of rainfall.

Because of these two different flood-frequency regimes, data are needed from both types. A storm-event version of the watershed model is available to model these rainfall-runoff events. This storm model has been coupled to the daily-flow model and is calibrated to individual storms based on rainfall intensity and runoff data. Simulation of a long period of rainfall-flood events (20 or more years) requires an equivalent long-term record of rainfall-intensity data. Predicted flood peaks are thus derived by the model, and a synthetic flood-frequency curve can be obtained. The existing network of rainfall data is not adequate to support the storm-event model calibration. Consequently, there is an immediate need for an evaluation of available rainfall data and expansion of the network.

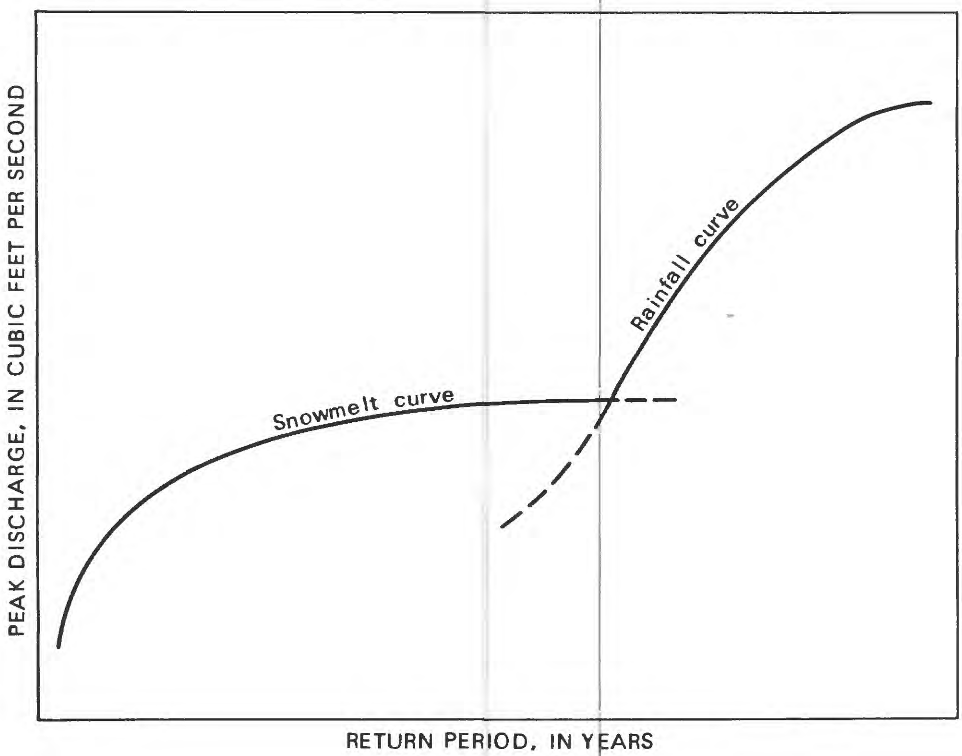


Figure 19.--Hypothetical flood-frequency curve showing the relation between the snowmelt flood frequency and the rainfall flood frequency.

SURFACE-WATER QUALITY

By K. J. Covay and R. O. Hawkinson

As described in preceding chapters of this report, oil-shale development will potentially impact water quality of streams in the Piceance basin. Consequently, data gathering must be accomplished to describe predevelopment conditions and to monitor water-quality changes as development expands. With an unlimited budget, all water-quality components could be monitored or sampled, thereby providing a complete information base. Economics and manpower constraints dictate that only select basins or sites can be monitored for selected constituents. Thus, it is necessary to (1) Select representative drainage basins for frequent monitoring, (2) select sites for periodic (less frequent) monitoring within representative basins, (3) analyze selected, potentially harmful water-quality constituents that are expected to be produced by oil-shale development, (4) correlate water-quality information with other hydrologic information in the basin to acquire information necessary to explain cause and effect, and (5) provide techniques for transfer of hydrologic information from monitored to unmonitored basins. Based on the five preceding points, the following sections present a more detailed approach to understanding areal and temporal variation in dissolved and suspended constituents and aquatic species as well as the potential impact of oil-shale development.

Dissolved Constituents

Dissolved-constituent data should be compiled from all completed or current studies to evaluate the adequacy of the sampling frequency and type of water-quality information available. This compilation will provide a means for describing the variation in dissolved concentrations and loads as related to surface-water flow characteristics. In addition, recommendations can be made to modify the network configuration in the Piceance basin to improve the understanding of hydrogeochemical interrelationships on a regional basis. To provide a complete description and understanding of the dissolved-constituent transport within the Piceance basin requires ground-water and spring-discharge information, quality-of-water data for major aquifers, description of areal variability in aquifer properties, and surface-water quality and quantity information from a primary station network.

In addition, the following ancillary information is needed to support interpretation of water-quality data: (1) Chemical and mineralogic composition of rocks that comprise major geologic formations, (2) dominant land use and vegetation types, (3) significant changes in land use including start of mining and the various developmental and production phases, (4) dominant soil types, (5) water use of surface- and ground-water supplies, and (6) physical characteristics of drainage basins. Agencies such as the U.S. Soil Conservation Service, the U.S. Environmental Protection Agency, and the Colorado Department of Natural Resources, as well as energy-development companies, probably can provide some of this information. Acquisition of ancillary information not readily available should be planned concurrently with hydrologic investigations.

Primary sites should be selected on perennial streams in the Piceance basin for measurement of continuous streamflow, suspended sediment, specific conductance, and temperature. Sampling schedules should be established for chemical constituents, including major inorganic anions and cations, trace metals, and nutrients (see table 5). Specific conductance and temperature need to be monitored on a continuous basis. Samples for chemical constituents need to be collected three to four times per year during low-flow conditions; five or six samples are needed for the two or three runoff events per year. Assuming no changes are made in land use upstream from a monitoring site, continuous specific conductance and temperature data should be monitored until they are adequate to define the premining conditions. Analyses for the trace metal and special constituents listed in table 5 need to be reviewed after collection of 18 to 20 samples representing approximately four low-flow periods and three separate runoff periods. Constituents that are not indicative of premining conditions or which occur at insignificant levels can be deleted from the schedule. However, if the land or water-use patterns change, these constituents may need to be restored to the schedule. At that time, laboratory analytical schedules need to be reexamined. As organic and trace-constituent analysis progresses, the program must have sufficient flexibility to add determinations of those constituents identified as indicators of mining-induced changes in water quality. Initially, molybdenum, thiocyanate, acetic acid, and phenols need to be included as general indicators.

Table 5.--*Chemical constituents for consideration in network to monitor surface-water quality in the Piceance basin*

[All constituents are dissolved, unless otherwise noted]

Major constituents and determinations	Trace elements		Nutrients	Special analyses
Alkalinity, total (as $CaCO_3$)	Aluminum	Iron	Nitrite	Cyanide
Calcium	Arsenic	Lead	Nitrite plus nitrate	Thiocyanate
Sodium	Barium	Lithium	Ammonium	Thiosulfate
Chloride	Beryllium	Manganese	Ammonium plus organic nitrogen	Phenols
Magnesium	Boron	Mercury	Orthophosphate	Dissolved organic carbon
Potassium	Cadmium	Molybdenum	Total phosphorus	
Residue (calculated sum)	Chromium	Nickel		
Silica	Cobalt	Selenium		
Sulfate	Copper	Strontium		
	Fluoride	Vanadium		
		Zinc		

Partial-record sites are needed to monitor drainage areas upstream from primary sites. Selection of partial-record sites should be based on present and potential land use, vegetation type, geologic formations, and on sources of baseflow as they affect water quality. Laboratory analyses should be made for the same chemical constituents that constitute primary analytical schedules. Also, streamflow-discharge and suspended-sediment measurements need to be made at the same time water-quality samples are collected so that these data may be correlated.

After the data network is established, analysis and interpretation should begin as soon as possible. The initial modeling and the statistical approaches to be used should be selected prior to data collection. As an example, parametric statistical tests, F or t tests, can be used to determine significant differences in mean concentrations or loads of chemical constituents in areas associated with specific land use, vegetation types, geologic formations, and areas undergoing substantial energy development. Failure to establish well-defined objectives and statistical techniques to be used in data analysis can result in a data base that is inadequate for most program objectives.

Evaluation of chemical loads requires knowledge of the ground- or surface-water flow regime. Models provide methods of analyzing and estimating the various flow components that affect dissolved loads in streams. Surface-water models are available for use in estimating daily and peak flows and flood volume from basins before and after changes in land use. Precipitation is the primary variable in utilizing these models to estimate streamflow and in extending records for the purpose of increasing knowledge of streamflow characteristics. Improving confidence in the model's ability to represent hydrologic processes requires additional meteorological data to estimate evaporation, soils information to estimate infiltration rates and moisture-holding capacities, and vegetation-type definition. Generally the success of transferring models from gaged to ungaged basins will be dependent upon the ability to determine the preceding watershed variables. Ground-water flow and solute-transport models can be used to estimate the natural discharge to streams from seeps and springs and to provide the basis for estimating solute traveltime and changes in solute concentrations within aquifer systems. In addition, models can be used to predict possible effects of pumpage or injection on streamflow and stream quality.

Statistical techniques are necessary to summarize and interpret water-quality information from the Piceance basin. The Statistical Analysis System, SAS[1] (Barr and others, 1976), is available for statistical analysis of water-quality data. Mean, median, range, and standard deviation can be used to characterize areal water-quality conditions for a specific streamflow regime, given limited water-quality data at several sites within a homogeneous geologic or land use area. The flow duration (percentage of time that a specified flow is exceeded) is assumed to be similar throughout the basin during a water-quality reconnaissance. The areal variability of the data can be determined by examining differences in group means, standard deviations, and ranges by grouping the water-quality data from areas of similar land use, geology, or vegetation.

[1]The use of brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

As more data become available for a specific site, regressions and correlations can be developed to relate dissolved constituents to specific conductance and water discharge to specific conductance (Gaydos, 1980). Regressions and correlations of specific conductance to dissolved constituents can be used for the following purposes:

1. Identification of water types in the base-flow and overland-flow components of runoff.

2. Estimation of constituent concentrations based on field determinations of specific conductance.

3. Determination of regression parameters which, if developed for conditions before and after mining, can be analyzed using statistical tests to determine if mining has made a significant impact on dissolved constituents in the surface-water system. Regression and correlations developed for water discharge and dissolved constituents before and after mining, or upstream and downstream from mining, will provide information concerning the impact of mining on dissolved-constituent loads. Tests of significance can be used to determine if computed constituent loads are significantly different before and after mining.

Finally, mean or median concentration information for specific flow regimes before and after mine development can be evaluated using nonparametric statistical tests such as Kendall's rank correlation coefficient and Mann-Whitney U test (Steele and others, 1974). Such tests of trend will indicate if mining has had a significant effect on the water quality of the base flow, snowmelt runoff, and storm runoff.

Suspended Sediment and Bedload Transport

Erosion, deposition, and attendant sediment-transport loads in streams probably will be affected by oil-shale development. Interpretive studies (Frickel and others, 1975) and erosion data (Frickel, 1978) suggest that sediment yield in the Piceance basin will be altered by dam construction, changes in streamflow, retorted-shale disposal, changes in land use and vegetation, and open-pit mining. Furthermore, sediment changes may be greater during construction periods than during production periods. Sediment increases in streams will reduce the capacity of surface reservoirs, destroy life in the aquatic environment in streams, and serve as a transport site for pesticides and trace elements. Therefore, monitoring of suspended-load transport in streams is needed. The location of suspended-sediment stations operated by the U.S. Geological Survey in the Piceance basin is shown in figure 20.

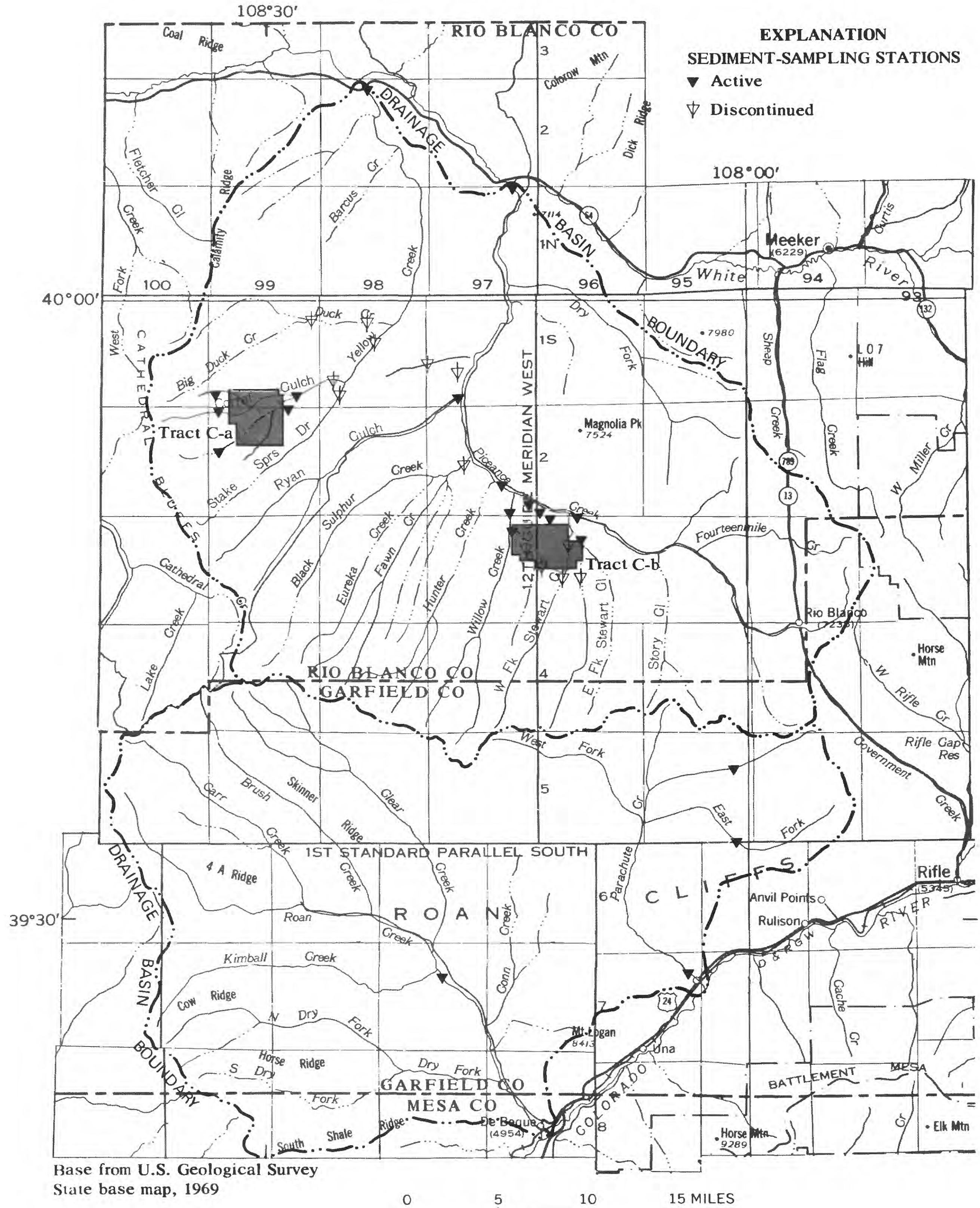


Figure 20.--Suspended-sediment sampling stations operated historically and currently by the U.S. Geological Survey.

Suspended-sediment data are needed on a daily basis because sediment transport is poorly defined in the basin. These data can be collected using automatic sediment samplers. Bedload and bed material need to be measured and sampled in conjunction with suspended-sediment cross-section measurements. The particles in the bedload material in this region are often thin, angular, and of low density. These properties facilitate transportation of the bedload. Bedload needs to be measured monthly and bed material sampled semiannually. Particle-size analyses need to be done on selected samples of suspended load and on all samples of bedload and bed material. Periodic calculations of total load are needed to determine the relation between the suspended load and the bedload. Changes in erosion rates, sediment migration, and streamflow may require adjustments in the sampling network, sample types, and sample frequency.

In the Piceance Creek drainage basin, the present sediment program needs to be strengthened by establishing two additional sediment-sampling sites. One control site on Piceance Creek needs to be located at Rio Blanco, a site that would not be disturbed by oil-shale development. The second site needs to be located on Cow Creek, a tributary to Piceance Creek, below Rio Blanco. Observations of spring runoff in Cow Creek suggest it is an area of high sediment yield. Daily suspended-sediment records and bedload measurements need to be obtained at both sites.

The Roan Creek and Parachute Creek drainage basins also could be subjected to augmented erosion due to accelerated oil-shale development. A sediment-sampling program needs to be established to determine the amount of sediment being transported out of these basins and into the Colorado River. The following daily collection sites need to be considered in a sampling network:

Roan Creek basin

Roan Creek upstream from confluence with Clear Creek
Clear Creek
Kimball Creek
Roan Creek downstream from Kimball Creek
Conn Creek at mouth
Dry Fork near De Beque
Roan Creek at mouth

Parachute Creek basin

West Fork Parachute Creek
Northwater Creek
East Middle Fork Parachute Creek
Middle Fork Parachute Creek
East Fork Parachute Creek
Parachute Creek at Parachute

Suspended loads in the White River could significantly change if diversions or reservoirs are constructed. Considering the hydrologic changes that could occur from the construction of proposed dams and reservoirs (see fig. 26) and from activity associated with energy development, a study of the sediment characteristics of the White River is proposed. Suggested sites to be monitored, frequency of sampling, and type of load are presented below:

North Fork of White River at Buford - periodic, suspended load;
South Fork of White River at Buford - periodic, suspended load;
White River above Coal Creek - daily, suspended load;
White River below Meeker - daily, suspended load; periodic, total load; and
White River above Rangely - daily, suspended load; periodic, total load.

Suspended-sediment samples were collected from Douglas Creek, which joins the White River near Rangely, during the 1977 and 1978 water years. During the spring and summer, concentrations of suspended sediment ranged from about 30,000 mg/L to about 80,000 mg/L. Douglas Creek could be a major source of sediment to the White River. In order to determine accurately the sediment yield from Douglas Creek, a network of daily monitoring sites needs to be established.

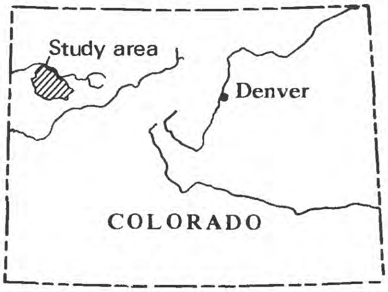
The source areas and rates of movement of sediment might be determinable from studies of the chemical and mineralogic characteristics of the sediment. For example, the sediment eroded from spoil piles may be distinct from sediment eroded from natural materials. Periodic sampling of sediment distribution over a wide area might permit the calculation of rates of movement from various sediment-source areas.

Aquatic Biology

Oil-shale development is most likely to cause changes in the aquatic environment of the surface waters in the Piceance basin. Biological communities in running water are influenced by the chemical and physical properties of the stream. Degradation of stream quality can be caused by introducing toxic substances or suspended sediment into the stream. Toxic substances can completely eliminate an aquatic community. Thermal pollution associated with toxic substances can increase the ambient stream temperature and decrease oxygen to levels where the physiological processes of the aquatic organisms are affected. Increased suspended sediment can: (1) Decrease light penetration and interfere with primary production; (2) cover large cobbles--thus eliminating clinging organisms; and (3) clog the gills of many organisms. Fine silt and clay can bury a cobble substrate, causing a shift in community composition and trophic relations. Biological communities can be altered by reservoir releases that cause changes in streamflow, sedimentation, temperature, and dissolved oxygen.

The organisms that exist in an aquatic environment range from the lowest forms of micro-organisms, such as algae, to the highest forms of plants and animals. Within the animal segment, benthic invertebrates comprise a major entity. Benthic invertebrates are animals without backbones which live in or on the bed material of streams and lakes. They most often consist of immature forms of insects, but also include aquatic worms, snails, scuds, leeches, clams, and mites, and are a major link in the aquatic food chain. Benthic invertebrates are useful indicators of the water quality in which they live because they have relatively long life spans, are relatively immobile, and are sensitive to changes in their environment.

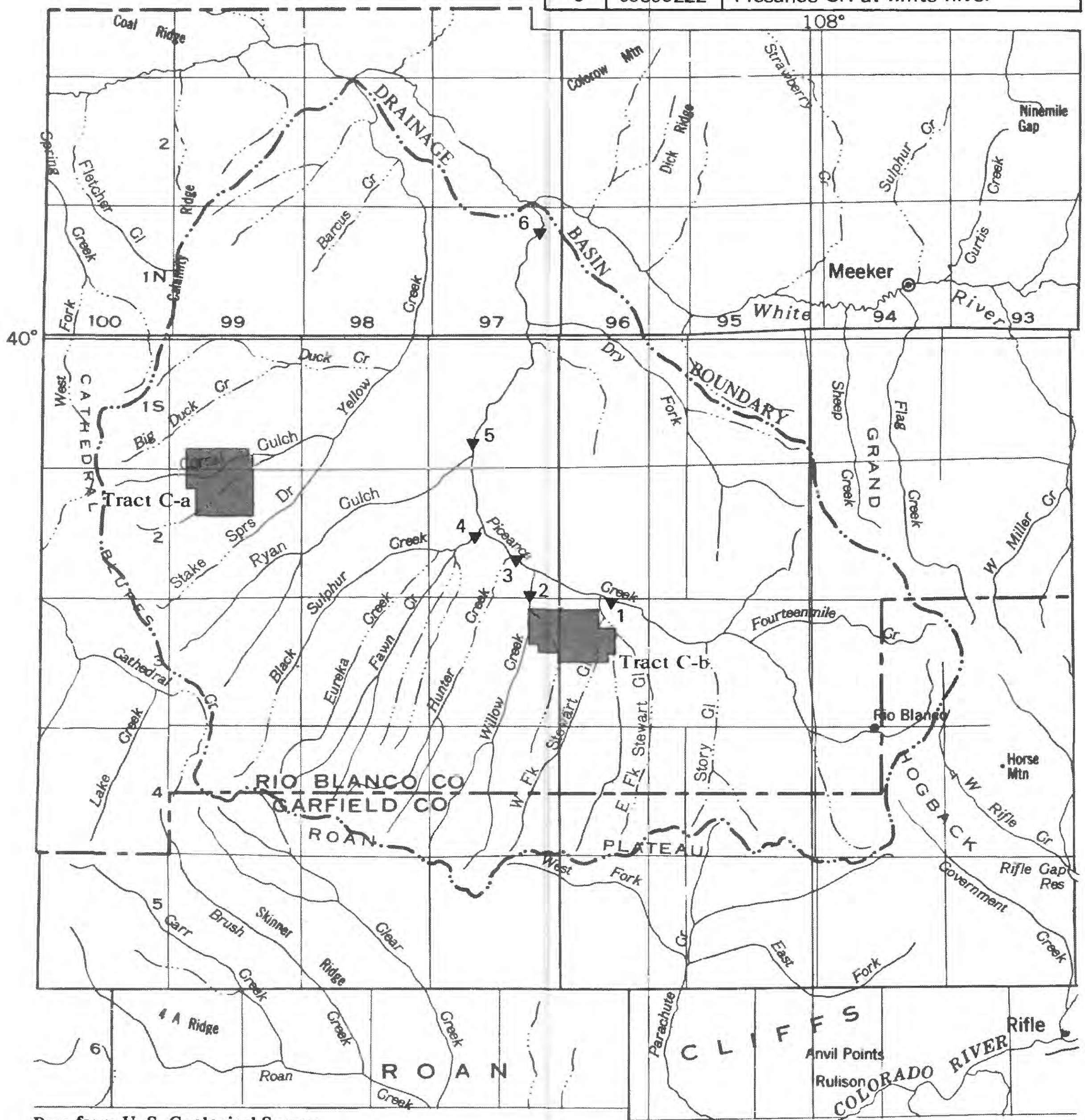
Biological monitoring of benthic invertebrates at six sites (fig. 21) in the Piceance Creek drainage basin began in 1976. The most frequently collected insect organisms belong to the order Diptera (two-winged flies). Other insects collected less frequently belong to the orders Ephemeroptera (mayflies), Plecoptera (stoneflies), Trichoptera (caddisflies), Coleoptera (beetles), Hemiptera (true bugs), and Odonata (dragonflies). Aquatic worms were the most frequently collected noninsects. Preliminary analysis of the data indicates that the biota in streams in



EXPLANATION

▼2 SAMPLING SITE AND NUMBER

Site	Station	Location
1	09306007	Piceance Cr. below Rio Blanco
2	09306058	Willow Cr. near Rio Blanco
3	09306061	Piceance Cr. above Hunter Cr., near Rio Blanco
4	09306175	Black Sulphur Cr. near Rio Blanco
5	09306200	Piceance Cr. below Ryan Gulch, near Rio Blanco
6	09306222	Piceance Cr. at White River



Base from U. S. Geological Survey
State base map, 1969

0 5 10 15 MILES

0 5 10 15 KILOMETERS

Figure 21.--Biological sampling sites of the U.S. Geological Survey in Piceance Creek drainage basin.

this area cannot withstand significant disruption. In addition, previous reports (Everhart, 1973; Gray and Ward, 1977; and Ames, 1977) generally indicate that streamflow and sediment transport adversely affect benthic-invertebrate colonization in Piceance Creek, Yellow Creek, and the White River.

Identification and enumeration of organisms, as well as the calculation of numerical indices, were conducted on benthic-invertebrate samples collected in the Piceance Creek basin. At five of the six sites, organisms of the order Diptera, especially chironomids, dominated the sample composition. Chironomids, or midges, are wormlike organisms capable of living in streams having low dissolved oxygen. Dipteran organisms in general are more tolerant of extreme ranges of several water-quality conditions, including pH, temperature, and salinity. As mentioned above, sediment probably plays a role in restricting colonization of other invertebrates because fewer types and numbers of organisms were collected during or after high flow when sediment transport and deposition may have been the greatest.

One type of index used in determining biological quality is the diversity index. The diversity index, $\bar{d}$, (Wilhm and Dorris, 1968) is:

$$\bar{d} = -\sum_{i=1}^{s} \left(\frac{n_i}{n}\right) \log_2 \left(\frac{n_i}{n}\right),$$

where: n_i=the number of individuals per taxon,

n=the total number of individuals, and

s=the total number of taxa in the sample.

Diversity values can range from zero to any positive number. Values less than 1 usually indicate organically polluted water, and values between 3 and 4 usually indicate clean water. Calculated diversity-index values for Piceance Creek basin range from 0 to 3.62 and indicate a variety of stream-quality conditions. In general, the number of organisms and the corresponding diversities decreased downstream during the study period. No organisms were collected at two sites, and diversity was calculated to be zero at one site. There probably is a seasonal fluctuation in diversity of organisms in the Piceance basin, because of extreme variations in flow with its attendant physical and chemical changes, and because of the orderly succession of organisms. However, the wide range of diversity also may indicate that more samples are required at a greater frequency to narrow this range. Some statistical tests can be generated to address this problem.

The similarity index: $s = \frac{2C}{A+B}$,

where: A=the number of taxa in sample A,
B=the number of taxa in sample B, and
C=the number of taxa common to both A and B,

is a method used to compare taxa between different sets of samples (Odum, 1971). Similarity-index values can range from zero to 1. A value of 0 indicates the two samples have no taxa in common, and a value of 1 indicates total similarity between two samples. Similarity-index values for sites in the Piceance Creek basin range from 0 to 0.83.

Trophic relations (Merritt and Cummins, 1978) of aquatic invertebrate organisms is another method of analyzing data. In this approach, each organism is assigned to a function group. The functional groups are based on feeding mechanisms and dominant food types and thus give an indication of the interaction among the organisms. The functional groups consist of shedders, collectors, scrapers, piercers, engulfers, and parasites. In a well-balanced aquatic ecosystem, no one group would be dominant over any other group.

The present aquatic-biology program in northwest Colorado needs to be expanded to include an assessment of Yellow Creek, the White River, Roan Creek, and Parachute Creek--all of which may be impacted by extensive mining operations. The White River also may be significantly altered by construction of dams, reservoirs, and diversions. Any changes in present water-quality conditions will result in changes of the aquatic biology.

Yellow Creek and its tributaries drain Colorado oil-shale tract C-a. Four to six biological sampling sites need to be established in the Yellow Creek basin. Sampling sites could include Yellow Creek near Rangely, Corral Gulch near Rangely, Corral Gulch at 84 Ranch, and Box Elder Gulch upstream from the confluence with Corral Gulch.

Roan and Parachute Creeks drain areas of the Piceance basin that include numerous patented claims and fee lands. Benthic-invertebrate sampling in these creeks is advisable to detect biologic effects of oil-shale development. Preliminary sampling in Roan Creek drainage basin has been conducted at Dry Fork, Kimball Creek, Clear Creek, Conn Creek, and Roan Creek. Preliminary sampling sites in Parachute Creek drainage basin include the Middle Fork, East Fork, and West Fork of Parachute Creek, and Parachute Creek near Parachute.

The White River needs to be sampled intensely due to impending impoundments and because Piceance Creek and Yellow Creek flow into it. Possible sites are on the North and South Forks of the White River, White River upstream from Coal Creek, White River near Meeker, White River downstream from Meeker, White River upstream and downstream from the confluence with Piceance Creek, White River upstream from Rangely, and White River near Watson.

In summary, biological analyses indicate the response of aquatic life to changes in water quality. Analyses of benthic invertebrates provide a useful means for assessing environmental changes. Analysis of benthic invertebrates, however, is not the only biological method available for water-quality studies. Other aquatic organisms that can be useful are bacteria, periphyton, phytoplankton, and zooplankton. Determinations of chlorophyll, biomass, primary productivity, and algae-growth potential are also useful for assessing water quality.

WHITE RIVER BASIN QUALITY ASSESSMENT

By Daniel P. Bauer

The White River receives streamflow from the Piceance basin (see fig. 2). Possible degradation of water quality in surface- and ground-water resources in the Piceance and Yellow Creek drainage basins also may degrade water quality in the White River valley where the effects could accumulate. Therefore a water-quality assessment is proposed for the White River, primarily to determine the baseline hydrology of the basin prior to significant development and also to determine if similar assessments are needed in the Colorado River basin or other basins of the region.

The current (1982) water-quality data-collection program of the U.S. Geological Survey in the White River basin consists of 23 two-parameter continuous monitors of specific conductance and temperature; 4 four-parameter continuous monitors of specific conductance, temperature, dissolved oxygen, and pH; and 20 sediment stations (PS-69 automatic samplers) with 9 two-parameter continuous monitors, 2 four-parameter continuous monitors, and 13 periodic sediment stations (fig. 22). Most water-quality data were collected in the Piceance Creek basin using 11 two-parameter continuous monitors, 4 four-parameter continuous monitors, and 17 sediment stations. A majority of the water-quality and sediment data were collected after 1974, and data completeness is sporadic within any given water year.

Ambient Stream-Quality Survey

To help to augment the existing water-quality data, an ambient stream-quality survey is proposed as part of the study effort. The first part of this effort would be to evaluate information accumulated as part of past or current programs; for example, regional data or long-term data on stream temperature, specific conductance, and major inorganic constituents will be used. The second part would include the design and implementation of a data-collection program to complement the prior knowledge. The initial data effort would include a basinwide reconnaissance at approximately 50 locations throughout the basin during the stream low-flow season (fig. 23). On the basis of the reconnaissance results, approximately 25 of these sites would be selected for additional seasonal sampling. These sites would be sampled approximately four to five times during spring-runoff season to help to determine the response of the stream quality to variations in stream discharge. The 50 sites illustrated in figure 23 include the following types: Primary control (no upstream water use), secondary control (some upstream effect), potentially affected (mining or municipal wastewater effects), and miscellaneous (geological, land use, or other considerations). Some of the sites also would be located where previous water-quality information has been collected. Water-quality constituents to be included would be patterned after the Yampa River basin assessment (Wentz and Steele, 1980).

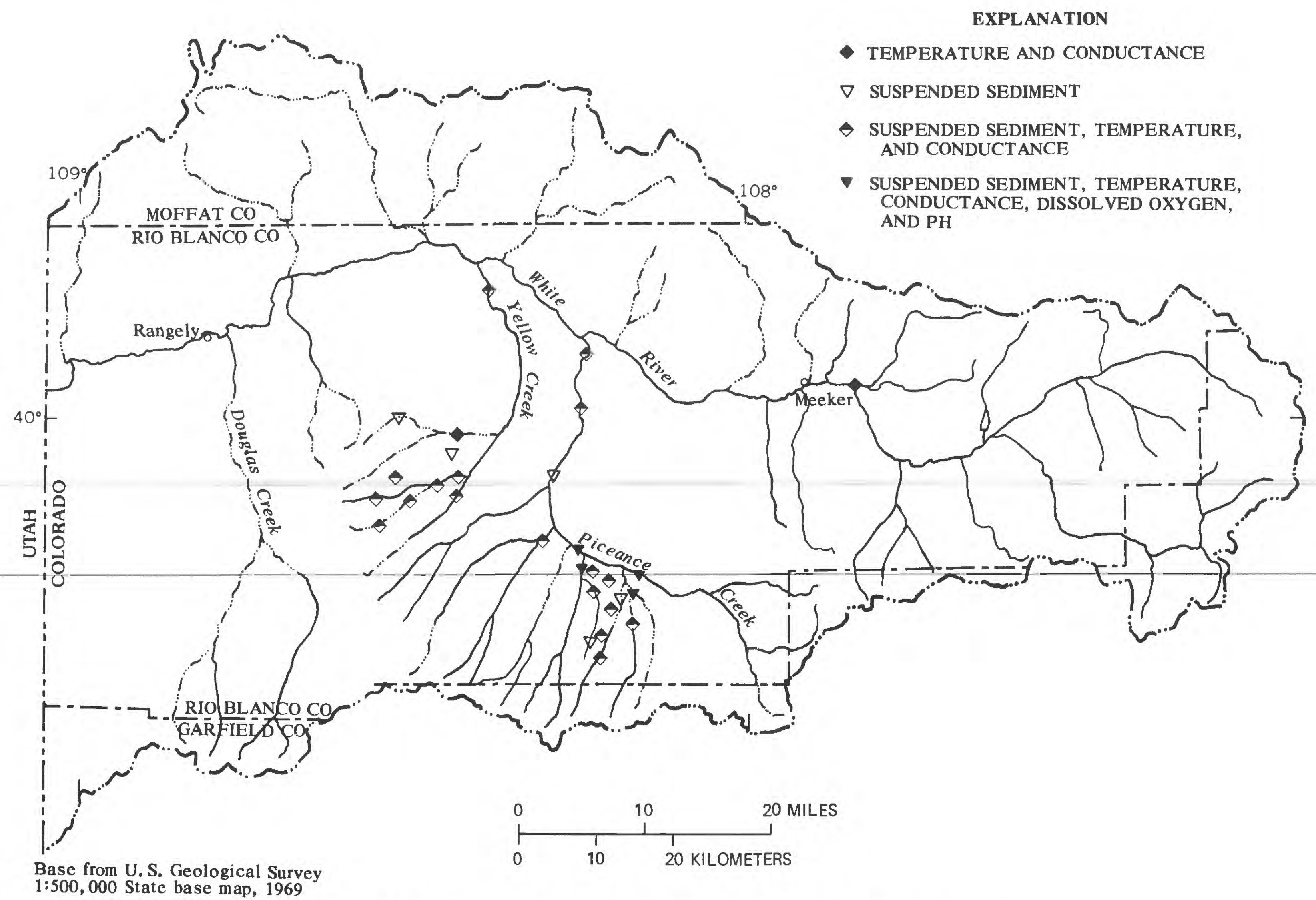
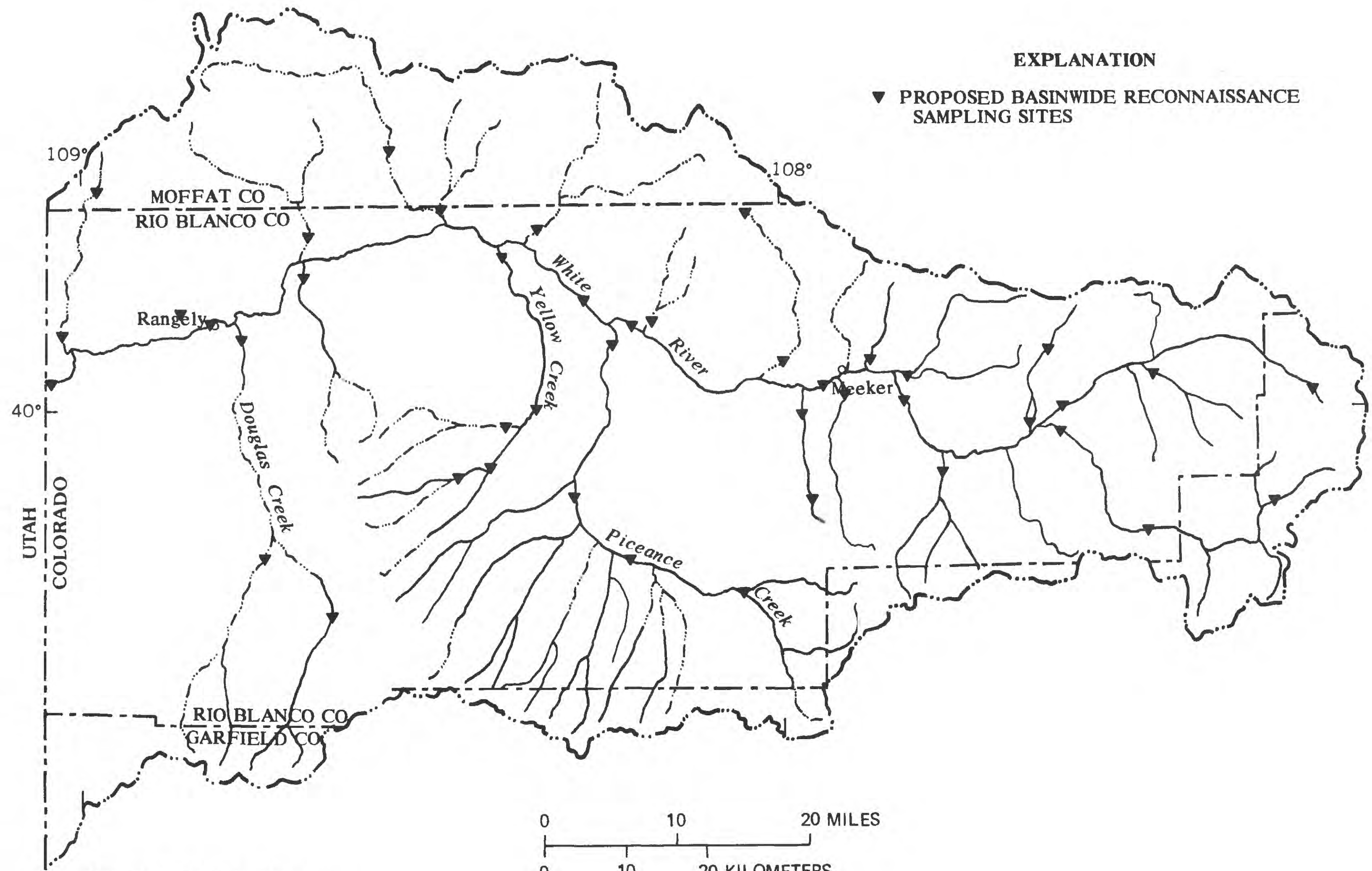


Figure 22.--Water-quality sampling sites in White River basin, 1982.



Base from U.S. Geological Survey
1:500,000 State base map, 1969

Figure 23.-- Proposed sites for reconnaissance sampling of stream quality.

Effects of Oil-Shale Development on Stream Quality

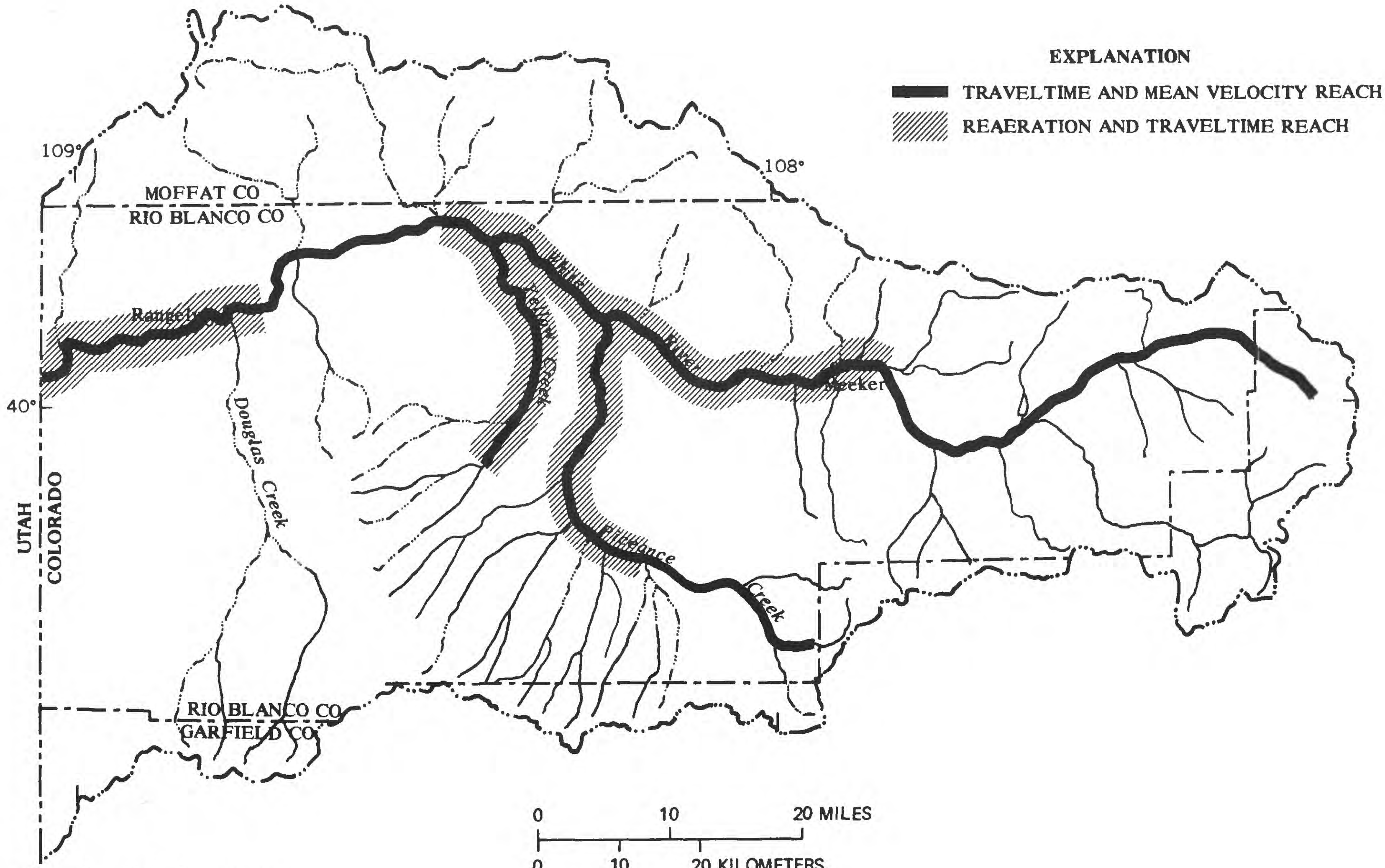
The effects of proposed oil-shale development on stream quality could be evaluated using two different methods: (1) By comparing stream quality at several sites downstream from operating mines with comparable data collected from streams draining undeveloped basins that are geologically and hydrologically similar; and (2) by comparing stream quality downstream from an existing mining operation with stream quality upstream from the same operation. Mass-balance models can be used to study the effects of mining on the inorganic water quality. A study of Trout Creek in the neighboring Yampa River basin, for example, found that coal-mined areas covered 14 percent of the watershed, but contributed 52 percent of the dissolved solids leaving the watershed. Comparison of stream quality upstream and downstream from a mine site can be done using a mass-balance model similar to that described by McWhorter and Rowe (1976). Because of large changes in geology and hydrology within the White River basin, it would be necessary to divide the geological and hydrological areas into small subbasins.

Seasonal stream-temperature changes as a result of mining could be assessed using a harmonic-analysis procedure described by Ward (1963) and Collings (1969). The harmonic analysis could be applied to all sites having either intermittent or continuous stream-temperature data. Harmonic coefficients, harmonic mean, amplitude, and phase angle, need to be applied on a regional basis.

Methodology from Iorns and others (1964) could be used to develop linear, bivariate, least-square regressions relating major inorganic constituents to specific conductance. Site-specific regression relationships also could be developed using long-term (10 years or more) data at available stations in the basin. Both methods could be used to simulate selected inorganic concentrations for selected sites in the basin. The time-trends of certain constituents also can be analyzed; for example, a similar analysis in the Yampa River basin indicated an increase of specific conductance with time in the Yampa River and was attributed to increased agricultural, municipal, and mining water use (Wentz and Steele, 1980).

Reaeration, Traveltime, and Mean Velocity

Reaeration, traveltime, and velocity studies also are proposed for selected stream reaches shown in figure 24 in the White River basin. The reaeration and traveltime studies would provide a rough index of the assimilative capacity or cleansing characteristics for anticipated organic waste loadings from mines or municipalities in the basin. These studies would provide additional information including: (1) The velocity at which liquid-borne wastes move downstream, (2) waste dispersion, and (3) desired empirical or semiempirical reaeration formulas for the reaches studied. The basic field procedure for the stream-reaeration rate determination consists of injecting a quantity of inert tracer gases into the stream and determining a desorption coefficient for the gas from measurements of the gas concentrations at various points downstream (Rathbun and others, 1975). The stream-reaeration rate is computed from the desorption coefficient. The reaeration field studies would be conducted on four stream reaches (fig. 24) in the



Base from U. S. Geological Survey
1:500,000 State base map, 1969

Figure 24.--Reaeration, traveltime, and mean velocity study reaches.

White River basin and would include two reaches on the White River main stem downstream from Meeker and Rangely, and one reach on each of the Piceance and Yellow Creek main stems. These reaches were selected because of expected increased municipal waste loadings downstream from Meeker and Rangely and possible stream organic loadings as a result of oil-shale development within the Piceance and Yellow Creeks drainages.

The stream traveltime and mean velocity are measured through the use of a fluorescent dye tracer, rhodamine WT. Field techniques include the instantaneous injection of dye at selected locations and detection of the dye downstream with an instrument called a fluorometer. Field data would be collected during a spring medium-flow season. Data collected from this effort could be analyzed by a computer model developed by McQuivey and Keefer (1976). The model analysis would be used to develop traveltime and mean velocity relationships for varying stream-discharge conditions. Results of model simulations for an earlier study in the Yampa River basin (Bauer and others, 1979) were within 5 percent of measured data.

Wasteload-Assimilative Capacity Analysis

A wasteload-assimilative capacity analysis is needed to estimate the effects of large projected increases of municipal population on the stream water quality and quantity. These impacts are of particular importance for basins such as the White River basin which now has a small population, limited water resources, and abundant energy resources. This study phase would be used to evaluate the wasteload-assimilative capacity of given study reaches for an approximate low Q7/10 (mean low-flow discharge occurring over a consecutive 7-day period with a 10-year recurrence interval) streamflow condition and projected future municipal populations and industries in the basin. The analysis using the low Q7/10 streamflow condition could be used to estimate the wasteload-assimilative capacity under low-flow conditions. However, sites of contamination may be located on normally dry tributaries or normally dry reaches of streams. The combination of these types of contamination sites with local precipitation events may result in a wasteload-assimilative capacity of the stream that is lower than estimated, using the low Q7/10 streamflow condition. Permanent populations of selected municipalities, for example, of the neighboring Yampa River basin with similar energy development are expected to increase approximately three to four times by the year 2010 (Bauer and others, 1978). The wasteload-assimilative capacity analysis effort would include field-sampling efforts for two reaches on the White River (fig. 25). The field efforts would include the sampling of water-quality data at selected locations for the reaches over an approximate 48-hour time period for two different stream low-flow periods. One set of field data collected for the assimilative-capacity analysis would be used as input to a steady-state water-quality model for calibration of the two stream reaches. The second set of data would be used to verify the model for the study reaches. Water-quality constituents that would be included are as follows: Dissolved oxygen, biochemical-oxygen demand, coliform bacteria, nitrogen, and phosphorus species. The reaeration, traveltime, and mean velocity data described earlier could also be used as input information for the steady-state model. The calibrated model would be used in a simulation mode to evaluate future projected domestic wasteloading impacts on the White River.

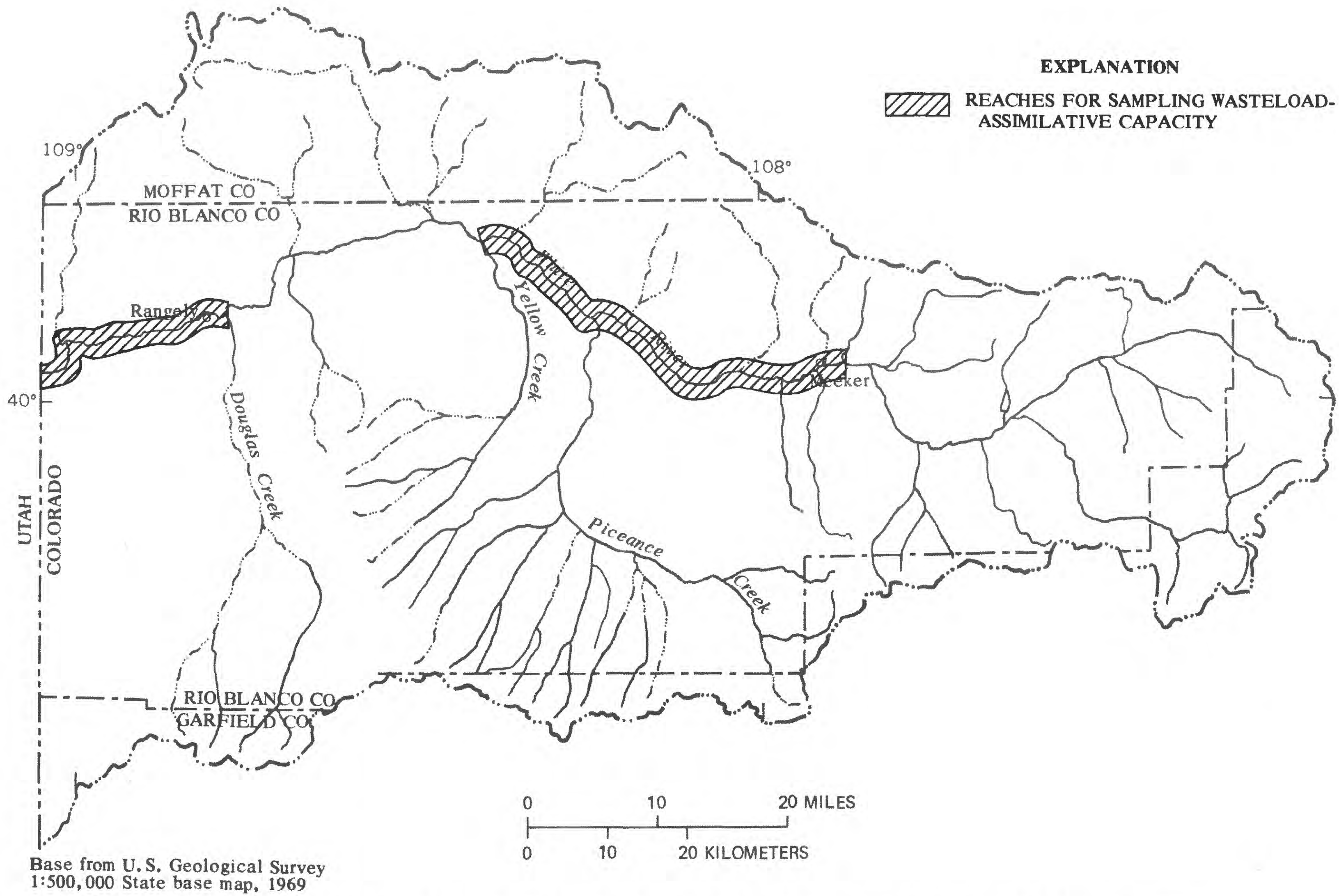


Figure 25.--Proposed reaches for sampling the wasteload-assimilative capacity of the White River.

Water Quality and Dissolved-Solids Concentration

The proposed water-use development in the White River basin will have direct impact on the water quality and dissolved-solids concentration of the water resources. Piceance Creek, for example, could be subject to extensive degradation attributed to oil-shale development which, in turn, could affect the overall quality of the lower White River. Preliminary data analysis indicates that Piceance Creek contributes from 5 to 20 percent of the dissolved solids in the White River near Rangely, depending on the relative discharge of the two streams. Therefore, a reservoir model water-use study is proposed, describing the past, present, and projected water quality and dissolved-solids conditions of the White River. This study would include the entire White River basin because of the potential construction of dams and reservoirs. At the present (1982), surface-water regulation is minor in the White River basin, but several projects have been proposed. The more significant reservoir proposals include: Yellow Jacket project, Moon Lake project, Rio Blanco Oil Shale Co. tract C-a reservoir proposal, and Exxon Fourteen Mile Creek Reservoir. A study by the Colorado Department of Natural Resources (1979) shows 33 potential reservoir sites (fig. 26) in the White River basin.

Two multireservoir streamflow models could be used to simulate the streamflow conditions for different multireservoir configurations. The models use both monthly and daily data as input. The river-basin configurations are depicted in the models by designating control points at reservoirs, diversions, and stream confluences. Monthly and daily incremental inflow must then be provided for each control point in the system. Model outputs for this analysis would include summaries of streamflow conditions, reservoir conditions, and flow shortages in the basin.

The monthly data for a common period of record could be developed using the existing 57 streamflow-gaging-station records. Missing streamflow or precipitation values could be computed by a least-squares linear-regression technique. Limited evaporation data are available in the State of Colorado. For this analysis, measured evaporation rates from an existing reservoir from nearby basins with similar geometry and elevation characteristics could be used. The effects of a number of different reservoir-development schemes need to be considered for the basin.

Daily streamflow at selected streamflow sites could be used in conjunction with stream-system modeling approaches to reconstruct and to extend the daily discharge-data records for selected stations within the basin. Some or all of the modeling tools would be used in two different types of ventures, namely: (1) Reconstruct a daily discharge record to eliminate diversions or reservoir regulation effects upstream on all or part of the data record. In some cases the reconstruction may involve instead the addition of a diversion or reservoir regulation effect to a given discharge-data record, and (2) extend the discharge-data record at sites where data are of short duration. The extension of this record could be achieved using a flow-routing model and an upstream or downstream site with longer discharge records.

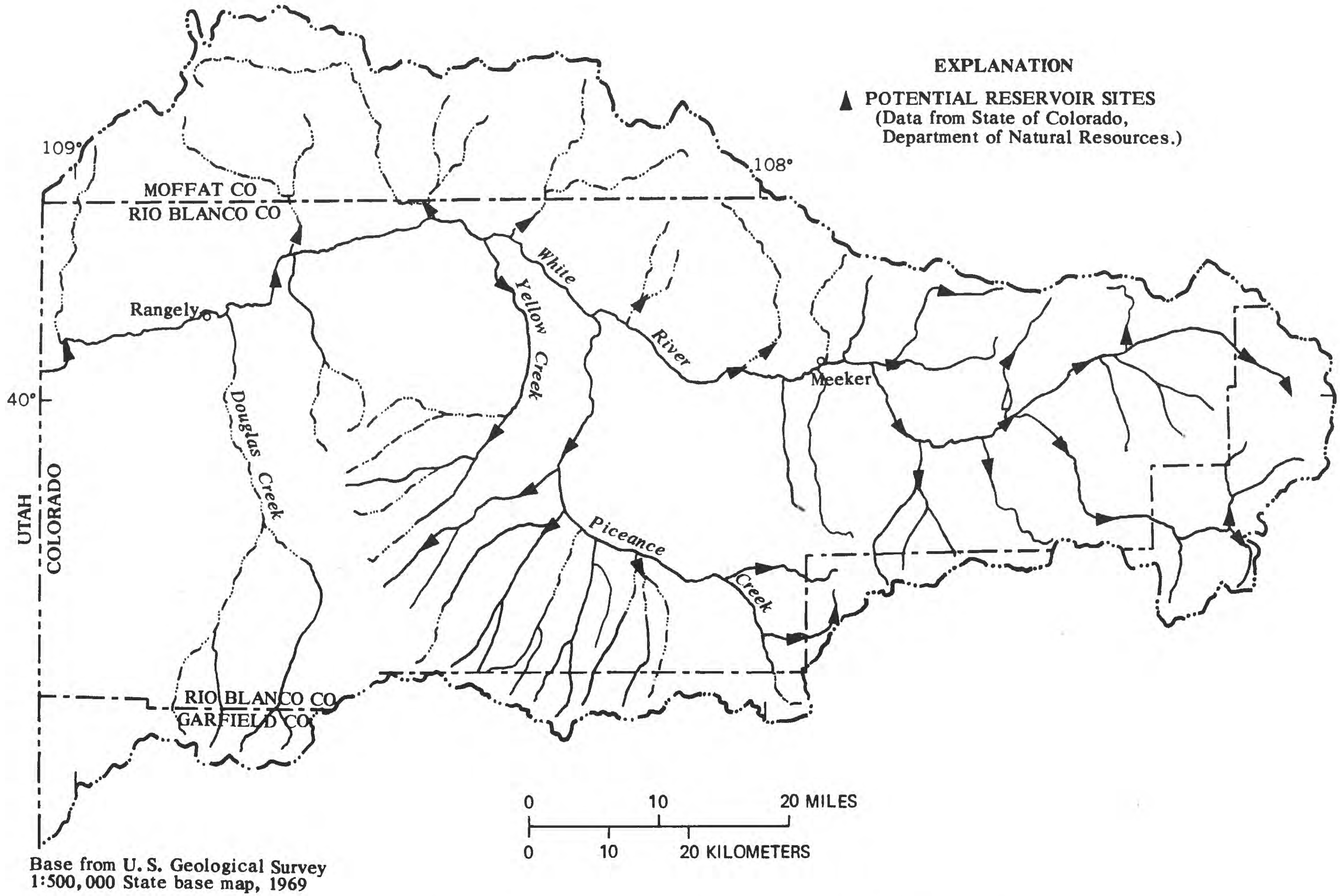


Figure 26.-- Potential reservoir sites within White River basin.

A second model analysis is needed to simulate the stream-salinity concentration at various locations in the basin. Specific-conductance data are available at approximately 31 locations (see fig. 22) in the basin. Most of these data were collected in the Piceance Creek basin after 1974. The existing specific-conductance data, in coordination with streamflow data, can be used for the calibration of a river-salinity model. The salinity model requires dissolved concentrations; therefore, the specific-conductance values will be converted to dissolved-solids concentrations using regression functions developed from the historical data (Steele and Matalas, 1974). Model projections can be simulated using a common 20-year time period and monthly data describing monthly streamflow, evaporation, and precipitation.

The number of different configurations considered for the water-quality and dissolved-solids model analysis would be limited only by the time, personnel, and money available for the study. The multireservoir water quantity and salinity model simulations predict the stream quantity and salinity concentration at various locations in the basin. The river-basin configuration is depicted in the models by designating control points at reservoirs, diversions, and gaging stations, similar to the streamflow model configuration. Output from the salinity and quantity model would include monthly dissolved-solids concentrations and streamflow.

Organic-Solute Assessment

Oil-shale resource development will produce solid, liquid, and gaseous wastes containing significant amounts of organic constituents. To determine the effect of soluble organic wastes upon water quality of the White River, a baseline organic-solute assessment needs to be conducted before development of the oil-shale resource. This assessment would focus upon organic constituents known to be present in the various wastes; it would also attempt to define the complete organic-solute composition at the "state of water-chemistry science" on a few selected samples. This comprehensive organic-solute assessment would be conducted by onsite processing of 1,000 to 10,000 gallons of water through extractive resin columns to isolate 80 to 90 percent of the organic solutes, followed by laboratory characterization of extracted organic constituents. After this initial assessment, the extraction procedure would be scaled down, and larger numbers of samples would be analyzed for organic constituents that are possible to determine in small sample volumes.

EMISSIONS TO THE ATMOSPHERE

By John T. Turk

The rock to be retorted for the production of shale oil contains a wide variety of elements, both volatile and nonvolatile. Emissions to the atmosphere would contain some fraction of essentially all elements found in the fresh shale; however, some elements are expected to have a greater potential for harm to the hydrologic environment than others, particularly sulfur and nitrogen. Throughout the retorting process, these elements can be found in various chemical forms that range from very reduced chemical species, such as ammonia and hydrogen sulfide, to highly oxidized forms of these elements. The oxidized forms of nitrogen, often denoted as NO_x, and of sulfur, generally denoted as SO_2, have been implicated in the production of "acid rain," which is thought to be the cause of many serious environmental problems. Harmful effects ranging from the corrosion of structures to the destruction of fisheries have been attributed to acid rain and associated interactions with susceptible hydrologic systems.

To predict whether or not acid rain is likely to become a major environmental hazard will require knowledge of:

1. The magnitude and characteristics of the retort emissions.
2. The transport and depositions characteristic of these emissions.
3. The geochemical and biological susceptibility of hydrologic systems likely to receive these emissions.

Most of the data necessary to make these predictions have not been collected. None of the data has been interpreted to the extent that models can be made that relate various emissions levels to various hydrologic impacts. It is possible, however, to estimate the magnitude of the emissions, the sites to which probably they will be transported, and the likelihood that susceptible systems will receive significant amounts of the emissions.

At present (1982), only a single atmospheric-emissions permit for a commercial-size retort has been granted--for a proposed 47,000-bbl/d plant to be built by Colony Development. By comparing the average emissions to the atmosphere permitted for this operation with emissions from other nearby sources we can begin to visualize what level of emissions should be expected. The permit levels for the proposed Colony Development facility are 1,240 tons/yr of SO_2 and 6,820 tons/yr of NO_x. Assuming these figures are representative of emissions levels for other facilities and that a 1 million-bbl/d industry is developed, average emissions of 26,400 tons/yr of SO_2 and 145,000 tons/yr of NO_x should approximate the total emissions of the Piceance basin from retorts alone, discounting additional electrical-generation capacity that may be built in the area. For comparison, the average emissions from the Colorado Ute powerplant at Craig, which uses two units rated at 400 megawatts each, are 9,300 tons/yr of SO_2 and 12,000 tons/yr of NO_x. Thus, for a 1 million-bbl/d oil-shale industry, the sulfur emissions would be equivalent to about three new coal-fired powerplants the size of the Craig facility, and the nitrogen emissions would be equivalent to about 12 new coal-fired plants, all concentrated into a relatively small area. Additional local power-generating capacity required for the increased population and the operating requirements of the industry would greatly increase these emission levels.

Atmospheric Transport and Deposition

Gaseous and particulate emissions from surface and underground retorting will disperse from the retort as a function of temperature, atmospheric pressure, particle-settling velocity, wind speed, wind directions, and turbulence. The large topographic relief of the area complicates the application of present atmospheric models for simulation of plume dispersion of gases and particles and will necessitate additional modeling efforts, as well as intensive site-specific data collection of meteorological variables. In the absence of such models, however, some crude estimates of dispersion can be made with regards to direction and relative deposition rates.

Data on wind speed and direction in the vicinity of the Piceance basin are derived from the long-term records from the U.S. Weather Service station at Craig and stations operated by the lessees at tract C-a. The wind-rose data summaries for two stations are shown in figure 27, as a function of season. The two major components of wind direction are from the north-northeast and the southwest, with the season of the year being important in determining which component is dominant. The seasonal effect on wind direction is important because snowpack accumulation is also seasonally dependent. A large component of wind direction from the north-northeast in winter months suggests that identification of oil-shale retort emissions in snowpack may be complicated by the concurrent deposition of emissions from coal-burning powerplants near Craig and Hayden. For this reason, and because sulfur emissions can be expected from oil-shale and coal-plant sources, atmospheric precipitation chemistry must be determined from individual storms over the Piceance basin, rather than reliance on analyses of snow cores that may contain similar deposits from different sources.

Snowpack accumulation and precipitation generally result from a strong orographic effect controlled by local topography. Orographic regions such as the Flat Tops and Grand Mesa (see fig. 28) will cause precipitation from air masses passing over the Piceance basin area to collect the emissions before extensive dispersion has occurred. Thus, the Flat Tops and Grand Mesa may accumulate a larger fraction of the emissions than might be expected from their areas. The higher annual deposition rates on these mesas and the proximity to emissions sources should combine to accentuate the deposition of retort emissions.

Even without direct scavenging of emissions by precipitation and subsequent deposition, emissions can accumulate in a watershed. The interaction of leaf and stem material with gaseous and particulate emissions is capable of causing a deposition of emissions on watersheds as a result of subsequent plant uptake or washoff during periods of precipitation. This process is suspected of playing a major role in the transfer of atmospherically transported emissions in the northeastern United States; however, the lack of adequate sampling techniques has prevented direct quantification of its importance. In the area surrounding active retorts, precipitation and slope aspect play major roles in determining the type of vegetative cover. Thus, the same areas subject to the orographic effect as well as north-facing, lower-altitude slopes will have larger amounts of leaf and stem surface available to directly scavenge emissions from the air and transfer them to the plant itself or the watershed.

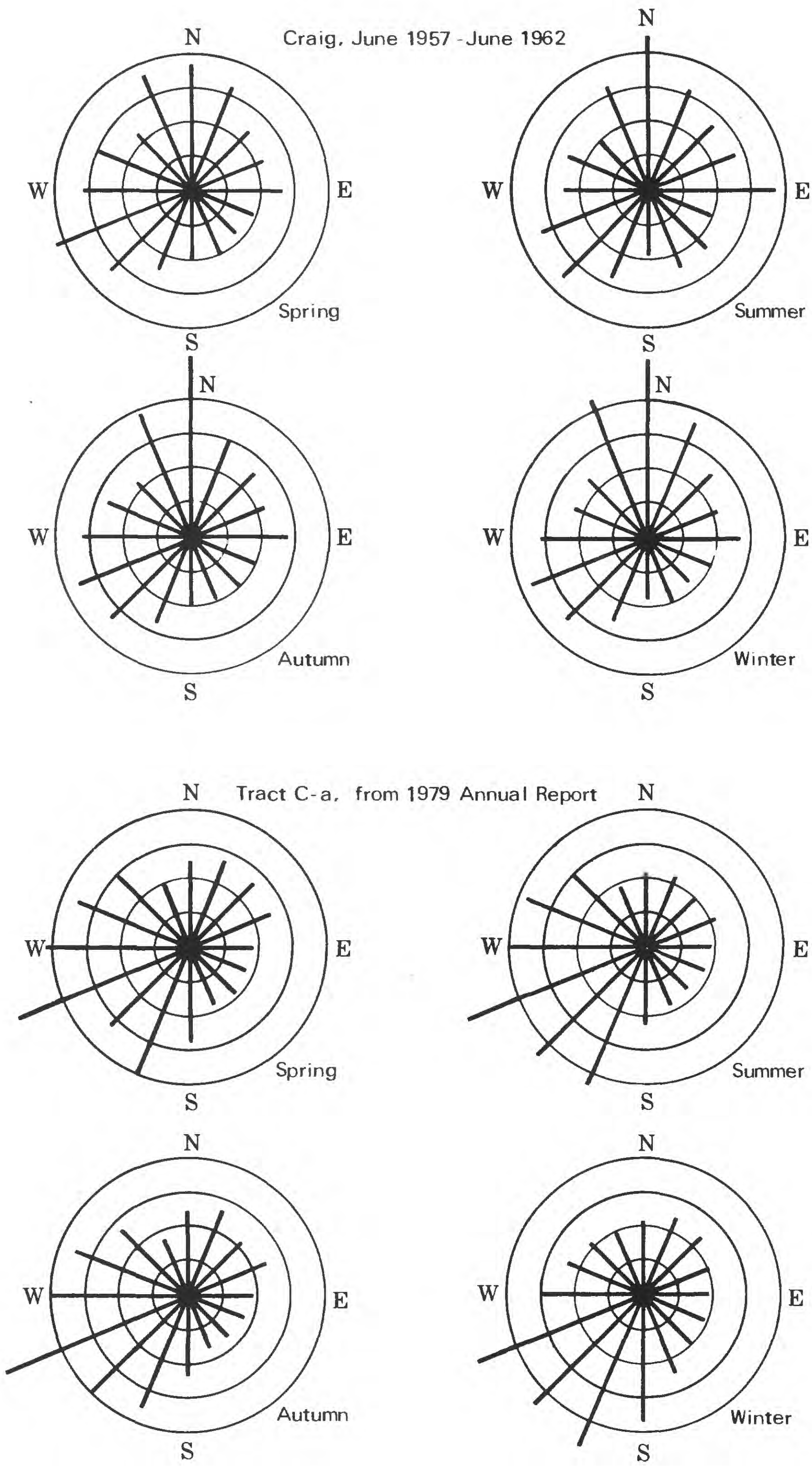
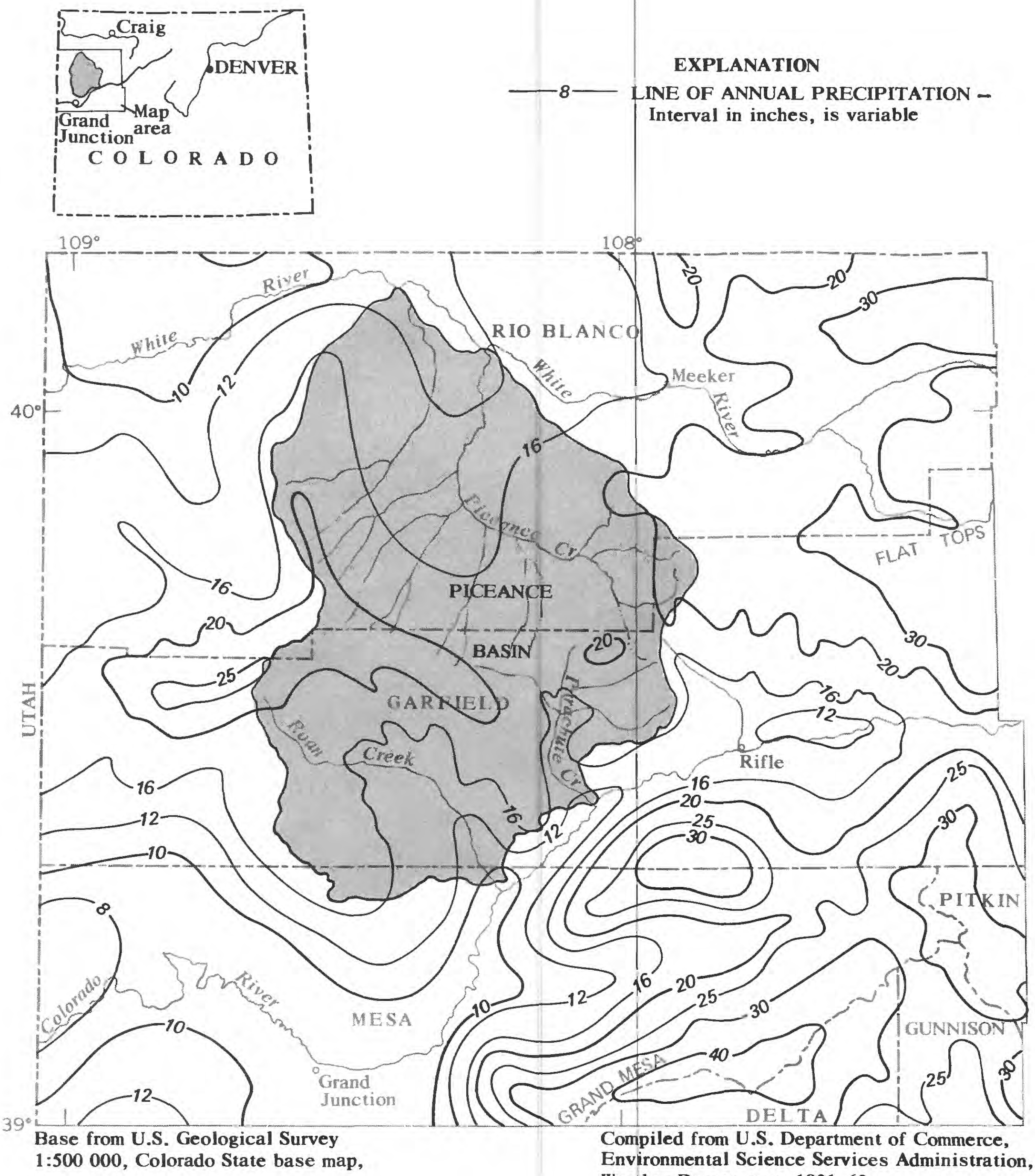


Figure 27.--Representative wind-rose diagrams for northwestern Colorado.



Base from U.S. Geological Survey 1:500 000, Colorado State base map,

Compiled from U.S. Department of Commerce, Environmental Science Services Administration, Weather Bureau map, 1931-60

0 10 20 30 MILES

0 10 20 30 KILOMETERS

Figure 28.--Distribution of annual precipitation, northwestern Colorado.

Nature of Susceptible Water Resources

Water resources can be affected noticeably by atmospheric emissions from retorts if the concentration of precipitation-collected emissions is large and the hydrologic system is not capable of rapidly reacting to inactivate the emissions. In the immediate vicinity of the retorts, alkaline soils and sedimentary bedrock may not only neutralize acid water resulting from emissions, but the naturally high weathering rates may produce large amounts of nutrients and potentially toxic materials. Thus, additional amounts of acid, water, nutrients, or toxic materials might be more readily neutralized or overshadowed by natural conditions than they might be on less reactive bedrock, which is found within the range of expected atmospheric transport. The less reactive types of bedrock are in the high basalt mesas and the granitic Rocky Mountains, which also produce orographic effects that enhance the deposition of emissions.

Other characteristics of the areas underlain by basalt and granite combine to increase their probable susceptibility to alteration. These areas have thin soils characteristic of alpine and subalpine regions that are less capable of buffering the effects of acid water than are the deeper soils characteristic of watersheds on sedimentary rock. In some areas, particularly on the mesas, extensive bog development serves as a natural source of low pH water; additional anthropogenic sources of acid water from outside the watersheds may cause further lowering of the pH of water to harmful levels. The same characteristics that cause accumulation of snowpack and enhanced deposition of emissions in these areas also provide a tendency for more prolonged and intense exposure to the emissions than might occur in watersheds at lower altitudes.

The prolonged exposure is caused by the persistence of the snowpack; accumulated snow normally melts over a period of 1 to 2 months in late spring to early summer. Therefore, the snowpack is exposed longer than that on watersheds receiving primarily rain or undergoing many thawing cycles during the winter. Snowpack causes high-altitude watersheds to be more intensely exposed to emissions than low-altitude watersheds. Recrystallization in the snowpack causes the formation of a layer of highly contaminated snow--in effect concentrating the pollutants from the entire snowpack into a comparatively thin layer. Because of its greater salt concentration, the snow in this zone has a slightly lower melting point than the bulk of the snowpack and is released in the initial melting of the pack, undiluted by less-contaminated snow. Upon running off to lakes, this cold water often overrides the slightly warmer water present in the thawing lake, forming a concentrated near-surface zone of highly contaminated water in the lake. The most susceptible water resources will be surface waters, particularly lakes. Documented damages to water resources have primarily been to fisheries, thus restricting the area of prime concern to surface waters. Orographic effects on precipitation result in many lakes on the high-altitude mesas and in the Rocky Mountains near the retorts. The effects of atmospheric emissions on downstream river systems may be neutralized by the reactivity of the sedimentary bedrock. Before atmospheric emissions become detectable in downstream systems, upstream systems may be severely affected.

Effects of Atmospheric Emissions on Water Resources

The deposition of atmospheric emissions on watersheds potentially affects vegetation, fisheries, piscivorous mammals and birds, and human health. Documented effects of deposition show fisheries and human health to be the most readily susceptible. Acid rain currently is being investigated, mostly in studies on fisheries and human-health effects related to atmospheric emissions. By lowering the pH of receiving lakes and streams, acid rain exerts a direct effect on pH-dependent physiology and perhaps a more important indirect effect through the mobilization and speciation of metals. The toxicity of naturally occurring elements such as copper is increased at lower than normal pH. Even aluminum, the third most abundant element in the Earth's crust, has been shown to be mobilized to concentrations that are toxic to trout in acidified lakes of the northeastern United States and in Scandinavia. The end result of the direct effect of lake acidification is the loss of the lake ecosystems. Approximately 45 percent of the high-altitude lakes in the Adirondack region of New York State have become fishless, and embryonic mortality of salamanders in these lakes has been increased by approximately two orders of magnitude as a result of acidification. Water with low pH not only mobilizes naturally occurring metals from watersheds, but also mobilizes metals commonly found in domestic water-supply systems. In particular, lead from either lead pipes or soldered copper pipes has been shown to be mobilized in concentrations exceeding drinking-water standards at the pH values typical of acidified lakes and streams.

In addition to the transport of acidity and subsequent mobilization of metals from a watershed, many examples of the direct transport of toxic materials from point sources of atmospheric emissions to susceptible watersheds are present in the literature. Whereas power generation by the burning of fossil fuels is sufficient to affect the acidity of precipitation, most examples of significant transport of toxic elements have resulted from the processing of rock materials. The heat of smelting processes, for example, volatilizes some elements, whereas simple dust entrainment in exhaust gases mobilizes more refractory elements. The retorting of oil shale, particularly by use of the high-temperature methods, is similar to smelting in its potential to mobilize elements from the source rock for atmospheric transport. The prime difference is that smelting processes concentrated ores of a few elements, whereas the retorts process material having moderate concentrations of many elements. In addition, the mobilization of organic compounds during retorting may release harmful materials for atmospheric transport--for example, benzo (a) pyrene.

Other effects on water resources may not be of a directly toxic nature, although their impact may be as significant. In oligotrophic systems on unreactive bedrock much of the nutrient input is contributed by precipitation or dustfall. The release of nitrogen and phosphorus from retorting may change the nutrient flux in oligotrophic lakes by a sufficient amount to alter primary production. If a pronounced increase in productivity occurs, oxygen depletion during the long period of winter ice cover may seriously damage or eliminate a high-altitude fishery. Increased weathering of the watershed caused by water of lower pH also may contribute increased nutrient runoff to the lake systems from nutrients originating in the regolith of the watershed.

The objectives of atmospheric emissions studies can be considered in terms of short-term needs that can be answered by a reconnaissance study, intermediate term needs that require detailed geochemical and biological characterization of selected "index" lake systems, and long-term needs for the monitoring of trends in precipitation chemistry and lake processes. These needs are listed below:

Short-Term Needs:

1. Delineate the areas in Colorado which are most susceptible to changes in the quality of atmospheric deposition. Areas most susceptible to changes in the quality of atmospheric deposition will most likely have the following characteristics: In close proximity to and downwind from present and proposed emissions sources; a relatively unreactive bedrock type--probably granitic or basaltic; geomorphic characteristics that contribute to direct precipitation on the lake surface or rapid runoff; and orographic effect which maximizes the deposition of emission-contaminated precipitation and fallout. Such areas can be selected based on information from the Colorado geologic map, topographic maps, wind-rose diagrams from weather stations, and a knowledge of where most energy development will occur.

2. Rank lakes within the most susceptible areas on the basis of their probable sensitivity to changes in the quality of atmospheric deposition. Lake sensitivity to changes in the quality of atmospheric deposition should be influenced by the intensity of chemical weathering within the basin. Rapid chemical weathering is conducive to relatively large alkalinity values that counteract the effects of acidification, large metal and nutrient fluxes to dilute the effect of additional fluxes from outside the basin, and a more eutrophic biotic community tolerant to additional stress. The intensity of chemical weathering can be ranked among watersheds of similar runoff characteristics by simple field determination, such as pH, specific conductance, and alkalinity. Basins with the largest values of pH, specific conductance, and alkalinity should have the greatest weathering rates and be the least susceptible to changes in precipitation and fallout quality.

3. Select several lakes in each area to serve as representative sites for characterization of basic limnological processes. Lakes can be selected by statistical tests of the chemical data and consideration of geology, morphometry, and location.

Intermediate-Term Needs:

4. Determine baseline conditions of algal primary productivity; macroinvertebrate, algal, and fish-population structure; and major dissolved constituents. Algal primary productivity normally varies throughout the growing season, making a thorough assessment difficult for even a small number of lakes. For this reason, the net algal primary productivity would be determined during specific reference periods such as immediately after ice-out, during midsummer, and in the fall overturn to use as an index of the yearly primary productivity. Macroinvertebrate-population structure would be determined by identification of specimens from

sieved bottom-material grab samples. Algal-population structure would be determined by microscopic examination of composited water samples to eliminate the possibility of missing smaller forms by use of net collections. Fish-population structures would be determined by identification of specimens from standard collection techniques, such as net fishing or electrofishing.

Geochemical budgets will be crude for lakes with the basin characteristics of those selected for this study. Probably only a small fraction of water loading will be contributed through distinct channels into the lakes; most will come by sheet runoff or direct precipitation on the lake surface. Input loadings from direct precipitation can be measured by samplers more simple in design than those necessary to detect trends in precipitation chemistry. For example, open-bucket samplers and snow cores in the winter and a simple funnel-tubing-bottle sampler in the summer can provide reliable samples throughout the basins to determine chemical-loading rates from precipitation and fallout. The transport of materials within and from the lakes should be much simpler to determine than the inputs. Net accumulation within the sediments can be determined by Pb-210 and Cs-137 profiles, coupled with chemical analyses. Transport of materials from the lakes can be determined by periodic or continuous measurement of the discharge and selected sampling for chemical analysis for lakes with distinct outflows. Because of the problems in obtaining satisfactory input data, except for precipitation inputs, high priority will be given to the selection of lakes with distinct outflows.

Long-Term Needs:

5. Establish a precipitation-quality network to determine long-term changes in the quality of precipitation west of the Continental Divide in Colorado. Long-term changes in the quality of precipitation and fallout can be detected best by direct measurement of the quality of water from individual precipitation events and the chemical characteristics of fallout during selected seasons when wind patterns are most reproducible from year to year. Sampling and site selection would be in accordance with the procedure established by the National Atmospheric Deposition Program (formerly known as the NC-141 program), and the stations would be submitted for inclusion in this program. At present, there are five stations in the National Atmospheric Deposition Program located within Colorado. Four are located east of the Continental Divide, however, and will be of only limited utility to detect the effects from energy development. It is anticipated that approximately ten new stations will be necessary to monitor energy-development effects adequately.

6. Conduct periodic evaluations of basic limnological processes in the reference lakes to provide advance warning of problems common to the lakes in the area, such as lake acidification, toxicity problems with heavy metals or aluminum, or rapid increases in productivity. Periodic reevaluation of basic limnological processes is necessary to provide advance warning of adverse changes in the lakes studied and the nearby lakes they represent. In the absence of indications of deteriorating precipitation quality, such reevaluations could be scheduled on a rotating basis every 5 to 10 years. Should the precipitation samples show rapidly decreasing pH and rapidly increasing loads of metals or nutrients, the evaluations would be made at a greater frequency.

SPOIL-PILE GEOCHEMISTRY AND HYDROLOGY

By K. G. Stollenwerk

Classification of Spoil Piles

The largest quantity of waste in surface spoil piles from an oil-shale industry will be aboveground retorted oil shale. The estimated production rate of retorted shale is summarized in figure 29. Large rates of shale-oil production will result in large amounts of retorted shale, especially for lean oil shale or low recovery rates. The estimated retorted-shale production in tons per day was calculated in figure 29, presuming that the retorting process consumes 15 percent of the original weight of the untreated shale (U.S. Environmental Protection Agency, 1977). The estimated volumetric rate of retorted-shale production was calculated presuming that the shale is compacted to a bulk density of 90 lbs/ft^3. Current plans are to dispose of this waste by filling small canyons, by emplacing spoil piles on flood plains of major valleys, or by spreading over large areas on mesas.

The type and quantity of constituents leached from retorted oil shale depends upon the chemical and mineralogical composition of the unretorted-shale feedstock and retorted-shale waste, the particle-size distribution of the unretorted and retorted oil shale, the type of retorting process used, and the conditions under which leaching occurs. Significant concentrations of dissolved solids, boron, fluorine, and molybdenum have been measured in leachate from oil shale retorted using the TOSCO II process (Ward and others, 1971; Metcalf & Eddy Engineering Inc., 1975; Stollenwerk and Runnells, 1980, 1981) and from the Paraho direct combustion process (Harbert and others, 1979; Garland and others, 1979; Stollenwerk and Runnels 1980; 1981). Organic polynuclear aromatic compounds with mutagenic properties have been found in processed oil shale (Schmidt-Collerus, 1974). Oil shale processed at temperatures above 700°C produces calcined processed shale whose leachates are highly alkaline due to hydrolysis of calcium and magnesium oxides. The potential exists for the contamination of ground and surface water if significant quantities of leachate escape from spoil piles of oil shale retorted by either process. Several other waste products may be disposed of with the retorted oil shale and could modify the composition of leachate. These wastes include unretorted shale that has been crushed too fine to be used in the retort, construction and mining-related wastes, and wastes associated with the retorting process (Crawford and others, 1977; Shih and others, 1979). Although these wastes probably will comprise less than 5 percent of the total volume of a shale pile, they could modify the composition of the leachate.

In some spoil piles associated with modified in-situ retorting processes, the pile may consist almost entirely of unretorted oil-shale waste. If the shale that is brought to the surface is too low grade to be retorted economically, it probably will be stored or disposed of as waste. Leachate from unretorted oil-shale waste generally contains a smaller dissolved-solids concentration than leachate from retorted oil shale; however, the concentration of boron, fluorine, and molybdenum can be significantly higher in leachate from unretorted shale than in leachate from retorted shale (Stollenwerk and Runnells, 1981).

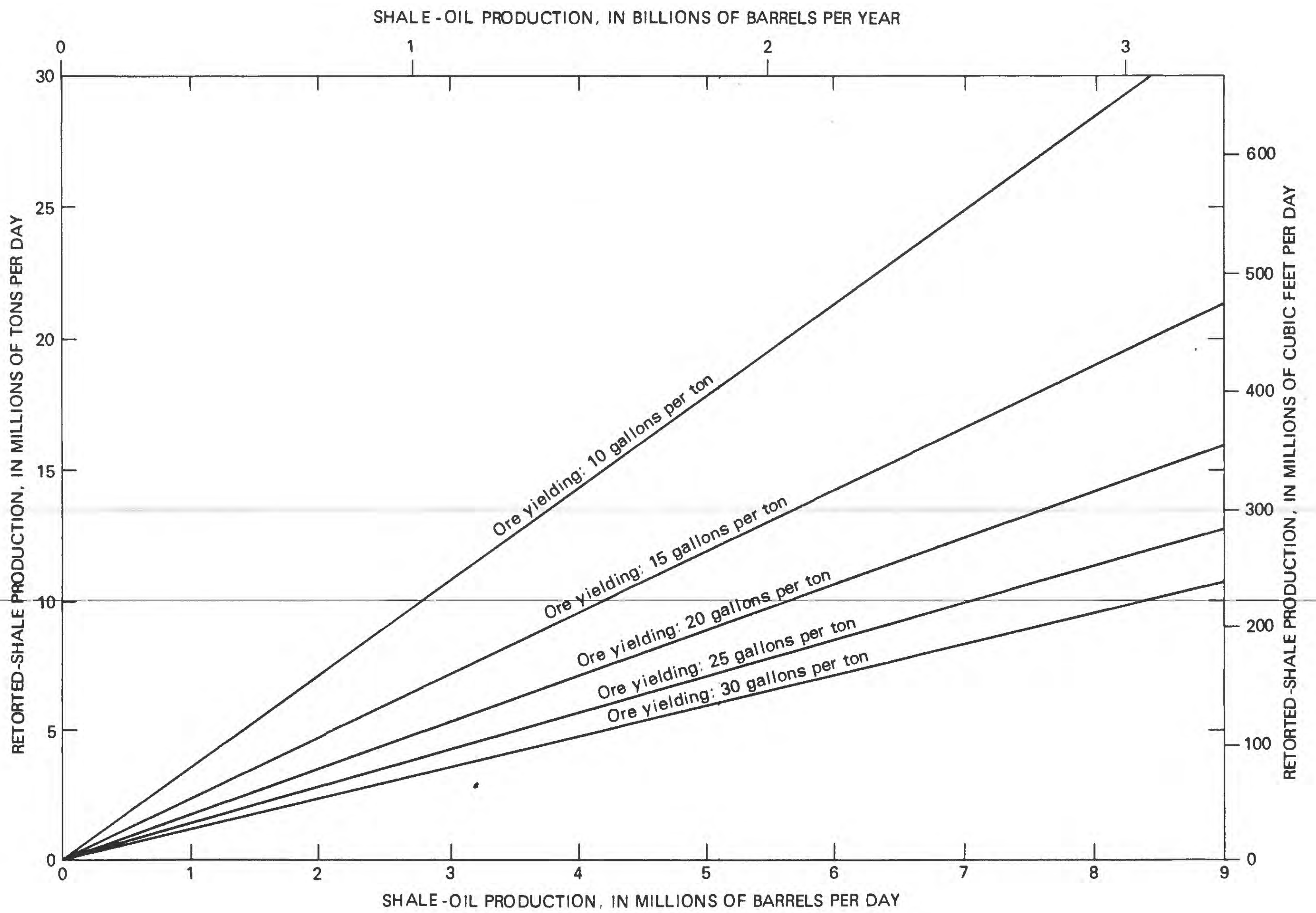


Figure 29.--Relation between shale-oil production and retorted-shale production from aboveground retorts.

Another potentially serious problem concerns the dissolution of surface salts by runoff from a shale pile. Most retorting processes produce retorted-shale material with a surface coating of readily soluble salts. When rainfall or snowmelt infiltrate the surface of a retorted shale pile, these readily soluble salts are mobilized. Subsequent evapotranspiration causes these salts to be redeposited on the surface of the spoil pile where they can be redissolved by runoff.

Characterization of oil-shale wastes must be site- and process-specific. With respect to the quality of leachate that might eventually migrate from a surface disposal pile of retorted oil shale and associated wastes, the following research is needed:

1. Characterization of leachates from all of the surface retorting processes. This would include an evaluation of the effect of variable operating conditions that could exist within the same retorting process and an evaluation of the physical and chemical properties of the retorted shale.

2. Further evaluation of the variability in the composition of leachate that might arise as a result of differences in the chemical and mineralogical composition of oil shale.

3. Determination of the contribution from other wastes to the composition of leachate.

4. Evaluation of the long-term microbiological, chemical, and physical transformations that might occur within a spoil pile.

5. Verification of studies to date that have dealt with wastes generated from pilot plants. Future work needs to determine if these wastes are comparable to those that will be generated in a commercial retort.

Impact of Leachate on Water Quality

The potential impact of leachate from a spoil pile on the quality of surface water and ground water in the Piceance basin will depend ultimately upon the quantity of leachate that escapes. This quantity will be related to precipitation and to the location of the spoil pile within a drainage basin. For example, the average annual precipitation in the Piceance basin ranges from 12 to 20 in. Most of the natural recharge to the basin occurs at the higher altitudes. Presumably the placement of a spoil pile in an area of recharge initially would reduce the natural recharge, allow recharge of the spoil pile, and result in the production of significant quantities of leachate. Another potentially dangerous location for a spoil pile is in the path of surface runoff where diversion channels would have to be constructed to direct the upstream runoff around the spoil pile. The diversion system would have to be maintained to prevent clogging by debris and to prevent surface runoff from flowing over or through the spoil pile, resulting in a significant increase in leachate production and erosion of the spoil pile.

Hydrologic Monitoring

The hydrology of a proposed spoil-pile site needs to be carefully evaluated. If it is determined that unacceptable quantities of leachate may be produced in relation to local hydrologic conditions, a different site needs to be selected. Hydrologic information needs for site selection include the following:

1. The seasonal distribution of precipitation at a proposed disposal site needs to be determined as well as the annual range in precipitation that can be expected over a long period.

2. The annual quantity of snowmelt and rainfall that will infiltrate a spoil pile needs to be estimated. Part of the water that infiltrates a spoil pile will be evapotranspired; however, natural recharge to the spoil pile probably will increase with increasing precipitation, up to a certain threshold. Recharged water eventually will percolate through and out of the spoil pile.

3. The subsurface hydrology in the vicinity of the spoil pile needs to be characterized. It is especially important to insure that a spoil pile is not located in a region where springs and seeps will contribute water to the spoil pile and increase leaching. It is also necessary to define the ground-water regime in the event that leachate from the spoil pile escapes into the aquifer system.

4. The hazard from runoff originating upstream from the spoil pile needs to be determined. This runoff could infiltrate the spoil pile, reduce stability, and produce leachate.

5. The potential for failure and hazards related to the spoil pile and retaining dam (used to contain runoff) needs to be determined, should an abnormal precipitation event occur.

6. After a spoil-pile site has been selected, baseline conditions need to be defined in order to evaluate any impact on the environment.

Hydrologic conditions need to be monitored during and after construction of selected spoil piles:

1. If saturated zones exist within the spoil pile, observation wells need to be established in order to monitor the distribution and movement of water. It is desirable that some wells extend beneath the spoil pile into underlying aquifers, and other wells need to be located near the spoil pile in order to detect the escape of any leachate into the subsurface. Surface-water quality downstream from the spoil pile also needs to be monitored.

2. Porous cups are needed to monitor flow conditions in the unsaturated zone. Water samples for analysis can be derived from core holes or extracted from the porous cups. Limited sampling is suggested in order to avoid extensive disruption of the flow system.

3. An appraisal is needed of the physical and chemical interactions, including weathering, that could occur between the leachate and the soils, alluvium, and bedrock through which the leachate might percolate.

4. Hydrologic-transport models may be needed to predict the impact of leachate on surface and ground water.

5. All monitoring programs need to be based on the realization that the problem of potentially toxic leachate escaping from spoil piles could persist for hundreds of years.

6. All sampling, interpretation, and prediction of spoil-pile flow systems need to be based on the premise that transient hydrologic conditions probably will persist for many years.

7. To evaluate the impact of leachate from waste oil shale, a field-demonstration spoil pile needs to be constructed, instrumented, and studied in the Piceance basin as soon as possible.

OIL-SHALE PROCESSING WASTES

By J. A. Leenheer

Processing of oil shale produces solid, liquid, and gaseous wastes. The quantity and composition of these wastes are highly dependent on the composition of the unretorted oil shale and on the particular retorting technology used in processing. Waste management is also highly dependent upon the retorting process used; for example, aboveground and in-situ retorting processes require very different waste-management techniques. Because of the dependency of waste composition and disposal upon shale composition and retorting, studies of the effects of oil-shale processing wastes upon the hydrologic environment should be site-specific and process-specific. Regional impacts of oil-shale processing wastes can be assessed by comparison of baseline hydrologic data with waste-input data from the various retorting processes used at multiple sites in the Piceance basin.

Solid Wastes

Solid wastes consist largely of unretorted and retorted oil shale. Surface retorting generates large quantities of retorted oil shale for surface disposal; however, in-situ retorting also may generate large quantities of retorted shale above and below ground. In-situ processes also have lower recovery rates than aboveground retorts and therefore may generate more retorted shale in order to maintain the same production. Solid wastes generated by surface-retorting processes have been extensively characterized (Cameron Engineers, Inc., 1975), and their potential environmental impacts have been assessed by the U.S. Environmental Protection Agency (Crawford and others, 1977). The geochemistry and hydrology of spoil piles are discussed in a separate section of this report. Much less is known about the nature of retorted shale produced in situ because of the difficulty of obtaining samples and because of the relatively recent development of in-situ technology. In general, in-situ retorted shale is much more heterogeneous than aboveground retorted shale because retorting conditions vary greatly within an in-situ retort. A schematic diagram of a modified in-situ retort shown in figure 30 indicates the potential for production of waste products. Hydrologic-information needs on in-situ retorted shale include:

1. Studies of the hydrologic properties of retorted shale in an in-situ retort.

2. Physical and chemical stability studies of retorted shale in an in-situ retort.

3. Studies of interactions of in-situ retorted shale with native ground water, process water, and unrecovered shale oil.

4. Studies of the effects of heating and cooling of in-situ retorts upon the subsurface hydrologic system.

5. Characterization and monitoring of solutes leached from in-situ retorted shale.

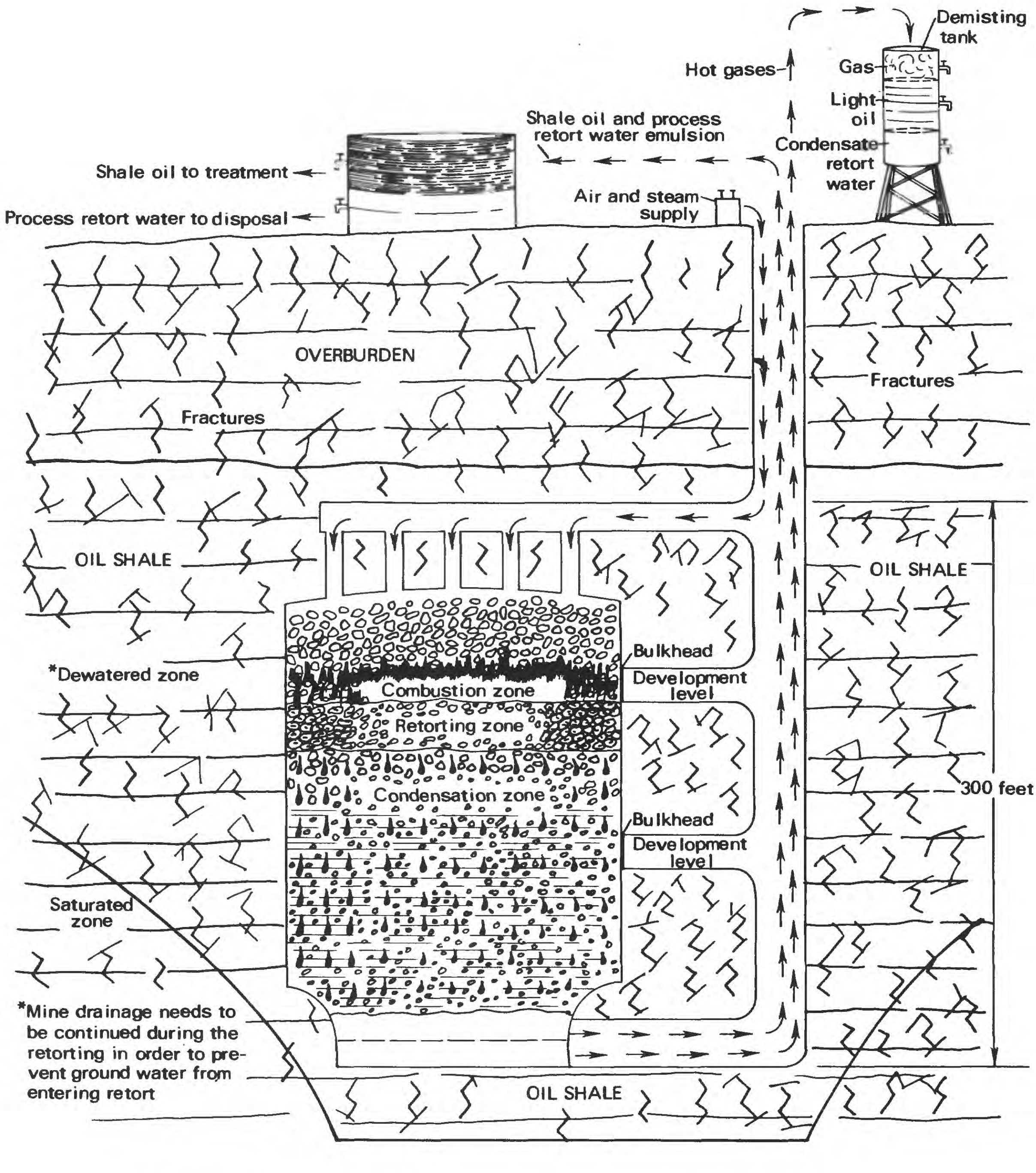


Figure 30.-- Schematic diagram showing a modified in-situ retort.

6. Studies of methods for sealing or otherwise flushing in-situ retorts to prevent the migration of liquid residuals and the leaching of salts from ground and surface water.

Unretorted oil-shale dumps are produced as storage piles for feedstock to aboveground retorts and as permanent disposal piles for shale removed from certain types of modified in-situ retorts. Primary areas of concern over unretorted-shale dumps are salt leaching and spontaneous combustion. In Scotland and Estonia, where large-scale oil-shale development has taken place, spontaneous combustion has occurred in unretorted oil shale that contained carbon. Therefore, hydrologic-information needs on unretorted shale disposed at land surface include:

1. Characterization and monitoring of solutes leached from crushed unretorted shale.

2. Study of spontaneous combustion and long-term weathering processes of unretorted shale which affect hydrology and water quality.

3. Study of effects of large-scale disposal of unretorted shale upon rainfall infiltration and runoff.

4. Study of slope stability.

Liquid Wastes

Liquid wastes consist of wastewater and unrecovered shale oil. The sources, characteristics, and volumes of wastewaters produced by various retorting processes were discussed by Jackson and others (1975), and their potential impacts were assessed by Crawford and others (1977). Wastewater production is relatively low for aboveground-retorting processes, but approximately equivalent volumes of wastewater and shale oil are produced by in-situ processes. Wastewater sources include "retort water" released during oil-shale retorting, process water from shale-oil refining, wastewater from mine drainage, leachate from retorted oil shale, wastewater from air-emission control systems, cooling water and boiler water blowdowns, and sanitary wastewater.

The wastewater unique to oil-shale processing, and the source of the major portion of potential contaminants, is retort water. Much research has been performed on the characterization (Fox and others, 1978) and waste treatment (Poulson, 1979-1980) of retort water. Retort water has high concentrations of ammonia, carbonate and bicarbonate, sodium, sulfate, thiosulfate, chloride, and organic amine bases. Thiocyanate, which occurs in moderate concentrations in retort water, can be utilized as a conservative tracer in monitoring for retort water (Leenheer, 1979). Retort water and other wastewater recovered during shale-oil production likely will be treated to recover ammonia and sulfur as byproducts, treated by chemical and biological processes, and used to moisturize processed oil shale during its disposal (Crawford and others, 1977). However, for in-situ processing, there is a significant possibility that a large proportion of the retort water and a small amount of shale oil will not be recovered and will affect ground-water quality directly. Hydrologic-information needs on liquid wastes from oil-shale processing include:

1. Determination of volumes of unrecovered retort water and shale oil produced by in-situ oil-shale processing.

2. Study of migration of ground water into, and wastewater from, the in-situ retorts.

3. Study of the attenuation of wastewater solutes by soil, retorted shale, and unretorted shale.

4. Development of methodology for the rapid determination of organic and inorganic solutes for use in monitoring programs.

5. Definition of organic solute composition of various wastewaters in quantitative terms.

6. Study of the biological toxicity effects (especially ammonia toxicity) of untreated wastewater introduced into surface water.

7. A study of the reducing properties of retort water (due to reduced sulfur species) upon oxidized sediments and on dissolved oxygen in surface water.

Gaseous Wastes

Oil-shale processing and shale-oil upgrading produces SO_2, H_2S, CO, CO_2, NO_x, NH_3, volatile hydrocarbons, and particulate emissions (Crawford and others, 1977). The major impact of these gaseous and particulate wastes upon water resources is upon atmospheric precipitation. Hydrologic-information needs on the effects of gaseous and particulate wastes include:

1. Predevelopment assessment of the susceptibility of surface waters to acid-rain impacts.

2. Assessment of the potential of gaseous emissions of various retorting processes to form acid rain.

3. Monitoring the effects of oil-shale processing upon precipitation chemistry and surface-water quality.

Atmospheric particulates are discussed in greater detail in the section entitled, "Emissions to the Atmosphere."

CONCLUSIONS

The Piceance basin of northwestern Colorado contains large reserves of oil shale. Expected development of oil shale will affect the regional hydrologic systems because most oil-shale mines will require drainage; industrial requirements for water may be large; and oil-shale mines, retorts, and waste may affect the quantity and quality of surface water and ground water. In addition, oil-shale industry may discharge particles and gases to the atmosphere that could alter the quality of high-altitude lakes and future surface-water reservoirs.

Additional ground-water information is needed for planning the drainage of oil-shale mines, developing the water resources efficiently, and minimizing the impact on the hydrologic system. Shallow test wells and aquifer testing of valley-fill alluvial aquifers along Yellow and Piceance Creeks and the White River main stem would improve understanding of the stream-aquifer relations that are important in predicting the effects of draining oil-shale mines. An extensive drilling and coring program also is proposed for the oil-shale aquifers of the Uinta and Green River Formations. These wells would provide stratigraphic and hydrologic information and permit measurement of geophysical and geochemical properties. The wells also would be used for detailed aquifer testing that is needed for simulation model studies. Geologic formations older than the Green River Formation may also contain large volumes of water. Before decisions are made to undertake the development of surface-water supplies, all of the ground-water resources should be defined or considered. These deep formations may constitute not only an alternative water supply but may be possible repositories for wastewater injection during the mining.

Ground-water networks for water-quality monitoring are needed to detect and to evaluate the effects of mine drainage, reinjected water, backfilling of mined material, leaching from in-situ retorts, and disposal of retorted shale. Wells and springs would provide sampling sites for the network. The ground-water networks need to be designed to detect changes in the aquifers that, under premining conditions, have dissolved-solids concentrations that are normally less than 2,000 mg/L but may range from 400 to 40,000 mg/L.

An inventory and sampling program is needed to provide more data on springs. For sampling purposes, the springs could be subdivided into groups based on geographic, geologic, or hydrologic characteristics. A systematic hydrologic study and geochemical sampling program would provide data on discharge, water temperature, specific conductance, pH, alkalinity, and trace elements.

Streams, as well as springs, are used for water supply in the Piceance basin, and streamflow requires further study. Historical data from the 33 streamflow gages can be interpreted correctly only through water-budget studies in major stream valleys, gain-and-loss studies in selected reaches of streams, and the preparation of calibrated watershed models. A regional flood-frequency analysis also is needed, especially because of the proposed disposal of retorted shale in stream valleys.

Networks are needed to monitor the water quality of streams under natural conditions and to determine development-related changes. Sampling goals, the geologic setting, and hydrologic conditions determine the sampling-network design. Data on chemical constituents determined in surface-water networks need to be analyzed to determine which constituents indicate mining-induced changes. Hydrologic models and statistical tests in conjunction with water-quality data analysis are needed to provide prediction techniques.

Suspended loads in streams probably will be altered by development-related changes, including dam construction, changes in surface runoff, retorted-shale disposal, removal of vegetation, changes in vegetation, and open-pit mining.

Additional sediment stations are needed to quantify the effects of development on suspended-sediment concentrations and stream discharge, as well as on bedload and type of bed material.

Limited data describing aquatic biology indicate that benthic invertebrates are useful indicators of water quality in streams of the region. Calculated indices show that biologic communities and stream-quality conditions are variable and that a small number of biologic samples does not represent stream quality accurately. Therefore, an expanded comprehensive biologic network is needed to detect expected changes related to the potential increase of toxic substances, sediment, and thermal pollution.

An assessment of water quality and quantity is proposed for the White River basin because of its location adjacent to the active oil-shale development on prototype lease tracts C-a and C-b and other planned sites. Ambient stream quality needs to be assessed and the resulting information used to design a data-collection program. Effects of oil-shale and other industrial development need to be measured using data describing the flow, dissolved-solids concentration, and temperature of streams. Organic wasteloading from municipal or industrial effluents needs to be studied initially by measurement of reaeration, traveltime, and mean velocity in selected reaches. Effects of municipal population increases on stream quality could be appraised further by determination and evaluation of the wasteload-assimilative capacity of selected downstream reaches by the use of a steady-state water-quality model. Regional effects of water-use development could be analyzed by means of reservoir-model studies of flow volumes and dissolved-solids concentration.

Atmospheric emissions from an oil-shale industry may contain potentially harmful amounts of the oxides of sulfur and nitrogen. These elements may cause acid rain that in turn is suspected to be a cause of corrosion problems and the destruction of fisheries. An accurate prediction of the hazard would require knowledge of future retort emissions, transport and deposition characteristics, and the geochemical and biological susceptibility of hydrologic systems. An intensive investigation of these phenomena would permit identification of the dominant controlling processes and probable environmental effects. Data from the study could be used to determine logically the emission limits for oil shale, coal, and other cumulative sources to prevent environmental degradation and to minimize emission-control costs.

Large quantities of retorted shale would be produced by a large oil-shale industry. Disposal of these wastes from retorts in spoil piles may allow precipitation to leach toxic materials that could reach hazardous levels. Unretorted shale stockpiles also may yield leachate of poor quality. Leachates may be transported in surface runoff or in recharge into shallow and deep aquifers. Site-specific studies are needed of spoil piles and nearby hydrologic regimes. These studies would include the physical, chemical, mineralogic, microbiologic, and hydrologic characteristics of the spoil pile and its surroundings. Other important factors for consideration in the studies include the impacts of extreme hydrologic events, changes in the characteristics of spoil piles over time, and the expected duration of releases of toxic leachates.

In-situ retorts produce solid, liquid, and gaseous wastes. Most of the solid wastes consist of retorted or unretorted shale. Site-specific studies of retorted shale are needed to assess the physical, chemical, thermal, and hydrologic properties of hot and cooling underground retorts. The hydrologic, chemical, and spontaneous-combustion characteristics of unretorted shale also need investigation. Liquid wastes include wastewater and unrecovered shale oil. Retort wastewater is expected to contain toxic concentrations of organic and inorganic constituents. Studies of expected volumes, migration, reaction, toxicity, and monitoring of retort wastewater are needed.

REFERENCES

Ames, E. L., 1977, Aquatic insects of two western slope rivers, Colorado: Fort Collins, Colorado State University, unpublished M.S. thesis, 94 p.

Barr, A. J., Goodnight, J. H., Sall, J. P., and Helwig, J. T., 1976, A user's guide to SAS 76: Raleigh, N.C., SAS Institute, 329 p.

Bass, N. W., and Northrop, S. A., 1963, Geology of Glenwood Springs quadrangle and vicinity, northwestern Colorado: U.S. Geological Survey Bulletin 1142-J, 74 p.

Bauer, D. P., Rathbun, R. E., and Lowham, H. W., 1979, Traveltime, unit concentration, longitudinal-dispersion, and reaeration characteristics of upstream reaches of the Yampa and Little Snake Rivers, Colorado and Wyoming: U.S. Geological Survey Water-Resources Investigations 78-122, 66 p.; available from U.S. Department of Commerce, National Technical Information Service, Springfield, VA 22161, as Report PB-80 129 521.

Bauer, D. P., Steele, T. D., and Anderson, R. D., 1978, Analysis of wasteload assimilative capacity of the Yampa River, Steamboat Springs to Hayden, Routt County, Colorado: U.S. Geological Survey Water-Resources Investigations 77-119, 69 p.; available from U.S. Department of Commerce, National Technical Information Service, Springfield, VA 22161, as Report PB-278 051.

Bradley, W. H., 1931, Origin and microfossils of the oil shale of the Green River Formation of Colorado and Utah: U.S. Geological Survey Professional Paper 168, 58 p.

Bredehoeft, J. D., and Papadopulos, I. S., 1965, Rates of vertical groundwater movement estimated from the Eearth's thermal profile: Water Resources Research, v. 1, no. 2, p. 325-328.

Bryant, Bruce, 1979 (1980), Geology of the Aspen 15-minute quadrangle, Pitkin and Gunnison Counties, Colorado: U.S. Geological Survey Professional Paper 1073, 146 p.

Cameron Engineers, Inc., 1975, Synthetic fuels data handbook: Cameron Engineers, Inc., Denver, Colo.

Cashion, W. B., and Donnell, J. R., 1972, Chart showing correlation of selected key units in the organic-rich sequence of the Green River Formation, Piceance Creek Basin, Colorado, and Uinta Basin, Utah: Washington, D.C., U.S. Geological Survey Oil Gas Investigations Chart OC-65, 1 sheet.

_____ 1974, Revision of nomenclature of the upper part of the Green River Formation, Piceance Creek Basin, Colorado, and Eastern Uinta Basin, Utah: U.S. Geological Survey Bulletin 1394-G, 9 p.

Coffin, D. L., Welder, F. A., and Glanzman, R. K., 1971, Geohydrology of the Piceance Creek structural basin between the White and Colorado Rivers, northwestern Colorado: U.S. Geological Survey Hydrologic Investigations Atlas HA-370.

Coffin, D. L., Welder, F. A., Glanzman, R. K., and Dutton, X. W., 1968, Geohydrologic data from the Piceance Creek basin between the White and Colorado Rivers, northwestern Colorado: Colorado Water Conservation Board Circular 12, 38 p.

Collings, M. R., 1969, Temperature analysis of a stream: U.S. Geological Survey Professional Paper 650-B, p. B174-B179.

Colorado Department of Natural Resources, 1979, The availability of water for oil shale and coal gasification development in the Upper Colorado River Basin: A report to the U.S. Water Resources Council prepared by the Office of the Executive Director.

Colorado State Engineer, Division of Water Resources, 1978, Piceance basin spring hydraulics investigation: Final Technical Report, 54 p.

Crawford, K. W., Prien, C. H., Baboolal, L. B., Shih, C. C., and Lee, A. A., 1977, A preliminary assessment of the environmental impacts from oil shale developments: U.S. Environmental Protection Agency, EPA-600/7-77-069, 174 p.

Dale, R. H., and Weeks, J. B., 1978, Hydrologic analysis of the U.S. Bureau of Mines' underground oil-shale research-facility site, Piceance Creek basin, Rio Blanco County, Colorado: U.S. Geological Survey Water-Resources Investigations 78-28, 35 p.

Dyni, J.R., 1974, Stratigraphy and nahcolite resources of the saline facies of the Green River Formation, Rio Blanco County, Colorado: U.S. Geological Survey Open-File Report 74-56, 27 p.

Environmental Science Services Administration, 1968, Climatic atlas of the United States: Environmental Data Service (reprinted by National Oceanic and Atmospheric Administration, 1974), 80 p.

Everhart, W. H., 1973, Effects of chemical variations in aquatic environments. Volume 1. Biota and chemistry of Piceance Creek: Fort Collins, Colorado State University, prepared for the Office of Research and Monitoring, U.S. Environmental Protection Agency, Washington, D.C., 117 p.

Federal Energy Administration, 1974, Potential future role of oil shale: Prospects and constraints: Final task force report of Project Independence Blueprint, under direction of U.S. Department of the Interior, 495 p.

Fox, J. P., Farrier, D. S., and Poulson, R.E., 1978, Chemical characterization and analytical consideration for an in-situ oil shale process water: Laramie, Wyo., Energy Technology Center, Department of Energy, Report of Investigations 7817.

Frickel, D. G., Shown, L. M., and Patton, P. C., 1975, An evaluation of hillslope and channel erosion related to oil-shale development in the Piceance basin, northwestern Colorado: Colorado Water Conservation Board Water-Resources Circular 30, 37 p.

Frickel, D. G., 1978, Hydrologic and geomorphic data from the Piceance basin, Colorado: U.S. Geological Survey Open-File Report 78-825, 169 p.

Garland, T. R., Wildung, R. E., and Harbert, H. P., 1979, Influence of irrigation and weathering reactions on the composition of percolates from retorted shale in field lysimeters: Proceedings, 12th Annual Oil Shale Symposium, Golden, Colorado School of Mines, p. 52-57.

Gaskill, D. L., and Godwin, L. H., 1966, Geologic map of the Marble quadrangle, Gunnison and Pitkin Counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-512.
Gaydos, M. W., 1980, Summary of water-quality data for selected streams in Colorado: U.S. Geological Survey Open-File Report 80-682, 148 p.
Gray, L. J., and Ward, J. V., 1977, Potential effects of oil shale extraction and processing activities on macroinvertebrates of Piceance and Black Sulfur Creeks, Colorado: Fort Collins, Colorado State University, Department of Zoology and Entomology, Environmental Research Paper 10, 18 p.
Harbert, H. P., Berg, W. A., and McWhorter, D. B., 1979, Lysimeter study on the disposal of Paraho retorted shale: U.S. Environmental Protection Agency, EPA-600/7-79-188, 171 p.
Imlay, R. W., 1980, Jurassic paleobiogeography of the conterminous United States in its continental setting: U.S. Geological Survey Professional Paper 1062, 134 p.
Iorns, W. V., Hembree, C. H., Phoenix, D. A., and Oakland, G. L., 1964, Water resources of the Upper Colorado River Basin--Basic data: U.S. Geological Survey Professional Paper 442, 1036 p., 4 pl.
_____1965, Water resources of the Upper Colorado River Basin--Technical report: U.S. Geological Survey Professional Paper 441, 370 p., 3 pl.
Jackson, L. P., Poulson, R. E., Spedding, T. J., Phillips, T. E., and Jensen, H. B., 1975, Characteristics and possible roles of various waters significant to in-situ oil shale processing: Golden, Colorado School of Mines Quarterly, v. 70, p. 105-134.
Johnson, R. C., May, Fred, Hansley, P. L., Pitman, J. K., and Fouch, T. D., 1980, Petrography, x-ray mineralogy, and palynology of a measured section of the Upper Cretaceous Mesaverde Group in Hunter Canyon, western Colorado: U.S. Geological Survey Oil and Gas Investigations Chart OC-91.
Leenheer, J.A., 1979, Assessment of various solutes as tracers to determine ground water migration of retort water produced by in-situ oil shale processing: Oral presentation at American Society for Testing and Materials Symposium on Wastewaters from Synthetic Fuel Production, Pittsburgh, June 1979 (abstract available from author).
MacLachlan, M. E., 1972, Triassic System, *in* Geologic Atlas of the Rocky Mountain region, Rocky Mountain Association of Geologists: Denver, A. B. Hirschfeld Press, p. 166-176.
Mallory, W. W., 1971, The Eagle Valley evaporite, northwest Colorado--A regional synthesis: U.S. Geological Survey Bulletin 1311-E, 37 p.
McQuivey, R. S., and Keefer, T. N., 1976, Convective model on longitudinal dispersions: American Society of Civil Engineers, Journal of the Hydraulics Division, v. 102, no. HY-10, p. 1409-1424.
McWhorter, D. B., and Rowe, J.W., 1976, Inorganic water quality in a surface-mined watershed: Paper presented at the American Geophysical Union Symposium on Methodologies for Environmental Assessments in Energy Development Regions, San Francisco, Calif., December 8, 1976, 27 p.
Merritt, R. W., and Cummins, K. W., eds., 1978, An introduction to the aquatic insects of North America: Dubuque, Iowa, Kendall/Hunt Publishing Co., p. 29-31.
Metcalf & Eddy Engineering, Inc., 1975, Water pollution potential from surface disposal of processed oil shale from the TOSCO II process: v. 1, prepared for TOSCO Corp., Denver, Colo.

Moench, A. F., and Prickett, T.A., 1972, Radial flow in an infinite aquifer undergoing conversion from artesian to water table conditions: Water Resources Research, v. 8, no. 2, April 1972, 6 p.

Murray, F. N., 1966, Stratigraphy and structural geology of the Grand Hogback Monocline, Colorado: Boulder, University of Colorado, Ph. D. thesis, 19 p., 8 tables, 19 figures, 1 plate.

Odum, E. P., 1971, Fundamentals of ecology (3d ed.): Philadelphia, W. B. Saunders Co., 574 p.

Papadopulos, I. S., 1965, Nonsteady flow to a well in an infinite anisotropic aquifer: International Association of Scientific Hydrology, Symposium of Dubrovnik, p. 21-31.

Poole, F. G., and Stewart, J. H., 1964, Chinle Formation and Glen Canyon Sandstone in northeastern Utah and northwestern Colorado: U.S. Geological Survey Professional Paper 501-D, p. 30-39.

Poulson, R.E., 1979-1980, Quarterly and annual reports of the Division of Environmental Sciences: Laramie, Wyo., Energy Technology Center. (Reports available from author.)

Price, Don, and Arnow, Ted, 1974, Summary appraisals of the Nation's ground-water resources--Upper Colorado Region: U.S. Geological Survey Professional Paper 813-C, p. C1-C40.

Rathbun, R. E., Shultz, D. J., and Stephens, D. W., 1975, Preliminary experiments with a modified tracer technique for measuring stream reaeration coefficients: National Space Technology Laboratories, Bay St. Louis, Miss., U.S. Geological Survey Open-File Report 75-256, 36 p.

Robson, S. G., and Saulnier, G.J., Jr., 1980, Hydrogeochemistry and simulated solute transport, Piceance basin, northwestern Colorado: U.S. Geological Survey Professional Paper 1196, 65 p.

Saulnier, G. J., Jr., 1978, Genesis of the saline waters of the Green River Formation, Piceance basin, northwestern Colorado: Reno, University of Nevada, Ph. D. thesis, 120 p.

Schmidt-Collerus, J. J., 1974, The disposal and environmental effects of carbonaceous solid wastes from commercial oil shale operations: National Science Foundation Report NSF-GI-34282X1; available from U.S. Department of Commerce, National Technical Information Service, Springfield, VA 22161, as Report PB-231 796.

Shih, C. C., Cotter, J. E., Prien, C. H., and Nevens, T. D., 1979, Technological overview reports for eight shale oil recovery processes: U.S. Environmental Protection Agency, EPA-600/7-79-075, 106 p.

Sorey, M. L., 1971, Measurement of vertical groundwater velocity from temperature profiles in wells: Water Resources Research, v. 7, no. 4, p. 963-970.

Stallman, R. W., 1960, Notes on the use of temperature data for computing groundwater velocity: 6th Assem. Hydraul., Societe Hydrotechnique de France, Nancy, France, 1960, Rapp. 3, question 1, p. 1-7. (Also *in* Bentall, Ray, comp., Methods of collecting and interpreting ground-water data: U.S. Geological Survey Water-Supply Paper 1544-H, p. 36-46, 1963.)

Steele, T. D., Gilroy, E. J., and Hawkinson, R. O., 1974, An assessment of areal and temporal variations in streamflow quality using selected data from the National Stream Quality Accounting Network: U.S. Geological Survey Open-File Report 74-217, 210 p.

Steele, T.D., and Matalas, N. C., 1974, Principal-component analysis of streamflow chemical-quality data, *in* International Symposium on Mathematical Models in Hydrology, Warsaw, Poland (July 1971): International Association Hydrological Sciences Publication, no. 100, p. 355-363.

Stollenwerk, K. G., and Runnells, D. D., 1980, Geochemistry of leaching of trace elements from oil shale, *in* Chappell, W.R., ed., Trace elements in oil shale, Progress Report, June 1, 1979-May 30, 1980, Denver, University of Colorado, Center for Environmental Sciences, p. 177-236.

_____1981, Composition of leachate from surface retorted and unretorted oil shale, Environmental Science and Technology, v. 15, no. 11, p. 1340-1346.

Taylor, O.J., 1982, Three-dimensional mathematical model for simulating the hydrologic system in the Piceance basin: U.S. Geological Survey Water-Resources Investigations Report 82-637, 35 p., 9 pls.

U.S. Department of the Interior, 1974, Water for energy in the Upper Colorado River Basin: U.S. Department of the Interior, Water for Energy Management Team, 71 p.

U.S. Environmental Protection Agency, 1977, Oil shale and the environment: Energy/Environment Research and Development Decision Series EPA-600/9-77-033, 29 p.

Ward, J. C., 1963, Annual variation of stream water temperature: American Society of Civil Engineers, Journal of Sanitary Engineering Division, v. 89, no. SA6, p. 1-16.

Ward, J. C., Margheim, G. A., and Lof, G. O. G., 1971, Water pollution potential of rainfall on spent oil shale residues: U.S. Environmental Protection Agency, Water Pollution Control Research Series, 140 30 EDB, 124 p.

Weeks, E. P., 1969, Determining the ratio of horizontal to vertical permeability by aquifer-test analysis: Water Resources Research, v. 5, no. 1, p. 196-213.

Weeks, J. B., Leavesley, G. H., Welder, F. A., and Saulnier, G.J., Jr., 1974, Simulated effects of oil-shale development on the hydrology of Piceance basin, Colorado: U.S. Geological Survey Professional Paper 908, 84 p.

Welder, F. A., and Saulnier, G. J., Jr., 1978, Geohydrologic data from twenty-four test holes drilled in the Piceance basin, Rio Blanco County, Colorado, 1975-76: Lakewood, Colo., U.S. Geological Survey Open-File Report 78-734, 132 p.

Wentz, D.A., and Steele, T.D., 1980, Analysis of stream quality in the Yampa River basin, Colorado and Wyoming: U.S. Geological Survey Water-Resources Investigations 80-8, 161 p.; available from U.S. Department of Commerce, National Technical Information Service, Springfield, VA 22161, as Report PB81-10890-4.

Wilhm, J. L., and Dorris, T. C., 1968, Biological parameters for water-quality criteria: Bioscience, v. 18, p. 477-481.

Wymore, I. F., 1974, Estimated average annual water balance for Piceance and Yellow Creek watersheds: Fort Collins, Colorado State University, Environmental Resources Center, Technical Report 2, 60 p.

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