Simulated Effects of Oil-Shale Development on the Hydrology of Piceance Basin, Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 908

Prepared in cooperation with the Colorado Department of Natural Resources

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By JOHN B. WEEKS, GEORGE H. LEAVESLEY, FRANK A. WELDER,
and GEORGE J. SAULNIER, JR.

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The hydrology of the oil-shale-rich area is described and digital watershed and ground-water models are used to simulate the hydrologic system

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PREFACE

The present report is the result of a 2-year investigation of the hydrology of Piceance Creek basin conducted by the U.S. Geological Survey in cooperation with the Colorado Department of Natural Resources. This project was one of four concurrent projects contracted in 1972 by the State of Colorado to investigate the possible effects of oil-shale development on the environment of the Piceance basin. Thorne Ecological Institute was contracted to make an environmental inventory and impact study; Colorado State University was contracted to study revegetation and rehabilitation of disturbed land; and the Oil Shale Regional Planning Commission was contracted to study regional development and land-use planning. The combined results of these studies should provide the base data necessary to monitor and evaluate the environmental effects of future oil-shale development.

To coordinate the activities of the four concurrent oil-shale studies, the Oil Shale Coordinating Committee was established. Within this framework, a Water Resources Steering Committee was formed to monitor the conduct and progress of the hydrologic investigations. Steering Committee members contributed their time, advice, and assistance to the completion of this project. These individuals were Donald B. Tait, Chairman, Atlantic Richfield Co.; Thomas N. Beard, Shell Oil Co.; Carolyn Johnson, Colorado Open Space Council; Donald L. Libbey, U.S. Geological Survey; Charles Pollock, AMOCO Production Co.; John W. Rold, Colorado Geological Survey; Frank J. Rozich, Colorado Department of Public Health; Frank W. Stead, U.S. Geological Survey; and Ben Weichman, Superior Oil Co.

Many government agencies and private companies have contributed information to these studies. In particular, the hydrologic investigation by the U.S. Geological Survey was assisted by Atlantic Richfield Co., Barodynamics, Inc., Cameron Engineers, CER Geonuclear, Colorado Division of Water Resources, Colorado Water Conservation Board, Equity Oil Co., Mobil Oil Corp., Occidental Petroleum Co., Shell Oil Co., Superior Oil Co., The Oil Shale Corp., Wolf Ridge Mineral Corp., and Wright Water Engineers.

It is not possible to acknowledge all those individuals who contributed their time and effort to the hydrologic investigation of the Piceance basin. However, particularly important contributions were made by Messrs. John D. Bredehoeft, Roger G. Wolff, and Eugene Shuter. They developed aquifer-testing equipment which was otherwise not available. In addition, they spent most of the summers of 1972 and 1973 in the Piceance basin conducting aquifer tests and developing the data needed to define the aquifer system in the basin. Mr. Bredehoeft also provided assistance in developing the ground-water digital model of the Piceance basin.

The basic hydrologic data collected and compiled during this study have been published in "Hydrologic Data from the Piceance Basin, Colorado," by John F. Ficke, John B. Weeks, and Frank A. Welder, Colorado Water Resources Basic Data Release No. 31; and in "Hydrologic and Geophysical Data from the Piceance Basin, Colorado," by John B. Weeks and Frank A. Welder, Colorado Water Resources Basic-Data Release No. 35. Studies conducted during the hydrologic investigation in order to obtain supplemental information for this report have been published in "An Evaluation of Hillslope and Channel Erosion in the Piceance Basin, Colorado," by Donald G. Frickel, Lynn M. Shown, and Peter C. Patton, Colorado Water Conservation Board Water-Resources Circular 30; and in "Estimated Average Annual Water Balance for Piceance and Yellow Creek Watersheds," by Ivan F. Wymore, Environmental Resources Center, Technical Report No. 2, Colorado State University.

The data and cooperation provided by the above companies, agencies, and individuals have made the following report possible.

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SYSTEM OF MEASUREMENT UNITS

The following report uses both the English and the metric systems of units. In the text the English units are given first, and the equivalent measurement in metric units is given in parentheses. The units are frequently abbreviated, using the notations shown below. The English units can be converted to metric units by multiplying by the factors given in the following list.

English unit *To convert*	*Multiply by*	*Metric unit* *To obtain*
Acres	0.4047	Hectares (ha).
	4.047×10^{-3}	Square kilometres (km^2).
Acre-feet	1.233×10^{-3}	Cubic hectometres (hm^3).
Acre-feet per square mile	4.76×10^{2}	Cubic metres per square kilometre (m^3/km^2).
Barrels	0.16	Cubic metres (m^3).
Cubic feet per second (ft^3/s)	2.832×10^{-2}	Cubic metres per second (m^3/s).
	28.32	Litres per second (l/s).
Feet	0.3048	Metres (m).
Feet per day (ft/day)	0.3048	Metres per day (m/day).
Square feet per day (ft^2/day)	0.0929	Square metres per day (m^2/day).
Gallons per minute (gpm)	6.309×10^{-2}	Litres per second (l/s).
Gallons per ton	4.17	Litres per metric tonne (l/t).
Inches	25.4	Millimetres (mm).
Miles	1.609	Kilometres (km).
Square miles	2.59	Square kilometres (km^2).
Short tons (tons)	0.9072	Metric tonnes (t)
		Milligrams per litre (mg/l)
		Micrograms per litre (μg/l)
		Micromhos per centimetre (μmhos/cm)

SIMULATED EFFECTS OF OIL-SHALE DEVELOPMENT ON THE HYDROLOGY OF PICEANCE BASIN, COLORADO

By JOHN B. WEEKS, GEORGE H. LEAVESLEY, FRANK A. WELDER, and GEORGE J. SAULNIER, JR.

ABSTRACT

The Piceance and Yellow Creeks drainage area is about 900 square miles (2,330 square kilometres) and is referred to as the Piceance basin or simply as the basin. The surface-water and ground-water systems in the Piceance basin are intimately related. The annual volume of runoff from the basin (Piceance and Yellow Creeks) is estimated to be 15,650 acre-feet (19.2 cubic hectometres). About 80 percent of the annual runoff is supplied by ground-water discharge.

Runoff from the basin is affected by irrigation diversions and by consumptive use by crops, native vegetation, and evaporation. Streamflow depletions resulting from irrigation are estimated to be 4,800 acre-feet (5.9 cubic hectometres) per year. In the absence of irrigation the mean annual runoff from the basin would be 20,450 acre-feet (25.2 cubic hectometres). The period of lowest flow normally occurs during spring and summer, when irrigation diversions are greatest. Peak flows from snowmelt and thunderstorms also occur during this period. A regional analysis, using the index-flood method, was made to estimate flood frequencies in the absence of irrigation diversions for the gaging stations Piceance Creek at White River and Yellow Creek near White River. The estimated mean annual floods are 800 cubic feet per second (22.7 cubic metres per second) for Piceance Creek and 390 cubic feet per second (11.0 cubic metres per second) for Yellow Creek. The peak flow observed during the 5 years of record on Piceance Creek at White River was 407 cubic feet per second (11.5 cubic metres per second) or about one-half the estimated mean annual flood. Yellow Creek is only slightly affected by irrigation diversions, and the peak flow for the single year of record was 468 cubic feet per second (13.3 cubic metres per second).

Irrigation return flows and ground-water discharge affect the quality of surface water in the Piceance basin. The concentration of dissolved solids ranges from less than 500 milligrams per litre in the upper reaches to more than 5,000 milligrams per litre in the lower reaches of Piceance Creek and from about 700 to 3,000 milligrams per litre in Yellow Creek. Water quality deteriorates in the downstream direction, owing to ground-water discharge from the Green River and Uinta Formations.

The ground-water system in the basin consists of two principal aquifers separated by the Mahogany zone in the Green River Formation. Recharge to the aquifers occurs mainly from snowmelt along the basin margins above an altitude of 7,000 feet (2,130 metres). Ground water flows from the basin margins toward the north-central part of the basin, where it is discharged in Piceance and Yellow Creek valleys as evapotranspiration and streamflow. Recharge and discharge from the aquifer system are estimated to average 26,100 acre-feet (32.2 cubic hectometres) annually. About 20 percent of the recharge is discharged in Yellow Creek drainage. Estimates of the volume of water in storage in the aquifers range from 2.5 to 25 million acre-feet (3,100 to 31,000 cubic hectometres).

Sodium minerals in the aquifer below the Mahogany zone are actively being dissolved by ground water. The Mahogany zone impedes the flow of water between the aquifers, and large chemical differences have developed. Water in the upper aquifer generally contains less than 2,000 milligrams per litre dissolved solids, whereas the water in the lower aquifer exceeds 30,000 milligrams per litre dissolved solids in the northern part of the basin.

Digital models were used to simulate the hydrologic system. A watershed model was adapted to the drainage above the gage on Piceance Creek below Ryan Gulch to evaluate the possible effects of precipitation changes on the hydrologic system due to the introduction of atmospheric pollutants from oil-shale development or from cloud seeding. A 10-percent decrease and 10- and 20-percent increases in the October to May precipitation were examined. Each 10-percent change in precipitation was found to result in a 40-percent change in ground-water recharge. The model study indicates that a 10-percent decrease in October–May precipitation results in a 30-percent decrease in mean annual runoff, whereas 10- and 20-percent increases in precipitation result in 40- and 85-percent increases in mean annual runoff.

A digital model of the ground-water system was used to evaluate the effects of mine dewatering on the hydrologic system. Hypothetical mines in oil-shale lease tracts C–a and C–b were considered. Both mines were assumed to be in the Mahogany zone and to be 4 square miles (10.4 square kilometres) in area. Dewatering of the mines was assumed to occur simultaneously for a period of 30 years. For the hypothetical dewatering scheme simulated, the model study indicates that the mine in tract C–a will not produce enough water to meet the demand for processing and disposal of oil shale, whereas the mine in tract C–b will produce water in excess of the demand. The concentration of dissolved solids of the water discharge from the mines may not exceed 5,000 milligrams per litre for the hypothetical dewatering scheme considered.

Dewatering the hypothetical mines will only slightly affect ground-water discharge in the Yellow Creek drainage. However, after 30 years of dewatering, the model indicates that ground-water discharge will cease in a 10-mile (16-kilometre) reach of Piceance Creek near tract C–b. The decrease in ground-water discharge in this reach could cause an increase in the concentration of dissolved solids in the downstream reach of Piceance Creek. After 30 years of dewatering the hydraulic head in the aquifers is decreased in 75 percent of the basin area, and about 500,000 acre-feet (620 cubic hectometres) of water is removed from storage in the aquifers.

It is concluded that oil-shale development will have significant effects on the surface- and ground-water systems in the Piceance basin.

INTRODUCTION

The Piceance Creek structural basin is in northwestern Colorado southwest of the city of Meeker. The present report describes the hydrology of the part of the structural basin drained by Yellow and Piceance Creeks, an area of about 900 square miles (2,330 km^2). The study area is shown in figure 1 and will be referred to as the Piceance basin or simply as the basin.

BACKGROUND

PREVIOUS INVESTIGATIONS

The geology and oil-shale resources of the Piceance basin have been investigated by the U.S. Geological Survey since the Green River Formation was recognized in the basin in 1874. Donnell (1961) summarized these investigations; however, the water resources of the basin were not investigated until 1964, when the Survey, in cooperation with the Colorado Water Conservation Board, began a reconnaissance study. Coffin, Welder, Glanzman, and Dutton (1968) and Coffin, Welder, and Glanzman (1971) reported on the study and laid the groundwork for the current investigation, which was initiated in 1972 by the U.S. Geological Survey in cooperation with the Colorado Department of Natural Resources.

OIL-SHALE RESOURCES

The largest known oil resource in the world occurs in the oil-shale deposits of the Green River Formation in Colorado, Wyoming, and Utah. The known deposits of oil shale in the Green River Formation include about 600 billion barrels (96 billion m^3) of oil in deposits at least 10 feet (3 m) thick and averaging 25 gallons per ton (105 l/t). An estimated 1,800 billion barrels of oil are contained in oil-shale deposits more than 10 feet (3 m) thick and averaging more than 15 gallons per ton (63 l/t). These oil-shale deposits represent a potential energy resource which could supply the Nation's oil demand for many decades. The potential of oil shale to alleviate the Nation's dependence on foreign oil supplies has stimulated industrial and Governmental interest in developing oil-shale technology. In 1971 the Department of the Interior announced plans to permit development of a small part of the oil-shale resources on public lands in Colorado, Wyoming, and Utah.

PROTOTYPE LEASING PROGRAM

Oil shale is a leaseable mineral subject to the provisions of the Mineral Leasing Act of 1920 and Executive Order 5327. No oil-shale leases had been issued since 1925 until 1974, when a prototype program was initiated. Two leases of not more than 5,120 acres (about 20.7 km^2) each in each of the three States were to be sold by competitive bidding for private development under controlled conditions to provide a new source of energy, permit an equitable return to all parties, and develop management expertise. In January 1974 the first lease sold was for Colorado tract C–a (fig. 1), which consists of 5,089.70 acres (20.60 km^2) in the Piceance basin. Gulf Oil Corp. and Standard Oil Co. (Indiana) were awarded the lease for submitting the highest bonus bid of $210,305,600. In February 1974 the second lease sold was for Colorado tract C–b (fig. 1), which consists of 5,093.90 acres (20.62 km^2) in the Piceance basin. The lease was awarded to Ashland Oil, Inc., Atlantic Richfield Co., The Oil Shale Corp., and Shell Oil Co. for their high bonus bid of $117,700,000.

A major objective of the prototype program is to determine methods for maintaining the environmental integrity of the areas to be affected. Considerable responsibility toward this objective will be borne by the lessees as well as by local, State, and Federal agencies.

In May 1970 the Governor of Colorado initiated a study of the environmental impact of the development of oil shale in the Piceance basin. The resultant report, entitled "Colorado Oil Shale Advisory Committee Study, Report on the Economics of Environmental Protection for a Federal Oil Shale Leasing Program," was released in 1971. A more comprehensive report covering the impacts of oil-shale development in each of three States, entitled "Environmental Statement for the Prototype Oil-Shale Leasing Program," was prepared in compliance with the National Environmental Policy Act of 1969 and was released by the U.S. Department of the Interior in 1973.

PRELIMINARY DEVELOPMENT PLANS

COLORADO TRACT C–a

The Preliminary Development Plan submitted to the Bureau of Land Management by Gulf and Standard in January 1974 proposes two alternative plans for mining oil shale in tract C–a. One plan calls for a combination open-pit and underground mine. The proposed open-pit mine will be about 2 square miles (5.2 km^2) in area and may reach a depth of 1,000 feet (305 m). Where the overburden limits the open-pit method, oil shale will be removed by underground mining from zones reached horizontally by adits from the sides of the pit. Mining of these zones will be by room-and-pillar method. The total area of the combined open-pit and underground mine will be about 3.5 square miles (9.1 km^2).

The alternative plan is an underground mine which extracts oil shale from three different levels, using the room-and-pillar method. The proposed mine will be about 2.5 square miles (6.5 km^2) in area. The depth of the lowest mining level will be determined by exploration data.

The mining zones for both plans are the richest oil-shale intervals in the Parachute Creek Member of the Green River Formation. (See fig. 2.) The Mahogany zone and underlying zones in the Parachute Creek Member are the principal mining intervals.

The initial commercial plant is expected to produce between 50,000 and 100,000 barrels (8,000 and 16,000 m^3) of oil per day. The Preliminary Development Plan estimates that water for processing the oil shale and disposal of the spent shale will be derived from ground water and that the water required for a 50,000-barrels-per-day plant is 11,500 acre-feet per year or 16 ft^3/s (0.45 m^3/s). The plan estimates that this water may be supplied by the mine-dewatering operation.

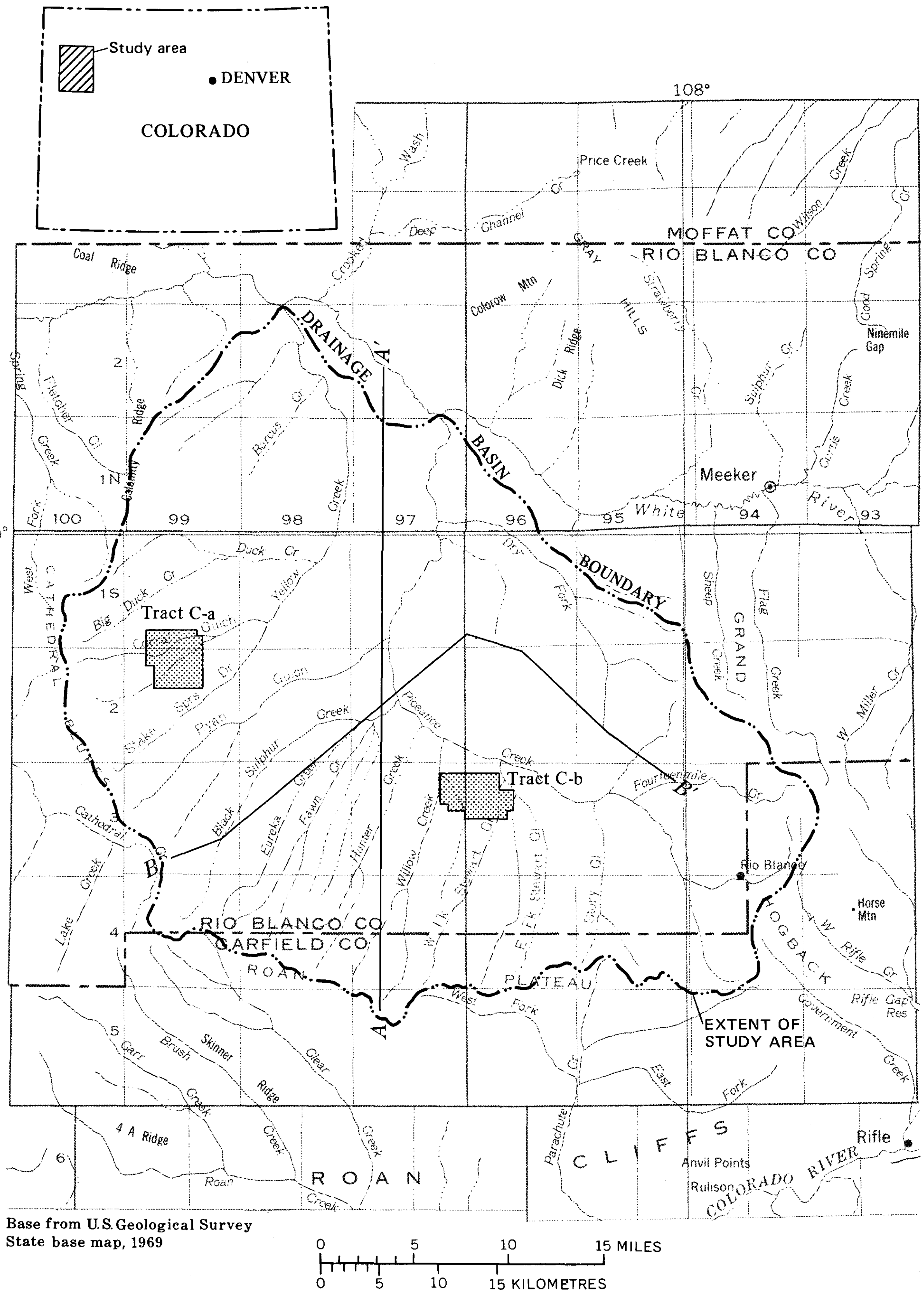


FIGURE 1. — Location of the Piceance basin and prototype oil-shale lease tracts C–a and C–b.

COLORADO TRACT C–b

The Preliminary Development Plan submitted by Ashland–ARCO–TOSCO– Shell in March 1974 proposes an underground mine in tract C–b. The preliminary plan is to develop a mine in the Mahogany zone and extract oil shale using the room-and-pillar method. More than 900 feet (275 m) of overburden precludes development by open-pit mining. The preliminary plan does not give the details of the mine location or size. In tract C–b the Mahogany zone ranges from about 900 to 1,400 feet (275 to 430 m) below land surface.

The initial commercial retorting plant is expected to produce 50,000 barrels (8,000 m^3) of oil per day. The water requirement for the processing and disposal of the oil shale is 10,000 acre-feet per year, or 14 ft^3/s (0.40 m^3/s). The Preliminary Development Plan estimates that this water will be available from ground water produced during the mine-dewatering operation.

A total water requiremant of 30 ft^3/s (0.85 m^3/s) will be needed for prototype oil-shale development in the two tracts. About half of the water required will be used to moisten the spent shale for transportation and compaction. The waste material (about 20 percent water by weight) will be disposed of in ravines and gullies on or near the tracts. The remainder of the water required will be consumed by evaporation in the retorting process.

PURPOSE AND SCOPE OF THIS REPORT

On June 29, 1971, the Department of the Interior announced plans for a prototype oil-shale development program on Federal lands in Colorado, Utah, and Wyoming. Protection of the environment of the oil-shale regions is a principal concern of the Department. In anticipation of the development of oil shale in the Piceance basin, the U.S. Geological Survey, in cooperation with the Colorado Department of Natural Resources, began a 2-year investigation of the water resources of the Piceance basin in 1972. The expected water requirements and mine-dewatering operations for development of the prototype leases will have a significant impact on the surface- and ground-water resources of the basin. Consequently, it is necessary to document the existing hydrologic conditions before development has altered those conditions. The hydrological investigation of the Piceance basin was initiated to meet the three following objectives:

1. To provide baseline data for determining the effects of future oil-shale development on the water resources of the basin.
2. To describe the hydrologic system in the Piceance basin.
3. To predict the effects of hypothetical mining operations on the hydrologic system.

To meet the above-stated objectives, a comprehensive data-collection program was undertaken. Data on surface-water quantity and (or) quality were collected at over 50 sites in the study area, including 32 stations operated by the Colorado Division of Water Resources. In addition, 31 stream-channel cross sections and 35 transects on hillslopes and alluvial fans were established to monitor erosion and aggradation. Geophysical logs, water levels, and aquifer-test data and (or) water-quality data have been collected or compiled for more than 100 wells in the basin. The data have been published in "Hydrologic Data from the Piceance Basin, Colorado," by John F. Ficke, John B. Weeks, and Frank A. Welder, Colorado Water Resources Basic-Data Release No. 31, and in the "Hydrologic and Geophysical Data from the Piceance Basin, Colorado," by John B. Weeks and Frank A. Welder, Colorado Water Resources Basic-Data Release No. 35. These reports include all the public data collected and compiled during the 2-year investigation and provide the basic data needed to meet the above objectives. Additional data on surface-water quantity and quality are published in Water-Supply Papers of the U.S. Geological Survey and in the annual series, Surface Water Records for Colorado, Part 1 (1961–73) and Part 2 (1964–73). Baseline geomorphologic data collected during the study have been published in "An Evaluation of Hillslope and Channel Erosion in the Piceance Basin, Colorado," by Donald G. Frickel, Lynn M. Shown, and Peter C. Patton, Colorado Water Conservation Board Water Resources Circular 30. Data on basin climate, topography, vegetation, and soils were compiled during the study and used to describe the hydrology of the basin in terms of water balance. These data and the water-balance analysis have been published in "Estimated Average Annual Water Balance for Piceance and Yellow Creek Watersheds," by Ivan F. Wymore, Environmental Resources Center Technical Report No. 2, Colorado State University.

The basic data were used to formulate the description of the hydrologic system and to develop digital models of the system. The models were used to predict the effects of development on the hydrology of the basin. The purpose of this report is to describe the hydrologic system, describe the digital models of the system, and predict the effects of development on the system.

PHYSICAL SETTING

PHYSIOGRAPHY

The part of the Piceance Creek structural basin between the White River on the north and the Colorado River on the south consists of about 1,600 square miles (4,140 km^2) in Garfield and Rio Blanco Counties. Land-surface altitudes range from about 5,000 feet (1,520 m) above sea level in the Colorado River valley to more than

8,000 feet (2,440 m) on the Roan Plateau and Cathedral Bluffs (fig. 1). The major physiographic feature within the structural basin is a dissected plateau standing as much as 4,000 feet (1,220 m) above adjacent lowlands.

In Rio Blanco County the northern part of the structural basin has been eroded into a topographic basin by the drainage networks of Yellow and Piceance Creeks, which are tributary to the White River. The topography is that of ridges and valleys with local relief of 200 to 600 feet (60 to 180 m). Most of the Federal oil-shale lands are in this part of the basin.

CLIMATE

The climate of the area is semiarid. Annual precipitation ranges from about 12 to 20 inches (300 to 510 mm) between altitudes of 5,500 feet (1,680 m) and 8,000 feet (2,440 m). Above an altitude of 8,000 feet (2,440 m) the areas along the Grand Hogback may receive as much as 25 inches (640 mm) of precipitation each year. Summer temperatures may exceed 40°C. Winter temperatures may drop to minus 40°C. The number of frost-free days varies from 120 at lower altitudes to 50 days per year at higher altitudes.

GEOLOGY

HISTORY

The Piceance basin has been the site of considerable sediment deposition beginning probably by Late Cretaceous time. During the Eocene Epoch, crustal warping created a huge lake which covered much of northwestern Colorado and northeastern Utah. Near the lakeshore, sand was deposited; in the deeper parts of the lake, clay and fine-grained sediments were deposited, especially in the northern part of the basin, where the lake deposits are as much as 3,500 feet (1,100 m) thick. As depositional and water-chemical conditions varied because of climatic changes, various amounts of organic material accumulated on the lake bottom. When conditions were such that plant and animal life in the lake were abundant, organic-rich layers were deposited as these organisms died and sank to the bottom. In response to changing physical and chemical conditions, minerals formed in various amounts in the lake deposits. Gradually, younger sediments buried the organic-rich sediment, and the lake was eventually filled with sand, silt, and clay carried in by streams. The weight of over lying sediments consolidated the lake deposits forming the sandstone, shale, and marlstone of the Green River and Uinta Formations and converted the organic material to a solid hydrocarbon called kerogen. The marlstone that is rich in kerogen is commonly called oil shale.

STRATIGRAPHY

Rock outcrops in the study area range in age from Cretaceous to Quaternary. A geologic map of the basin and a summary of the geology and oil-shale resources have been given by Donnell (1961). The geologic map and cross section published by Donnell (1961) is reprinted here as plate 1. The present report is concerned primarily with the Green River and Uinta Formations of Eocene age and the Quaternary alluvium in the stream valleys because they contain the principal aquifers. Permeability in the Green River and Uinta Formations is mainly due to fractures and faults, with some leaching and, possibly, collapse in the deeper, central part of the basin.

The Green River Formation rests conformably on the Wasatch Formation (pl. 1; fig. 2), which is of Paleocene and Eocene age. Bradley (1931) divided the Green River Formation into four members, here listed in stratigraphically ascending order (pl. 1): Douglas Creek, Garden Gulch, Parachute Creek, and Evacuation Creek. Cashion and Donnell (1974) revised Bradley's nomenclature on the basis of stratigraphic correlations. In the Piceance Creek structural basin, the name Evacuation Creek Member of the Green River Formation has been abandoned, and the rocks are now placed in the lower part of the Uinta Formation. The revised nomenclature is used throughout this report and is shown in figure 2.

The Douglas Creek Member is mainly sandstone; the Garden Gulch is a shaly, dolomitic marlstone. Both units are relatively impermeable. On the east margin of the basin a near-shore sequence of sandstones—the Anvil Points Member (pl. 1)—is the equivalent of the Douglas Creek and Garden Gulch Members and of the lower part of the Parachute Creek Member. It is relatively unimportant to this study.

The Parachute Creek Member, overlying the Garden Gulch Member, is composed of dolomitic marlstone (oil shale) and soluble minerals. Because of fracturing and the solution of minerals in the central part of the basin, this member is the principal bedrock aquifer in the study area. The Parachute Creek Member was divided into three zones on the basis of geologic and hydrologic characteristics by Coffin, Welder, and Glanzman (1971). The zones are identified by their resistivity properties on electric logs, as show in figure 3.

The lowermost zone contains rocks rich in kerogen and sodium minerals but with very little water content. The zone is characterized by high-resistivity values on electric logs and is referred to as the high-resistivity or "HR" zone. Because of deep burial and the pressure of the overlying rocks, the HR zone behaves as a plastic medium rather than a brittle one. It is relatively unfractured and relatively impermeable. This zone ranges from about 200 to more than 900 feet (60 to 270 m) thick and was described by Coffin, Welder, and Glanzman (1971). The absence of this zone away from the deeper part of

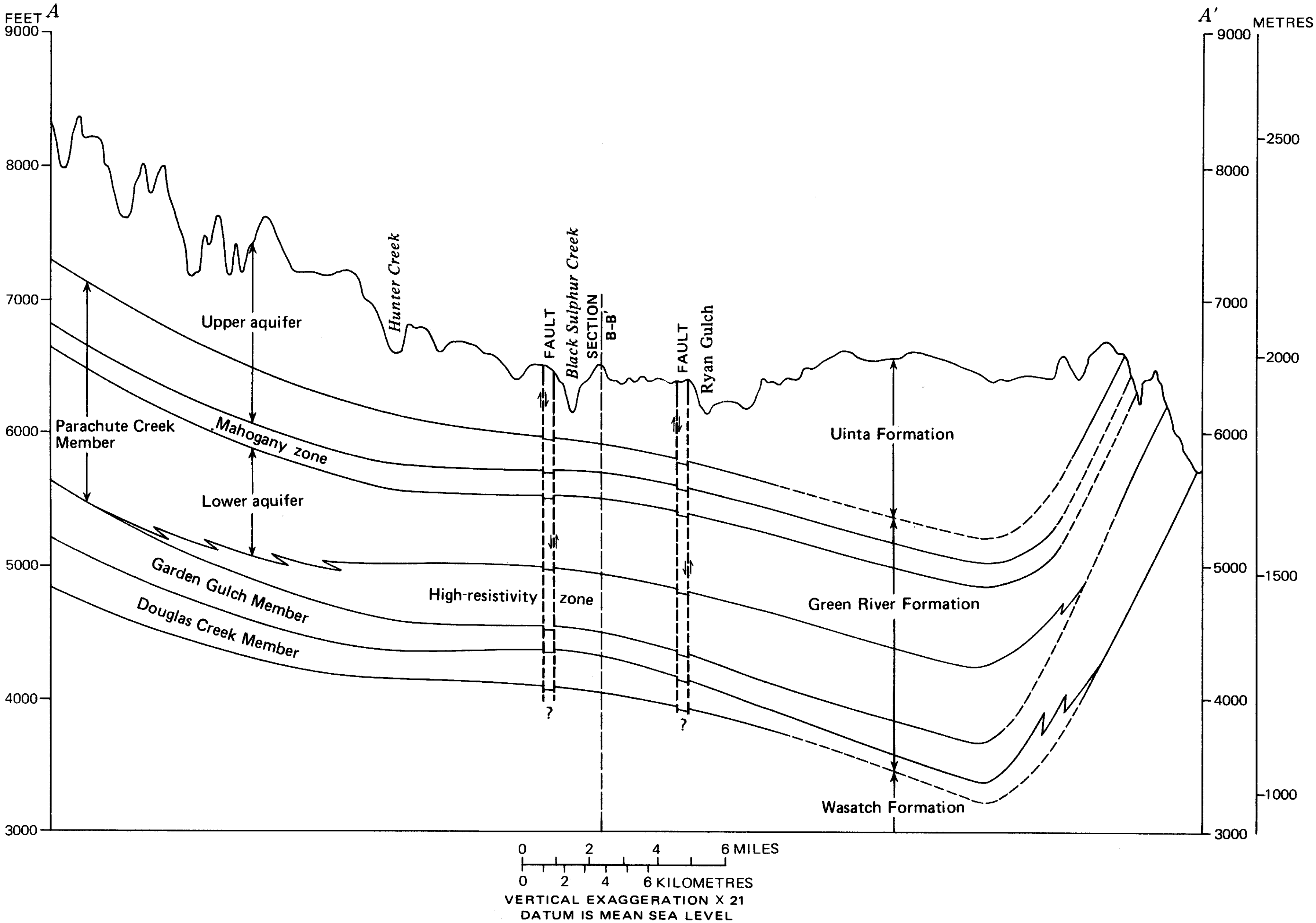


FIGURE 2. — Geologic section through the Piceance basin. Section is located in figure 1.

the basin, as shown in figure 2, may be due to lower oil-shale content, lower content of soluble minerals, and (or) higher water content.

Overlying the HR zone is a zone of low resistivity which has been fractured, permitting ground water to enter the rock and dissolve much of the original soluble minerals. This leached zone has relatively high permeability and ranges in thickness from 400 to 700 feet (about 120 to 210 m) in the central part of the study area. The leached zone is characterized by broken rock, which results in poor core recovery and loss of circulating fluid during drilling operations.

The Mahogany zone overlies the leached zone and consists of kerogen-rich strata which range in thickness from 100 to 200 feet (30 to 60 m) and which extend to all margins of the basin, as shown on plate 1. The Mahogany zone is the richest oil-shale interval in the section and is the zone of principal interest for oil-shale development. Where deeply buried, the Mahogany zone acts as a plastic semipermeable material. Under less pressure from overlying rocks, away from the deeper part of the basin, the Mahogany behaves as a brittle medium, vulnerable to fracturing and capable of containing and transmitting ground water. The Mahogany zone is overlain by less than 500 feet (150 m) of marlstone in the Parachute Creek Member, which is fractured and water bearing.

Sandstone, siltstone, and marlstone—the consolidated products of the sand, silt, and clay which filled the ancient lake—overlie the Parachute Creek Member (fig. 2). These rocks form the Uinta Formation and are the surface rock throughout most of the study area. The formation ranges in thickness from zero to as much as 1,250 feet (380 m) and generally thickens from west to east. The sandstone and siltstone are characterized by interstices, most of which have been filled and cemented together by sodium and calcium bicarbonate deposited by percolating ground water. Little or no primary porosity remains. Permeability is mainly due to fracturing, and the fractured marlstones are the principal water-bearing rocks. The formation is generally water bearing at or above the altitude of adjacent streams.

Quaternary alluvium consists of unconsolidated gravel, sand, and clay derived from the Uinta Formation. The alluvium is highly permeable and is an important aquifer in the major stream valleys, except where thick clay deposits exist, as described by Coffin, Welder, Glanzman, and Dutton (1968). The upper and lower bedrock aquifers are shown in figure 2. The aquifer system will be described in detail later in this report.

THE HYDROLOGIC SYSTEM

Climate, physiography, and geology directly affect the hydrology of the Piceance basin. Each of these

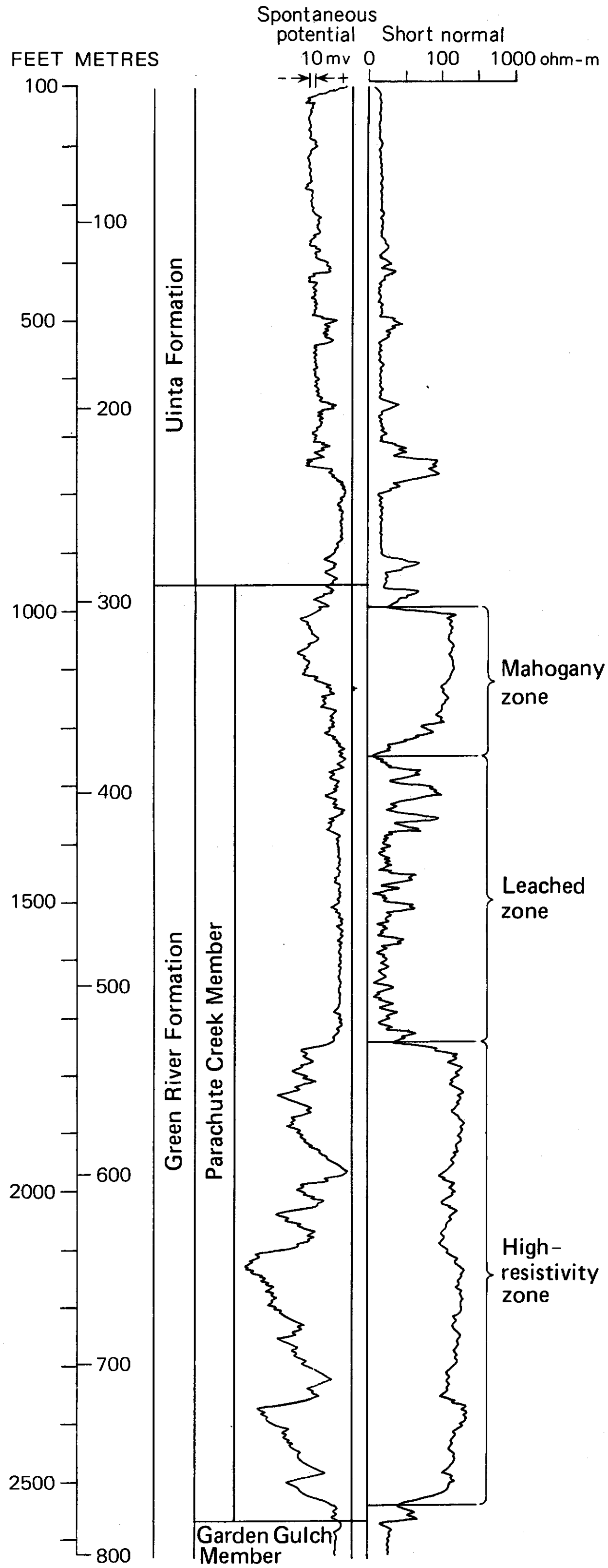


FIGURE 3. — Typical electric log, showing zones of the Parachute Creek Member of the Green River Formation.

characteristics influences the quantity and quality of surface water and ground water in the basin. In addition, man's activities affect the hydrologic system. At present, surface-water diversion for irrigation is the only activity affecting the system. However, future oil-shale development may cause major changes in the water resources of the Piceance basin. To evaluate the effects of development on the hydrologic system, the existing hydrologic conditions must be documented. The following sections of this report describe the surface- and ground-water systems and their interrelationship under existing conditions.

SURFACE WATER

DRAINAGE DESCRIPTION

Geomorphic descriptions of the Piceance basin were given by Frickel, Shown, and Patton (1974) and by Schumm and Olson (1974), and a regional geomorphic description was given by Thornbury (1965). The drainage patterns of Piceance Creek and Yellow Creek basins range from trellis to parallel, with the pattern appearing to be structurally controlled. Flat narrow alluvial valleys are bounded by valley sides whose slopes commonly exceed 30 percent. Valleys are separated by wide, gently rolling divides.

The physical and chemical properties of the soils in the Piceance basin vary widely. Soil depths range from near zero on the steeper valley slopes to several feet in the better upland and bottomland sites. A general soils map of the basin showing soil associations is available from the Soil Conservation Service, U.S. Department of Agriculture, and a general description of the physical and chemical properties of the soils in the basin was presented by Fox (1973) and by Campbell, Berg, and Heil (1974). A study of the infiltration rates of selected sites in the Piceance basin (J. R. Meiman, written commun., 1974) found that the soil-covered ridges and bottomlands had infiltration rates ranging from 5 to 10 cm/hr for storm durations of 1 hour. Wymore (1974) estimated the available water-holding capacities for typical soil profiles by using the characteristics of vegetation type and altitude.

Vegetation varies over the basin from a desert-shrub community in the drier, low-altitude sites to a forest community at the higher altitude sites, where more moisture is available. Ferchau (1973) gave a brief description of the vegetation in the basin. Also, a vegetation map was prepared by Terwilliger and Threlkeld (1974), showing the basin's seven major vegetation types, which are bottomland sagebrush, desert shrub, upland sagebrush, mixed mountain shrub, Pinyon-Juniper woodland, grassland, and forest. Each of these types has been described in detail by Ward, Slauson, and Dix (1974). In addition to the natural vegetation in the basin, approximately 5,100 acres (2,060 ha) in Piceance Creek and 200 acres (81 ha) in Yellow Creek drainage are maintained as irrigated pasture and hay meadows. On the basis of water use, the vegetation can be classified as upland and bottomland communities. Upland communities are supplied by natural precipitation, whereas bottomland communities have water sources that supplement precipitation, such as streamflow diversions for irrigation, runoff from adjacent slopes, and ground-water discharge.

Available surface-water records indicate that Piceance Creek and a few of its major tributaries are perennial streams. The majority of the tributaries to Piceance Creek are intermittent streams. The single year of record on Yellow Creek indicates that it is a perennial stream, but the magnitude of the low flows indicates that during a year of low precipitation it could become intermittent. Tributaries to Yellow Creek are all intermittent. The stream channels in both drainages are incised in the valley alluvium, which ranges in thickness from 0 to 140 feet (43 m) (Coffin and others, 1968; Coffin and others, 1971). Variations in the thickness of the alluvium are apparent in some channels during low-flow periods. Streamflow may disappear where the alluvium is thick and then reappear downstream where the alluvium thins and the saturated zone reaches the channel bottom.

STREAMFLOW

SURFACE-WATER HYDROLOGY

DESCRIPTION

Streamflow from the Piceance Creek and Yellow Creek drainage basins is typical of those regions where the primary source of streamflow is snowmelt. Precipitation for the months of November through March is stored in the snowpack at the higher altitudes of the basin and becomes available for recharge and runoff as the daily temperatures and the solar radiation increase in the spring. Snowmelt produces a period of high streamflow, starting in March or April, which continues through June or July. Streamflow for the remainder of the year is maintained almost totally by ground-water discharge which moves through the alluvium into the stream channels or appears as springs along the valley floors. Evapotranspiration demands during the summer are very large, and most of the precipitation that occurs during this period is evapotranspired. Only high-intensity thunderstorms, which are usually limited in areal extent, produce any significant contributions to summer streamflow.

The surface-water hydrology of the basin was described by Wymore (1974) in terms of a water balance. Using local and regional climatic data, basin descriptive data, and a modified Jensen-Haise technique for computing evapotranspiration (Jensen and others, 1969), Wymore computed a mean annual water balance for the total basin. The basin was subdivided on the basis of slope, aspect, altitude, and vegetation to account for variations in evapotranspiration associated with these factors. The basin was divided into upland and bottomland areas to account for variations in water availability to these two areas. As previously described, water in the upland areas is supplied only by precipitation, whereas in the bottomlands precipitation is supplemented with irrigation diversions, ground-water discharge, and runoff from adjacent valley slopes. Table 1 lists the areas of the basin and water-balance figures by upland and bottomland regions, for Piceance Creek and Yellow Creek drainage basins. Supplemental water use in the bottomlands is the difference between bottomland evapotranspiration and bottomland precipitation shown in table 1. The average annual runoff computed in table 1 is less than the error in the estimates of precipitation and evapotranspiration. However, the computed runoff appears to be very reasonable when compared with the measured mean annual discharge of 14,520 acre-feet (17.9 hm^3) for Piceance Creek and 1,130 acre-feet (1.4 hm^3) for Yellow Creek. The gaged flows are discussed in detail in the following sections.

DISCHARGE RECORDS

Table 2 lists the U.S. Geological Survey streamflow gaging stations on Piceance and Yellow Creeks and their respective periods of record. Figure 4 shows the locations of these stations. With the exception of the 1964–66 record for Yellow Creek, all records are published in the Water-Supply Papers of the U.S. Geological Survey and (or) the annual series entitled "Surface Water Records for Colorado, Part 1." The October 1964 to September 1965 hydrograph for Yellow Creek near White River was reported by Coffin, Welder, Glanzman, and Dutton (1968).

In addition to the discharge records listed in table 2, records of flow measurements made on a weekly basis at 5 stream stations and at 27 springs in the Piceance basin were reported by Ficke, Weeks, and Welder (1974) and by Weeks and Welder (1974). These 32 measurement stations are operated by the Colorado Division of Water Resources and were established between March 1968 and July 1972.

IRRIGATION EFFECTS

The surface-water supplies of Piceance Creek and Yellow Creek are fully developed for irrigation purposes. Approximately 5,100 acres (2,060 ha) in the Piceance Creek basin and 200 acres (81 ha) in the Yellow Creek basin are irrigated annually. Irrigation diversions begin in mid-March and continue through early November. The amount of water diverted and the number of acres irrigated at any one time are functions of water availability, water-right priorities, crop type, and weather conditions.

Streamflow losses from consumptive use by crops and evapotranspiration losses associated with irrigation practices have a marked influence on the streamflow hydrograph from March to November.

In addition, two irrigation ditches above gaging station 3 and one ditch above gaging station 4 (fig. 4) divert

TABLE 1. — *Water balance for the Piceance basin*

Area	Number of acres	Annual volume (acre-ft)		
		Precipitation	Evapotranspiration	Runoff
Piceance Creek:				
Upland	385,600	562,600	538,700	
Bottomland	+17,000	+21,100	+31,900	
Total	402,600	583,700	570,600	13,100
Yellow Creek:				
Upland	159,300	209,000	203,700	
Bottomland	+5,800	+6,500	+9,300	
Total	165,100	215,500	213,000	2,500
Total basin:				
Upland	544,900	771,600	742,400	
Bottomland	+22,800	+27,600	+41,200	
Total	567,700	799,200	783,600	15,600

TABLE 2. — *Streamflow gaging stations in the Piceance basin and their periods of record*

Station No.[1]	U.S. Geological Survey downstream order No.	Station name	Drainage area (mi²)	Period of record
1-----	09305500	Piceance Creek at Rio Blanco.	9	Oct. 1955-Sept. 1957.
2-----	09306000	Piceance Creek near Rio Blanco.	153	Oct. 1940-Sept. 1943.
3-----	09306200	Piceance Creek below Ryan Gulch.	485	Oct. 1964-Sept. 1973.
4-----	09306222	Piceance Creek at White River.	629	Oct. 1964-Sept. 1966. Oct. 1970-Sept. 1973.
5-----	09306255	Yellow Creek near White River.	258	[2]Oct. 1964-Sept. 1966. Oct. 1972-Sept. 1973.

[1]Stations shown in figure 4. [2]Unpublished record.

water above the gages for use on areas below the gages, further influencing the flow at the gages.

Records of streamflow diversions and acres irrigated for each irrigation ditch are maintained by the Colorado Division of Water Resources. The records usually consist of two or three discharge observations per month on each ditch in the basin. The observations are made by the local water commissioner. From the discharge observations made during the irrigation season, the commissioner computes the annual volume of diversion for each ditch.

RUNOFF CHARACTERISTICS

The runoff characteristics of the Piceance basin are described primarily on the basis of the gaging-station records for Piceance Creek below Ryan Gulch (fig. 4, sta. 3) and Piceance Creek at White River (fig. 4, sta. 4). The latter station is located at the mouth of Piceance Creek and reflects the total discharge from the basin. The gage below Ryan Gulch which has the longest record in the basin, measures a major part of the runoff from the basin and has concurrent records with the Piceance Creek gage at the White River, from which the shorter period record can be extended. The availability of only 1 year of record for the Yellow Creek drainage limits the hydrologic description to those characteristics which can be estimated from regional analyses.

MEAN ANNUAL FLOW

The measured and adjusted annual runoff for the gaging stations Piceance Creek below Ryan Gulch and Piceance Creek at White River are shown in figure 5. The adjusted runoff equals the amount measured plus the diversion around the gage, estimated by the Colorado Division of Water Resources. For the 9 years of record, the adjusted mean annual runoff at the gage below Ryan Gulch is 12,850 acre-feet (15.8 hm³) and for the 5 years of record for the gage at the White River is 14,910 acre-feet (18.4 hm³). The adjusted runoff for the water years 1967–70 for the gage at the White River was estimated by using a linear regression. An equation was derived which related the adjusted discharge at the gages on Piceance Creek at White River and below Ryan Gulch for the 5 years of concurrent record. The resulting equation had a correlation coefficient of 0.992, and the estimated runoff, using this equation, is shown as dashed lines in figure 5. Including the estimates for water years 1967–70, the adjusted mean annual runoff for Piceance Creek at White River is 14,520 acre-feet (17.9 hm³).

Records for the gage on Yellow Creek at White River are available only for the 1973 water year, and the total runoff was 1,130 acre-feet (1.4 hm³). There are no irrigation diversions past the gage; therefore, no adjustments are necessary.

The annual volumes of runoff shown in figure 5 represent only a portion of the surface water available in the basin. The total yield of the basin is equal to the adjusted flow plus the streamflow depletions resulting from irrigation. Irrigation losses are the result of consumptive use by crops plus losses incidental to irrigation, such as evapotranspiration from phreatophytes and other vegetation along irrigation ditches and adjacent to irrigated areas. Estimates of the average annual evapotranspiration from the irrigated acreage were made by Wymore (1974) in his estimate of the total basin water balance. Average annual streamflow depletion due to irrigation was computed to be 3,950 acre-feet (4.9

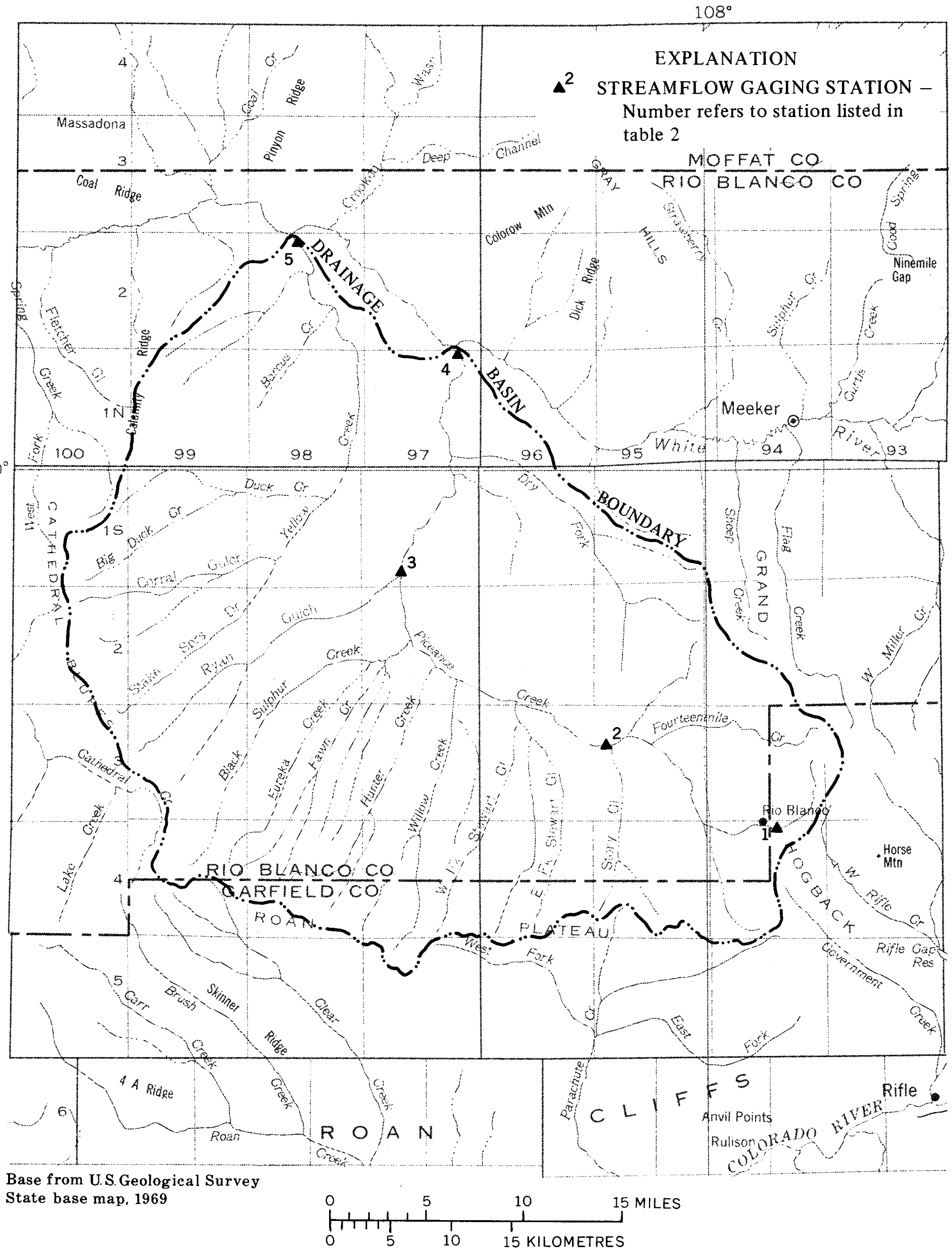


FIGURE 4. — Location of streamflow gaging stations.

hm³) in the Piceance Creek basin and 50 acre-feet (0.06 hm³) in the Yellow Creek basin. Data from appendix V, "Water Resources," and appendix XI, "Irrigation and Drainage," of the U.S. Water Resources Council (1971), studies of the Upper Colorado River basin, indicate that incidental irrigation losses for this region are ap-

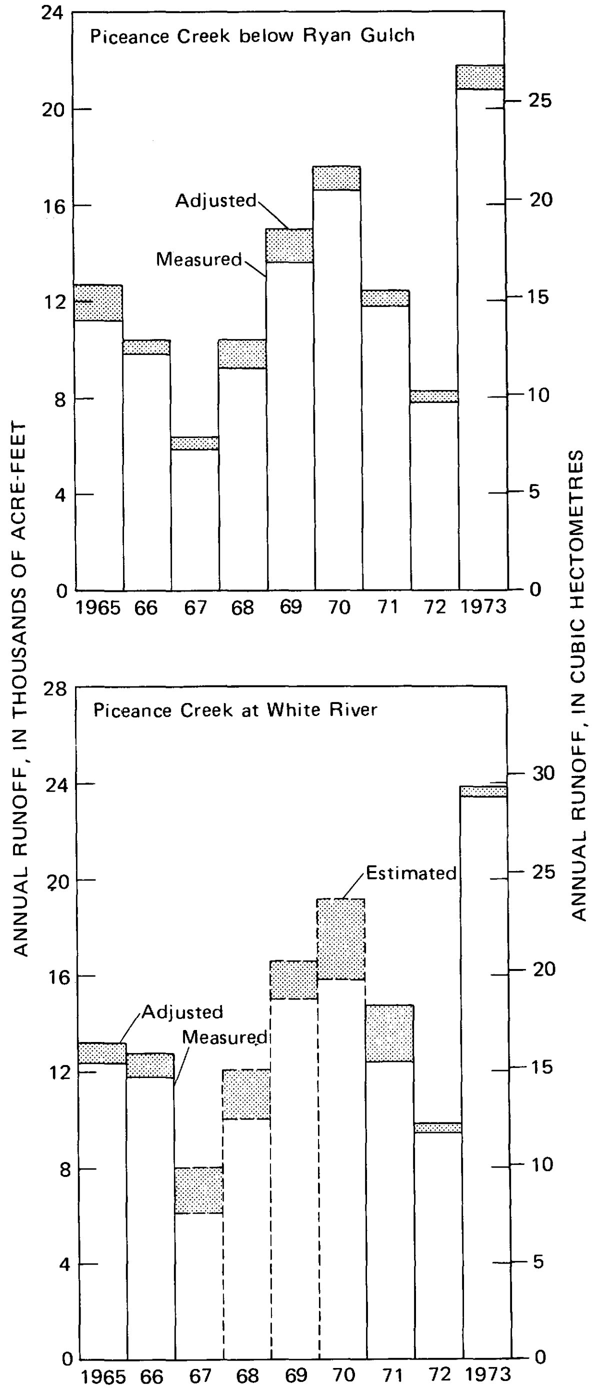


FIGURE 5. — Annual measured and adjusted runoff from Piceance Creek below Ryan Gulch and at White River.

proximately 20 percent of the consumptive use by irrigated cropland. This results in an additional loss of 790 acre-feet (0.97 hm^3) from Piceance Creek and 10 acre-feet (0.01 hm^3) from Yellow Creek. Summation of the adjusted mean annual runoff and irrigation depletions results in an estimate of the annual yield from Piceance Creek drainage of 19,260 acre-feet (23.7 hm^3) and an estimate of the 1973 water-year yield from Yellow Creek drainage of 1,190 acre-feet (1.46 hm^3).

RUNOFF DISTRIBUTION

The primary source of streamflow in Piceance Creek and Yellow Creek is snowmelt. The runoff distribution is typical of the snowmelt regions of northwestern Colorado. Mean daily streamflow reaches a peak during the snowmelt period of March through June, recedes through the summer months, and is normally at a minimum during the winter months. This pattern is shown by the hydrographs for the 3 years of record at Piceance Creek near Rio Blanco (fig. 4, sta. 2) shown in figure 6. The pattern is also shown by the hydrograph at Piceance Creek at Rio Blanco (fig. 4, sta. 1) shown in figure 7*A*. Streamflow at both gages is only slightly affected by irrigation. Weekly flow records from springs and streams in the Piceance basin reported by Ficke, Weeks, and Welder (1974) show a similar pattern.

The hydrographs of average monthly discharge shown in figures 7*B* and 7*C* for Piceance Creek below Ryan Gulch and Piceance Creek at White River show the effects of irrigation diversions on the distribution of runoff. Approximately 5,100 acres (2,060 ha) is irrigated above the gage at White River; this includes 4,000 acres (1,620 ha) above the gage below Ryan Gulch. The low flows in April at both gages indicate that, in the early part of the irrigation season, large volumes of water diverted for irrigation are stored in the soil profile for consumptive use by crops, incidental irrigation losses, and slow release as irrigation return flow.

The extremes (maximums and minimums) of monthly runoff shown in figure 7 vary with season. During November through February, streamflow is supplied almost entirely by ground-water discharge. The resulting small variations in the extremes reflect annual variations in ground-water recharge. During the irrigation season of March to November, the large variations in the extremes reflect the combined effects of climate and irrigation diversions. The maximum monthly flows in February and March are the result of heavy snowfall years, and the increases in maximum and minimum flows for the month of August are the result of high-intensity thunderstorms.

The monthly runoff for Yellow Creek near White River for the 1973 water year is shown in figure 8. The shape of the hydrograph resembles those for Piceance Creek near Rio Blanco (fig. 6) because diversions for irrigation are small, and snowmelt dominates the spring runoff. The effect of high-intensity thunderstorms in August is very evident in the hydrograph. This same effect was noted in the hydrographs for Piceance Creek.

FLOW VARIABILITY

Flow-duration curves are cumulative-frequency curves indicating the percentage of time that a given flow has

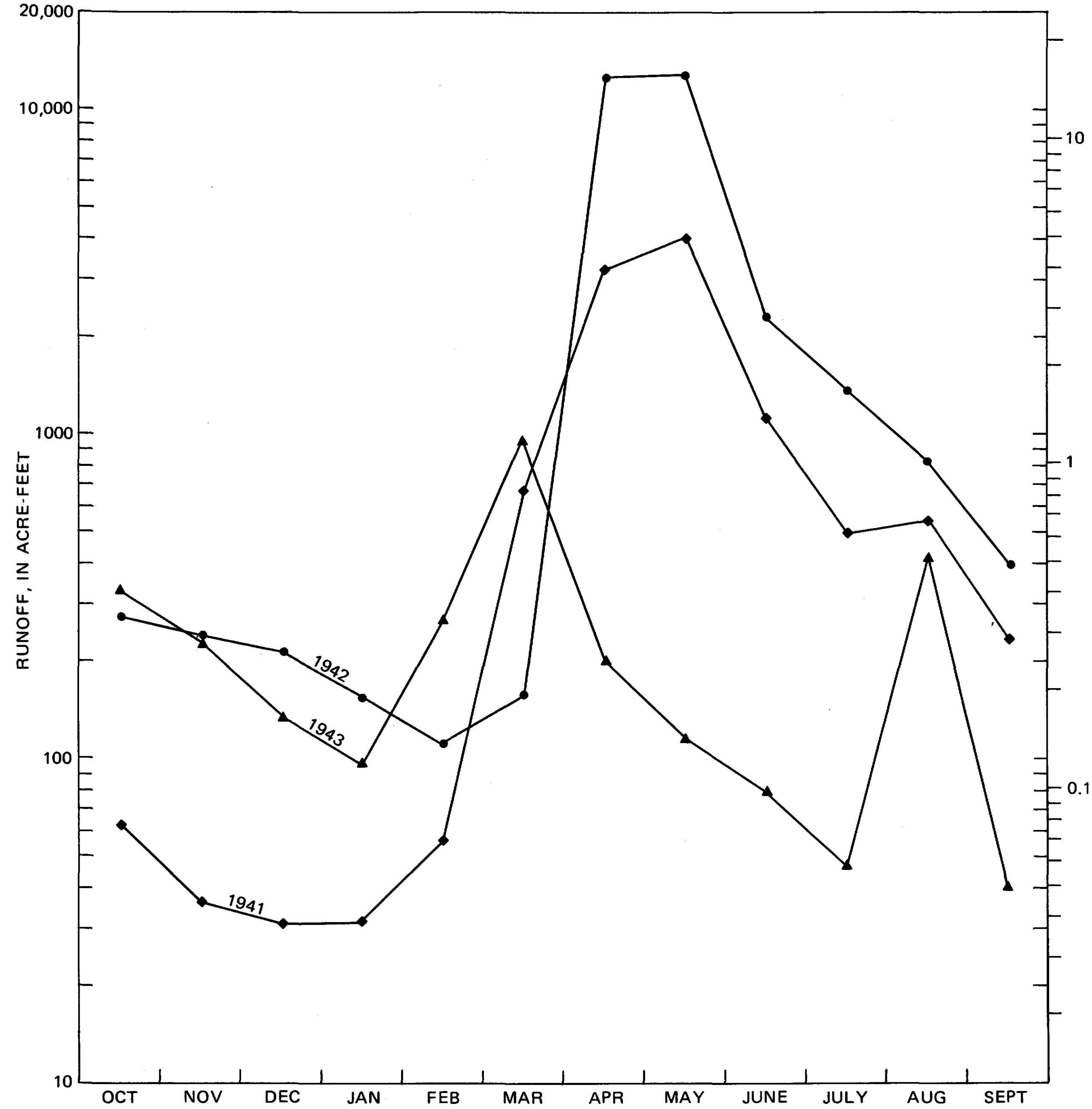


FIGURE 6. — Mean monthly runoff from Piceance Creek near Rio Blanco.

been equaled or exceeded during the period of record, and they are one measure of flow variability. Flow-duration curves for Piceance Creek below Ryan Gulch and Piceance Creek at White River are shown in figure 9. The record for Piceance Creek at White River was adjusted to the 9-year period of record at the gage below Ryan Gulch, using the technique presented by Searcy (1959). The duration curves are based on the discharge measured at the gages. Therefore, the shape of the curve is affected by irrigation practices.

The shape of the flow-duration curve is determined by the hydrologic and geologic characteristics of the drainage basin. Irrigation takes place in Piceance Creek drainage from March to early November, or about 65 percent of the year. The slope of the curves in figure 9 steepens between the 35-percent and 99.99-percent values. The shape of the lower part of the curves is typical of streams having little ground-water discharge to support baseflow. However, consumptive use reduces discharge and causes the duration curves to steepen at

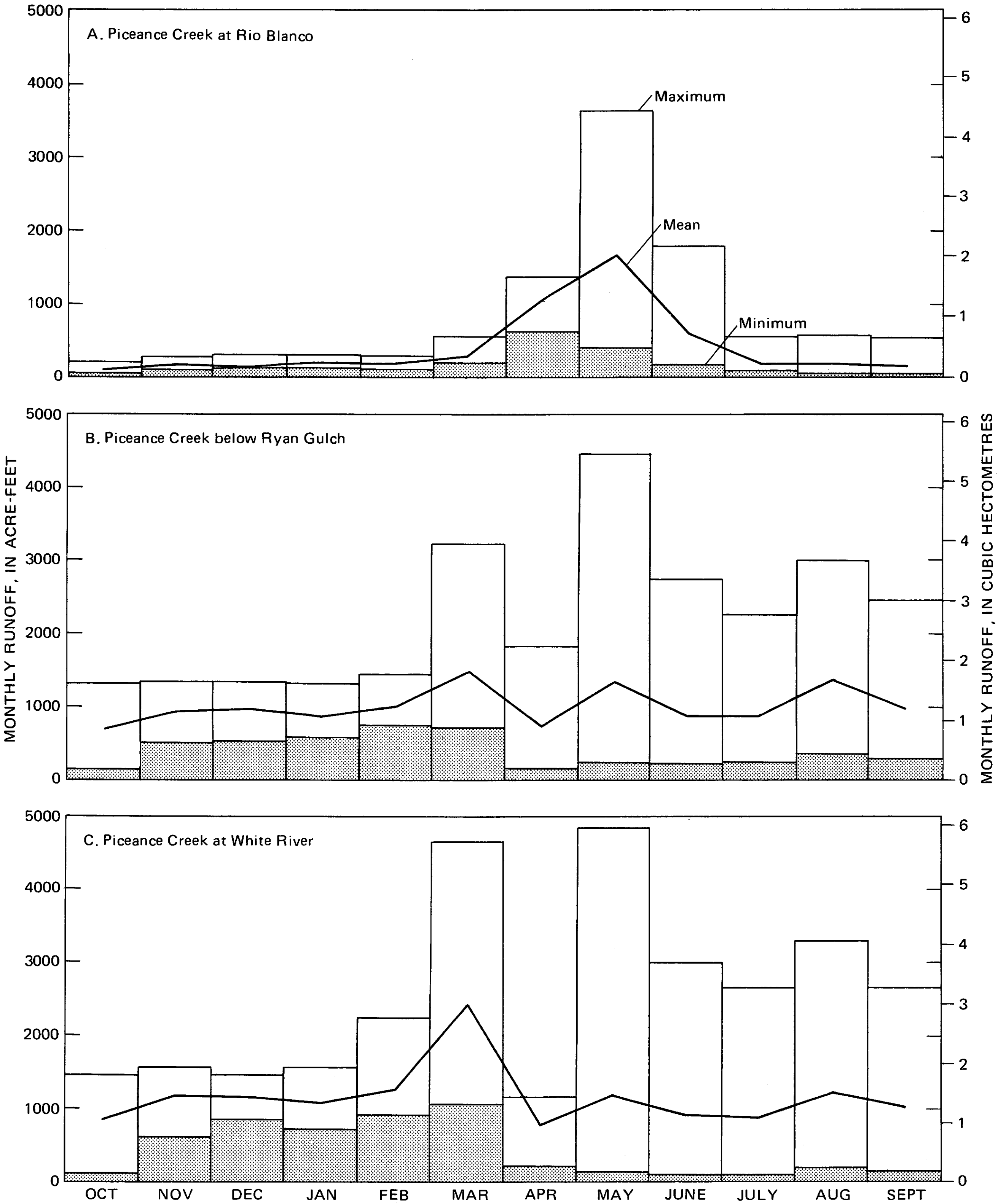


FIGURE 7. — Maximum, minimum, and mean monthly runoff from Piceance Creek at Rio Blanco, below Ryan Gulch, and at White River.

the low end. To be indicative of the natural flow conditions, the lower parts of the curves in figure 9 should have a larger magnitude and a much flatter slope. Likewise, the larger flows resulting from snowmelt are

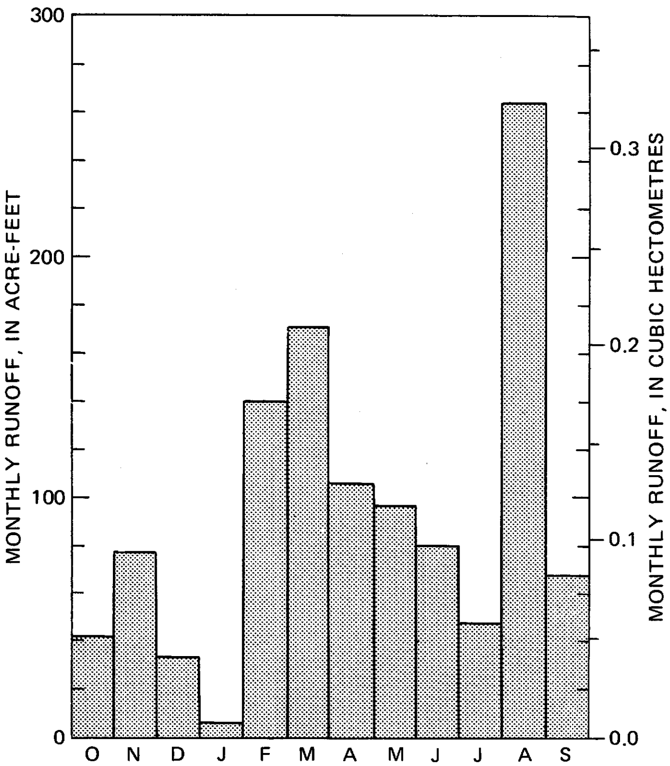


FIGURE 8. — Monthly runoff from Yellow Creek near White River, 1973 water year.

greatly reduced by irrigation. To reflect natural conditions, the upper part of the curves should be of a larger magnitude and a somewhat flatter slope.

The flow-duration curve for the 1973 water year at Yellow Creek near White River is shown in figure 10. The record was not extended because no reasonable relationship can be developed from a single year of record; therefore, it should not be compared directly with the curves for Piceance Creek based on 9 years of record. The low-flow end of the duration curve is typical for streams having little ground-water discharge. The high flow end of the curve is very steep, which is typical for streams where summer thunderstorms produce the peak flows. However, additional streamflow records on Yellow Creek may alter the shape.

LOW-FLOW ANALYSIS

The discharge records for Piceance Creek show two seasonal low-flow periods. The period of lowest flow normally occurs during the spring and summer months (April through October) as the result of irrigation practices. The second occurs during the winter months (December through February) owing to baseflow recession. To examine the mean flow and recurrence interval for low-flow periods of various length, low-flow frequency analyses were run on the summer and winter low-flow periods, using the 9 years of record for the gage on Piceance Creek below Ryan Gulch. The results for the winter period were adjusted (Riggs, 1972), using the 18-year record from the gage at Willow Creek above diversions, near Ouray, Utah—a hydrologically similar basin. The Willow Creek gage is about 60 miles (96.5 km) west of the Piceance basin. Attempts to adjust the summer period produced questionable results, owing to irrigation effects. Therefore, low-flow estimates for the irrigation season are based solely on the available 9 years of record. The summer- and winter-period estimates were used to estimate low-flow frequencies at the Piceance Creek at White River gage, using a linear relationship between discharge at the two stations on Piceance Creek.

The magnitude and duration of summer low flows depend on the size of the previous winter's snowpack and the irrigation practices in the basin. The estimated mean 1-day 20-year-low flow for the summer period is 0.2 ft^3/s (5.7 l/s) at both gages on Piceance Creek while the estimated mean daily 7-day 20-year-low flow is 0.7 ft^3/s (19.8 l/s) at the gage below Ryan Gulch and 0.3 ft^3/s (8.5 l/s) at the gage at White River.

The magnitude of winter low flows depends on the volume of recharge from the previous snowmelt period. For a basin of this region, under natural conditions, this flow may or may not be the lowest flow of the year. For the winter period, the estimated mean 1-day 20-year-low flow is 7.2 ft^3/s (204 l/s) and 9.8 ft^3/s (278 l/s) for the Piceance Creek below Ryan Gulch and at White River, respectively. For the same two sites, the estimated mean daily 7-day 20-year-low flow is 8.2 ft^3/s (232 l/s) and 10.4 ft^3/s (295 l/s), respectively.

No frequency analysis was possible for the single year of record on Yellow Creek. However, the record indicates that the lowest flows occurred during the winter period (December through February).

PEAK FLOWS

Peak flows in Piceance Creek are strongly influenced by irrigation practices. The peak flows resulting from snowmelt in the spring are greatly reduced by irrigation diversions. Peak flows resulting from high-intensity thunderstorms during the summer months are also reduced, depending on the location of the storm within the basin and the number of acres being irrigated between the storm location and the gage. Table 3 lists the annual peak flows and dates of occurence for the years of record at the Piceance Creek gaging stations below Ryan Gulch and at White River. The peak flow for the period of record is 400 ft^3/s (11.3 m^3/s) below Ryan Gulch and 407 ft^3/s (11.5 m^3/s) at White River. Of the nine peaks listed for the gage below Ryan Gulch, seven occur between February and May, indicating snowmelt runoff as their source. Two peaks occurred in late summer as the result of thunderstorms. Comparison of the dates the peaks occurred indicates that peaks resulting from snowmelt occurred at both gages on the

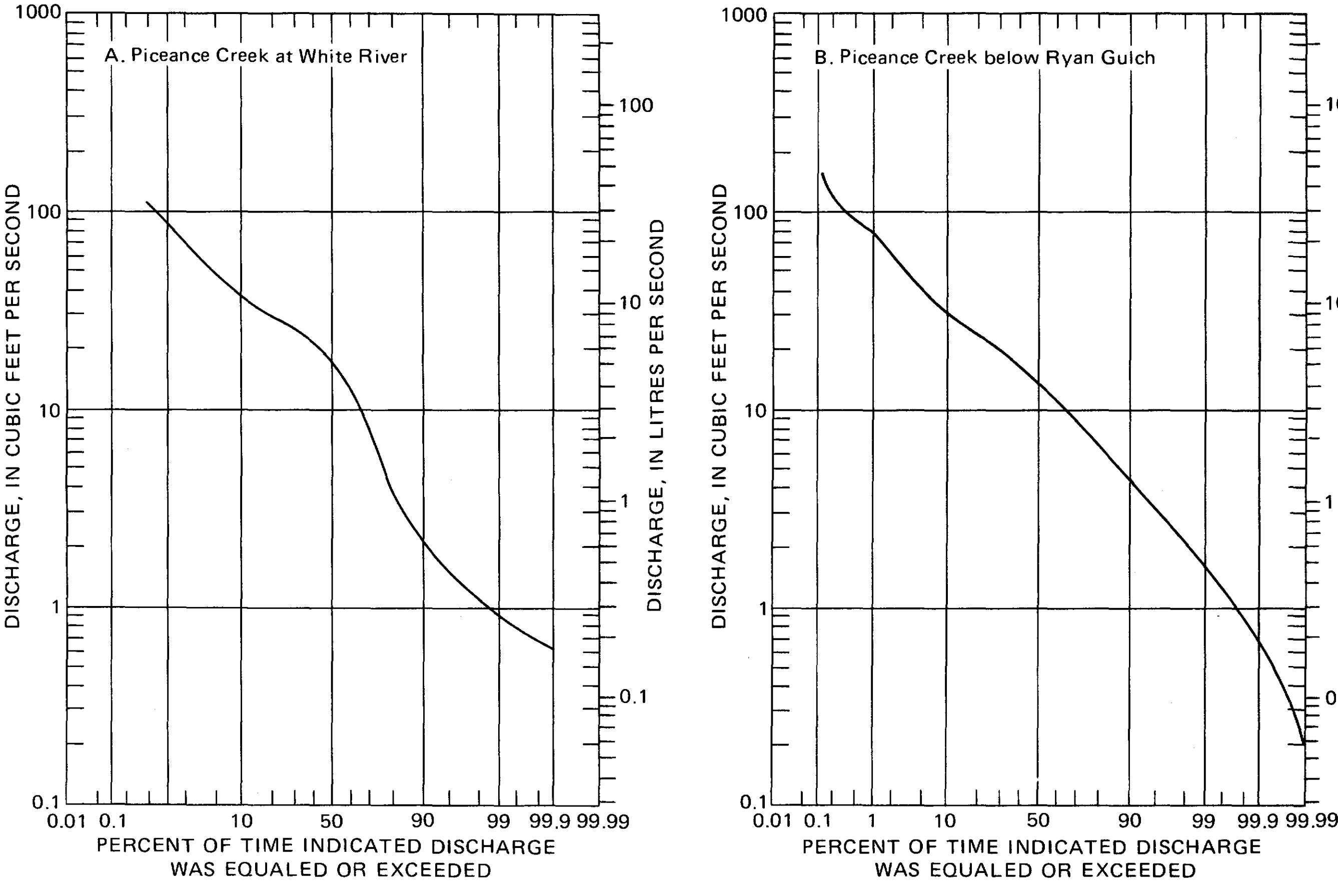


FIGURE 9. — Flow-duration curves for Piceance Creek at White River and below Ryan Gulch.

same date, whereas those resulting from thunderstorms did not. This reflects the influence of thunderstorm location and of irrigation effects on summer peak flows.

The smaller irrigated acreage in Yellow Creek drainage results in smaller effects on peak flows in Yellow Creek than on those in Piceance Creek. The peak flow for the single year of record for Yellow Creek was 468 ft^3/s (13.3 m^3/s) and occurred as the result of an August thunderstorm.

A Log Pearson Type III Flood-Frequency analysis made on the nine peak flows for the gage below Ryan Gulch produced a mean annual flood peak of 170 ft^3/s (4.8 m^3/s). The results of this analysis, which represents expected flood frequencies under current irrigation practice, are shown in figure 11. However, as pointed out in a study of flood-frequency curves by Benson (1960), 9 years of record are not sufficient to adequately define recurrence intervals beyond 10 years. Therefore, the part of the curve in figure 11 beyond the 10-year recurrence interval (dashed line) is highly speculative.

An empirical technique called the index-flood method for estimating magnitude and frequency of floods for any recurrence interval from 1.1 to 50 years, using the basin characteristics of drainage area and mean altitude, was presented by Patterson and Somers (1966) for the Colorado River basin. Using flood-frequency analyses of 342 gaging-station records and the relationship among the mean annual flood, drainage area, and mean altitude, the Colorado River basin was delineated into 23 hydrologic areas. The Colorado River basin was also divided into six homogeneous flood-frequency regions (A to F) on the basis of the slopes of the individual frequency curves. This resulted in the definition of six composite frequency curves relating mean annual floods to floods having recurrence intervals of 1.1 to 50 years. Flood-frequency estimates obtained using the index-flood method are for natural basin conditions and, therefore, exclude irrigation effects.

The 5 years of record for the gage on Piceance Creek at Rio Blanco was used in the Colorado River basin flood-frequency analysis. However, the site was never classified as belonging to a specific hydrologic area or flood-frequency region. Consequently, no peak-flow records from Piceance Creek or Yellow Creek were used to assign the basin to hydrologic area 13 and flood-frequency region C. Rather, it appears that the basin was classified on the basis of similar physiography and climate to adjacent basins having records available for

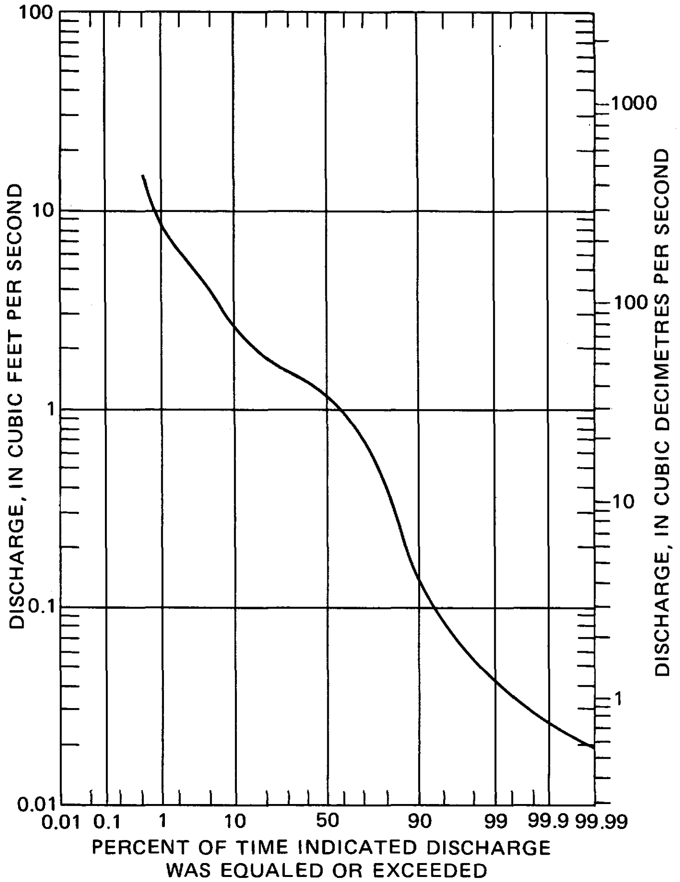


FIGURE 10. — Flow-duration curve for Yellow Creek near White River, 1973 water year.

analysis. Peak flows in region C may occur as the result of either rapid snowmelt or high-intensity thunderstorms.

Using the index-flood method, the estimated mean annual flood for Piceance Creek at the White River is 800 ft^3/s (22.7 m^3/s) and for Yellow Creek near the White River is 390 ft/s (11.0 m^3/s). The curves in figure 12 show the estimated flood-frequency relationships for Piceance Creek and Yellow Creek. The curves were derived using the estimated mean annual flood and the flood-frequency ratios of the mean annual flood to floods recurrence intervals of 1.1 to 50 years. Patterson and Somers (1966) stated that the flood-frequency ratios can only be used with confidence up to the 50-year recurrence interval; however, this relationship was extended to obtain an estimate of the magnitude of the 100-year flood. The curves in figure 12 provide estimates of flood frequencies for natural conditions, without irrigation diversions, in Piceance and Yellow Creek drainages.

Peak flows from small drainages resulting from high-intensity thunderstorms were examined by Meiman (1973). From available rainfall data, Meiman estimated the 100-year design storm and applied this storm to Sorghum Gulch, a 3.72-square-mile (9.63-km^2) basin tributary to Piceance Creek and located on oil-shale lease tract C-b (fig. 1). A peak flow of 117 ft^3/s (3.31 m^3/s) was computed for this storm using the Soil Conservation Service triangular unit-hydrograph procedure (SCS-NEH4, 1971, chap. 16), and a peak flow of 133 ft^3/s (3.76 m^3/s) was computed using the Soil Conservation Service emergency spillway hydrograph-analysis technique (SCS-NEH4, 1971, chap. 21).

TABLE 3. — *Annual peak flows in Piceance Creek below Ryan Gulch and at White River*

[Dash leaders (---) indicate no data available]

Water year	Piceance Creek below Ryan Gulch		Piceance Creek at White River	
	Date	Peak discharge in ft^3/s	Date	Peak discharge in ft^3/s
1965	Aug. 19	190	July 24	174
1966	Mar. 9	400	Mar. 9	407
1967	Feb. 25	75	-------	---
1968	July 28	184	-------	---
1969	Mar. 18	141	-------	---
1970	May 8	104	-------	---
1971	Mar. 27	211	Mar. 27	242
1972	Feb. 23	121	Feb. 23	150
1973	May 26	102	July 20	284

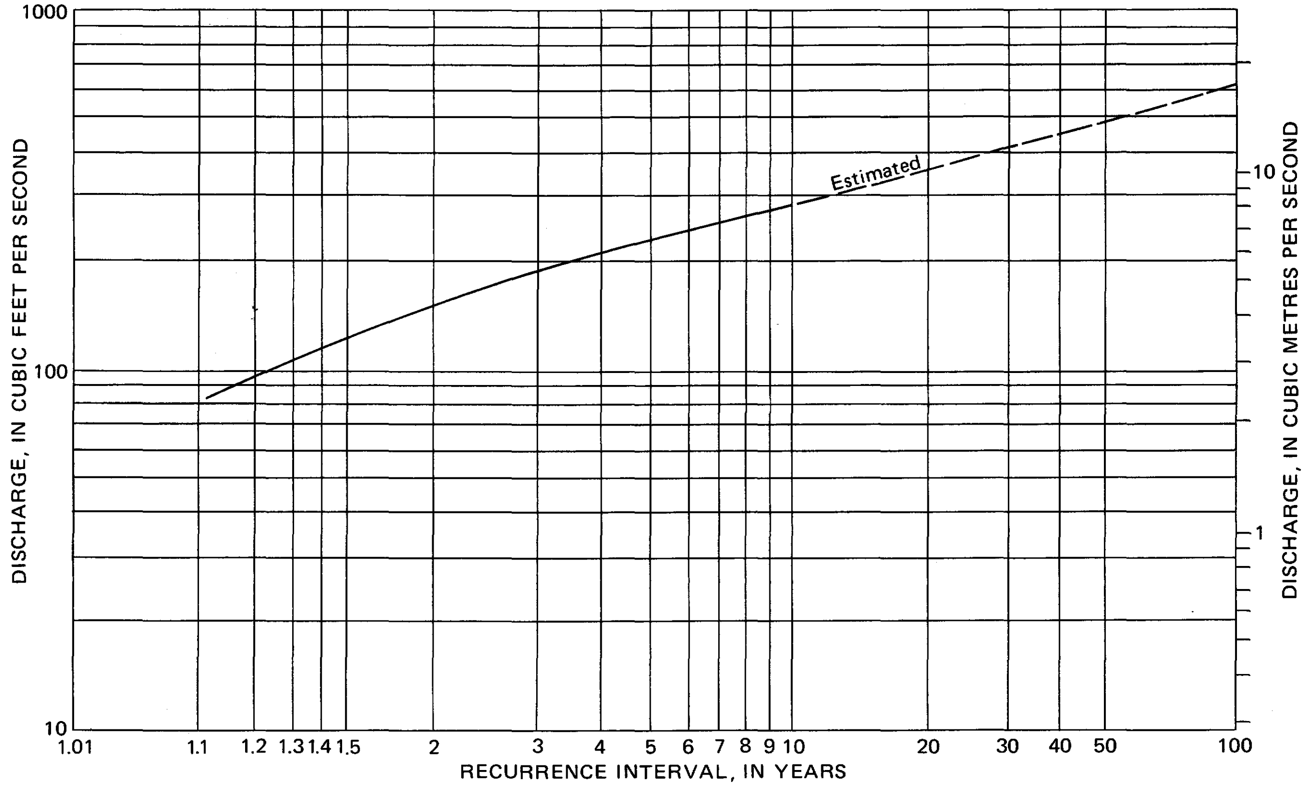


FIGURE 11. — Flood frequencies for Piceance Creek below Ryan Gulch (Log Pearson Type III).

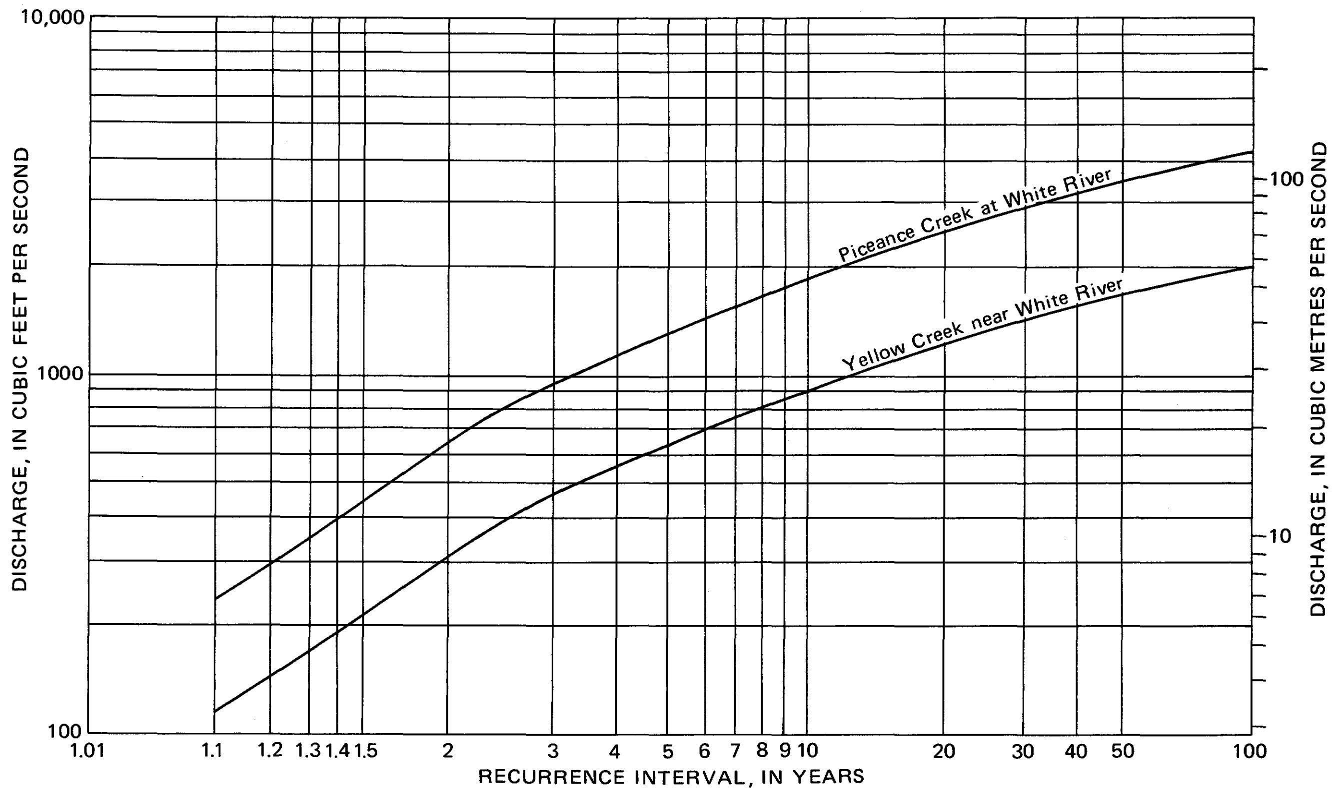


FIGURE 12. — Flood frequencies for Piceance Creek at White River and Yellow Creek near White River (index-flood method).

WATER QUALITY

CHEMICAL QUALITY

Water-quality samples have been collected monthly at three stations and intermittently at several stations on streams and springs. The station numbers and names are listed in table 4. The locations of these stations are shown in figure 13.

Chemical analyses of water samples collected from the stations listed in table 4 indicate that the surface waters of both Piceance and Yellow Creeks can be classified as a mixed bicarbonate type in the upper reaches, grading to a sodium bicarbonate type in the lower reaches. Concentrations of dissolved solids, sodium, chloride, and fluoride all increase in the downstream direction. Coffin, Welder, and Glanzman (1971) graphically showed the increase in sodium concentration in the downstream direction in Piceance Creek and reported an increase in dissolved-solids concentration of from 600 mg/l in the upper reach to 2,000 mg/l at the White River. Ficke, Weeks, and Welder (1974) report monthly specific-conductance measurements made at eight sites on Piceance Creek. The specific-conductance measurements all increase in the downstream direction, indicative of the increasing dissolved-solids concentrations.

The change in chemical composition in the downstream direction with respect to the major cations and anions is shown in figure 14 for Piceance Creek, Black Sulphur Creek, and Yellow Creek, respectively. Samples for the analyses shown were collected over a 30-day period between July and August 1973. Although the samples were not collected on the same date, they show valid trends in chemical changes. The increases in the concentration of dissolved solids, sodium, chloride, and fluoride in the downstream direction are apparent in figure 14. These water-quality changes are the result of contributions to surface runoff from irrigation return flows and from the ground-water discharge from the Uinta and Green River Formations. As discussed later in this report, ground water in the Parachute Creek Member of the Green River Formation—below the Mahogany zone (fig. 2)—generally contains high concentrations of sodium, bicarbonate, chloride, and fluoride. The increasing concentrations of fluoride shown in figure 14 indicate that ground water which originates in the Parachute Creek Member is discharged to Piceance Creek, Yellow Creek, and Black Sulphur Creek.

In addition to changes with movement downstream, the concentration of dissolved solids varies throughout the year. Figures 15 and 16 show the seasonal variation in the concentrations of dissolved solids and discharge measured at the gages on Piceance Creek at White River and below Ryan Gulch (fig. 13, stas. 4, 6) during the 1972 water year. During the high-flow period the dissolved-solids concentration decreased, owing to dilution from snowmelt runoff. During the low-flow period the concentration of dissolved solids increased, owing to the effects of irrigation return flows and ground-water discharge. The discharge was higher at the upstream station than the downstream station from April to September because of irrigation diversions and consumptive use in the reach between the stations. The concentration of dissolved solids is higher at the downstream station throughout the year. This is the result of the increasing concentration of dissolved solids in the ground-water discharge and, to some extent, irrigation return flow downstream from Ryan Gulch.

Numerous springs occur in the reach of Piceance Creek between Ryan Gulch and White River. Several of these springs discharge water that has high concentrations of dissolved constituents. In particular, the concentration of dissolved solids in the water from spring S1 (fig. 13) was found to be 2,610 mg/l and that from spring S2 (fig. 13) was 22,100 mg/l. These samples were collected in June 1973. The water chemistry of both springs is affected by ground water which moves upward from the Parachute Creek Member of the Green River Formation through the Uinta Formation to the stream valley. The concentration of dissolved solids in the ground-water discharge to Piceance Creek increases appreciably downstream from Ryan Gulch as evidenced by springs S1 and S2. Consequently, as shown by figures 15 and 16, the concentration of dissolved solids in Piceance Creek increases downstream from Ryan Gulch, especially during low flows. Although the water chemistry of spring S1 is not greatly different from that in Piceance Creek at station 4, the effects of ground-water discharge on the water chemistry of the stream are measurable a short distance downstream at station 5 (fig. 13). The small but measurable change in water chemistry between stations 4 and 5 is shown in figure 14*A*.

The increase in dissolved solids in the downstream direction in Yellow Creek (fig. 14*C*) also reflects the contribution of ground water from the Parachute Creek Member, which crops out in the lower reach of the stream (pl. 1). Chloride, fluoride, and dissolved-solids concentrations measured at station 7 were 8, 0.4, and 742 mg/l, respectively, whereas those measured at station 8 were 180, 3, and 3,070 mg/l, respectively. Only 200 acres (81 ha) are irrigated in Yellow Creek drainage so that irrigation return flow has a small effect on surface-water quality.

A study of the water quality of the Piceance basin and adjacent areas by Wilbur (1973) reported changes in water quality similar to those discussed above. Everhart and May (1973) reported 1 year of data on the biota and chemistry of Piceance Creek, Yellow Creek, and White River. Their trends in chemical composition and specific conductance were also similar to those reported above. In an analysis for the trace elements of cadmium,

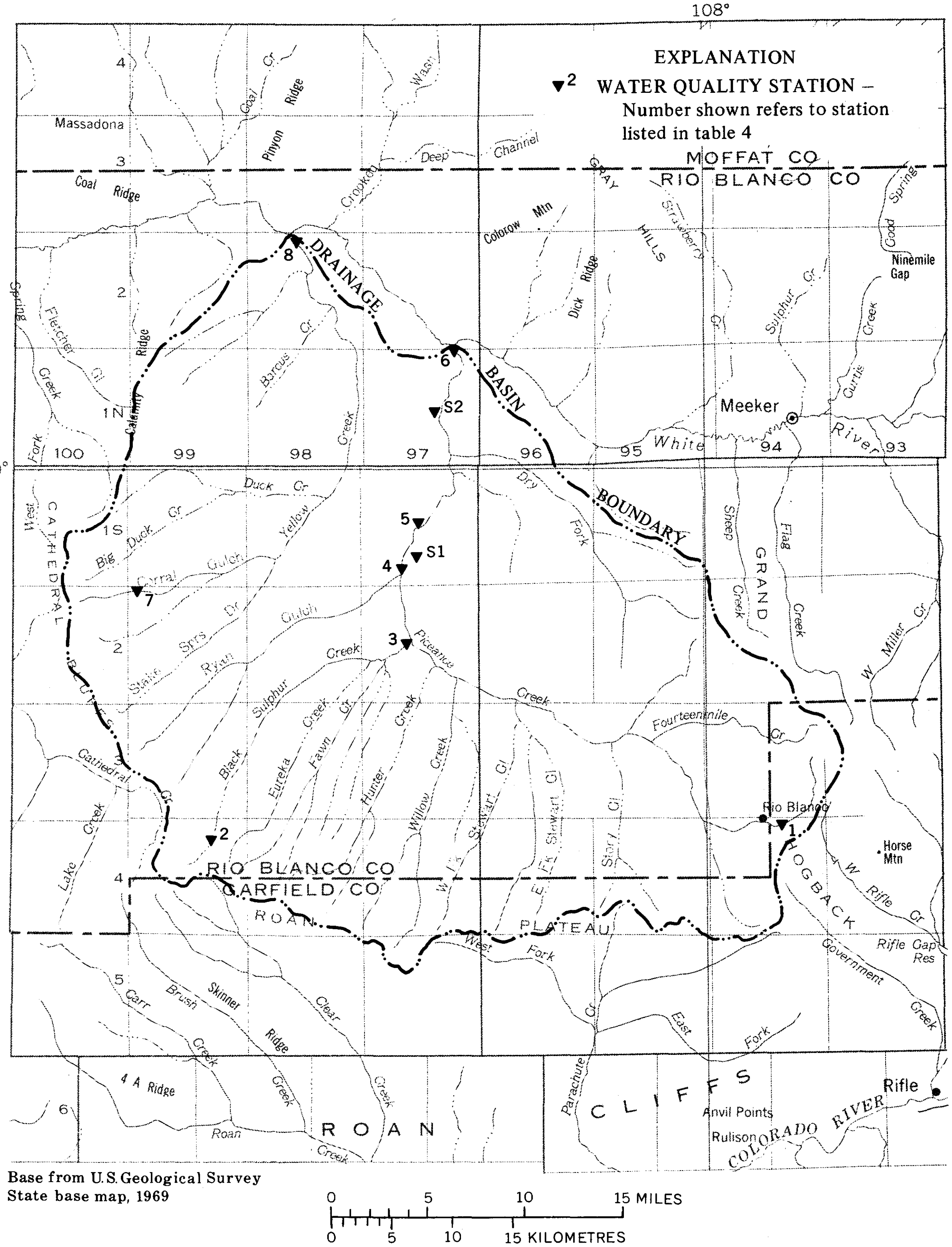


FIGURE 13. — Location of water-quality sampling sites on streams and selected springs.

copper, chromium, iron, lead, manganese, molybdenum, nickel, silver, and zinc, Everhart and May (1973) reported that concentrations of each remained less than 1 mg/l throughout the year with no seasonal trend in their occurence.

In the upper reaches of Piceance Creek and Yellow

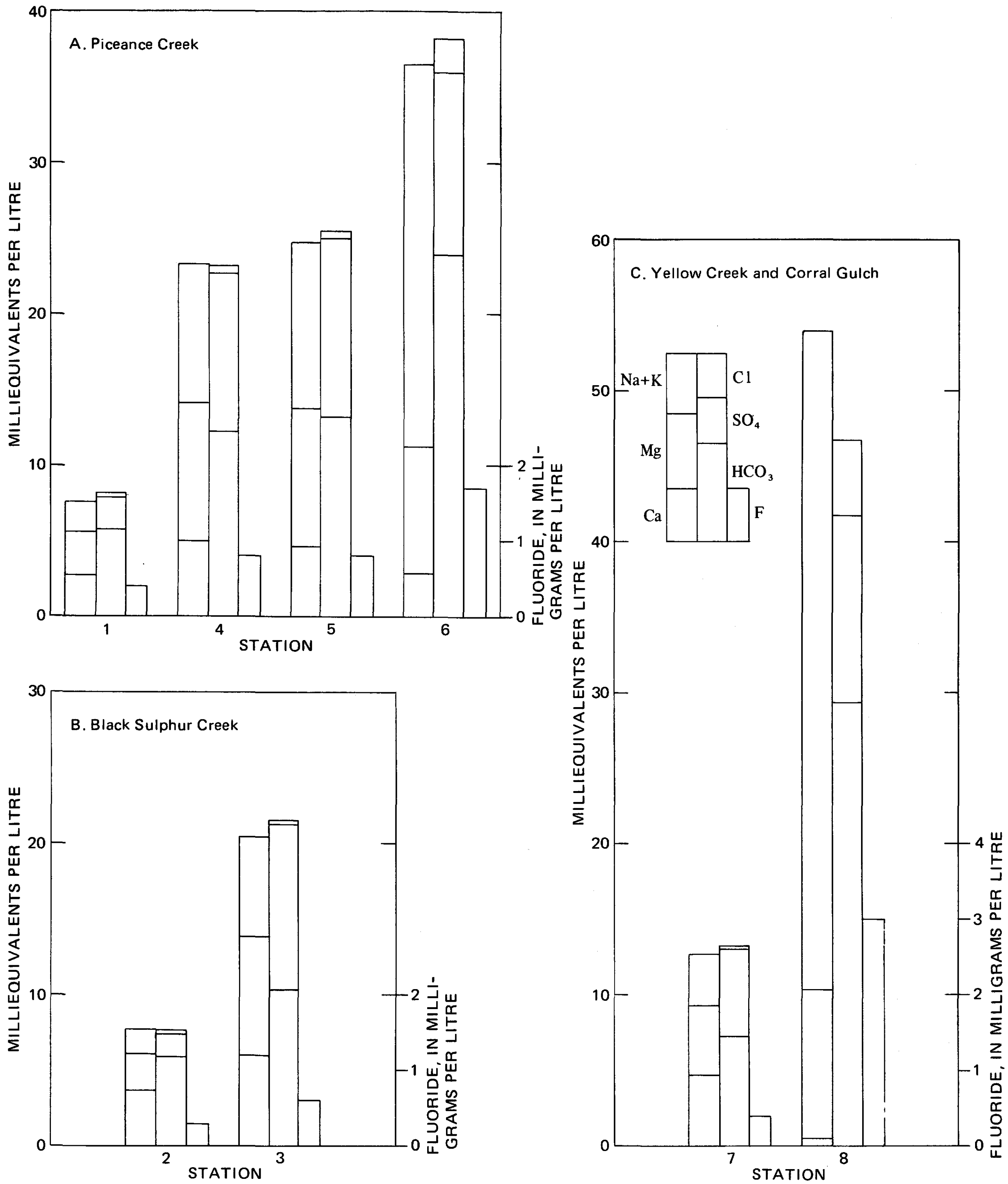


FIGURE 14. — Chemical composition of surface water in the Piceance basin, July–August 1973. Stations located in figure 13.

Creek, water-quality analyses indicate that the sulfate and dissolved-solids concentrations exceed the limits of 250 mg/l and 500 mg/l, respectively, established by the U.S. Public Health Service (1962) for public water supplies. Water in the lower reaches of these streams is unacceptable for domestic use because the fluoride concentrations exceed twice the optimum limit of 1.0 mg/l established by the U.S. Public Health Service (1962).

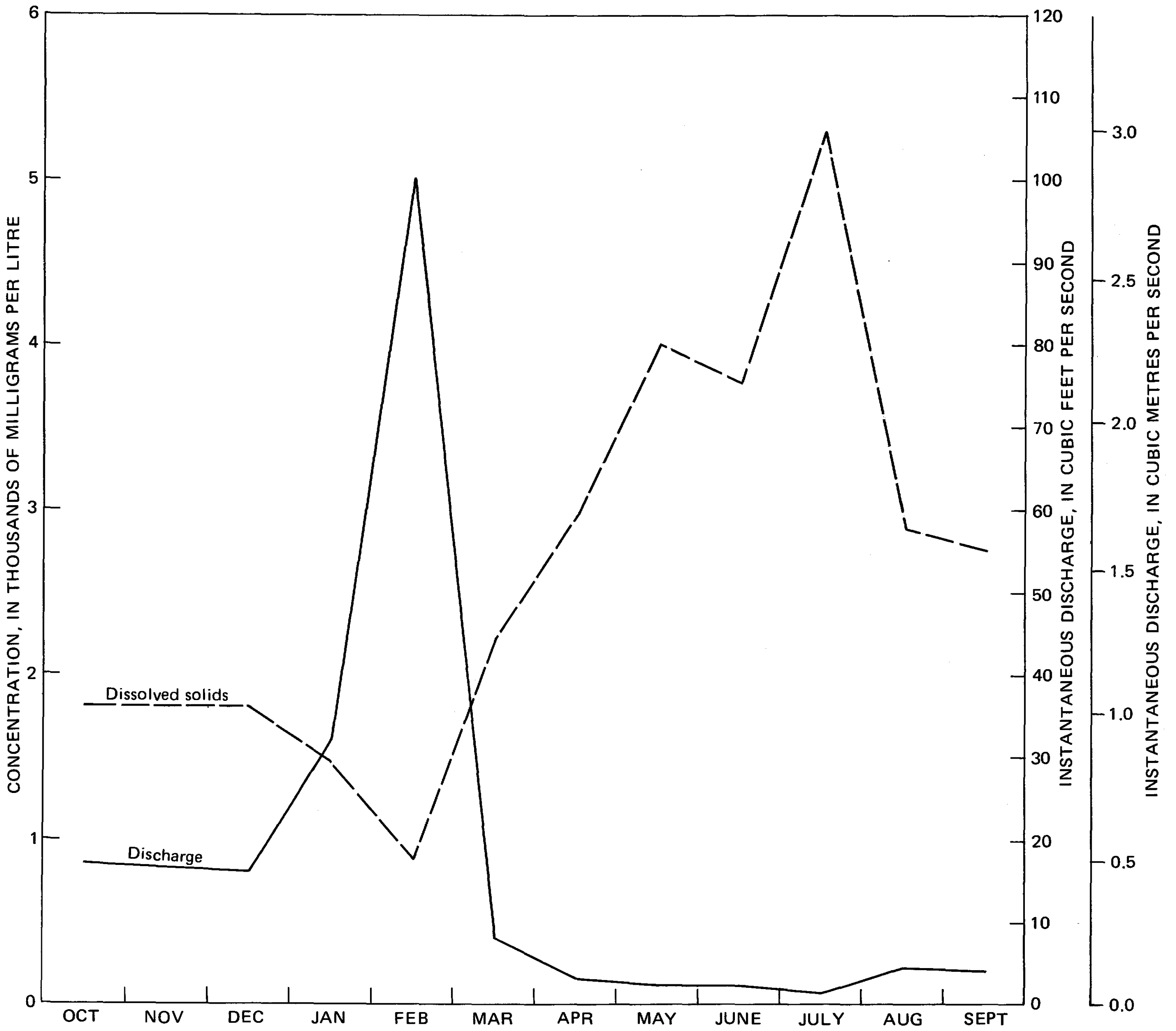


FIGURE 15. — Dissolved-solids concentration and discharge measured in Piceance Creek at White River, 1972 water year.

This limit is based on the average maximum daily temperature of the basin. Based on a dissolved-solids limit of 5,000 mg/l reported by Hem (1970), the water in both creeks during all but the lowest summer flows is acceptable for livestock watering.

The suitability of the water for irrigation varies with location and crop to be irrigated. The increase in dissolved-solids and sodium concentrations in the downstream direction produces an increase in the salinity hazard and sodium hazard. Using the U.S. Salinity Laboratory (1954) procedure for evaluating waters for irrigation, water in Piceance Creek above station 3 (fig. 13) has a low to medium sodium hazard and a high to very high salinity hazard. Water below station 3, which is available during the irrigation season, has a high to very high sodium hazard and a very high salinity hazard.

BIOLOGICAL QUALITY

To date, the most complete analysis of biota in Piceance Creek exists in a report by Everhart and May (1973). They reported the results of monthly sampling for aquatic invertebrates over the period December 1968 to December 1969 at five stations on Piceance Creek. The predominant aquatic invertebrate insects found, from most to least abundant, were the orders of Diptera, Ephemeroptera, Trichopterans, Coleopterans, and Plecopterans. Oligochaetes were the predominant non-insect aquatic invertebrates. The maximum abundance

TABLE 4. — *Water-quality stations on streams and selected springs in the Piceance basin*

Station No.[1]	U.S. Geological Survey station No.	Station name
1-----	394346107561800	Piceance Creek at Rio Blanco.
2-----	394312108290000	Black Sulphur Creek below Figure Four Spring.
3-----	395217108171500	Black Sulphur Creek at Piceance Creek.
4-----	[2,3]09306200	Piceance Creek below Ryan Gulch.
5-----	[2,3]09306210	Piceance Creek near White River.
6-----	[2,3]09306222	Piceance Creek at White River.
7-----	395420108320300	Corral Gulch at Water Gulch.
8-----	[3]09306255	Yellow Creek near White River.
S1-----	395529108173300	Spring below Ryan Gulch.
S2-----	400226108152800	Spring at Alkali Flats.

[1]Stations located in figure 13.
[2]Sampled monthly.
[3]Downstream order number.

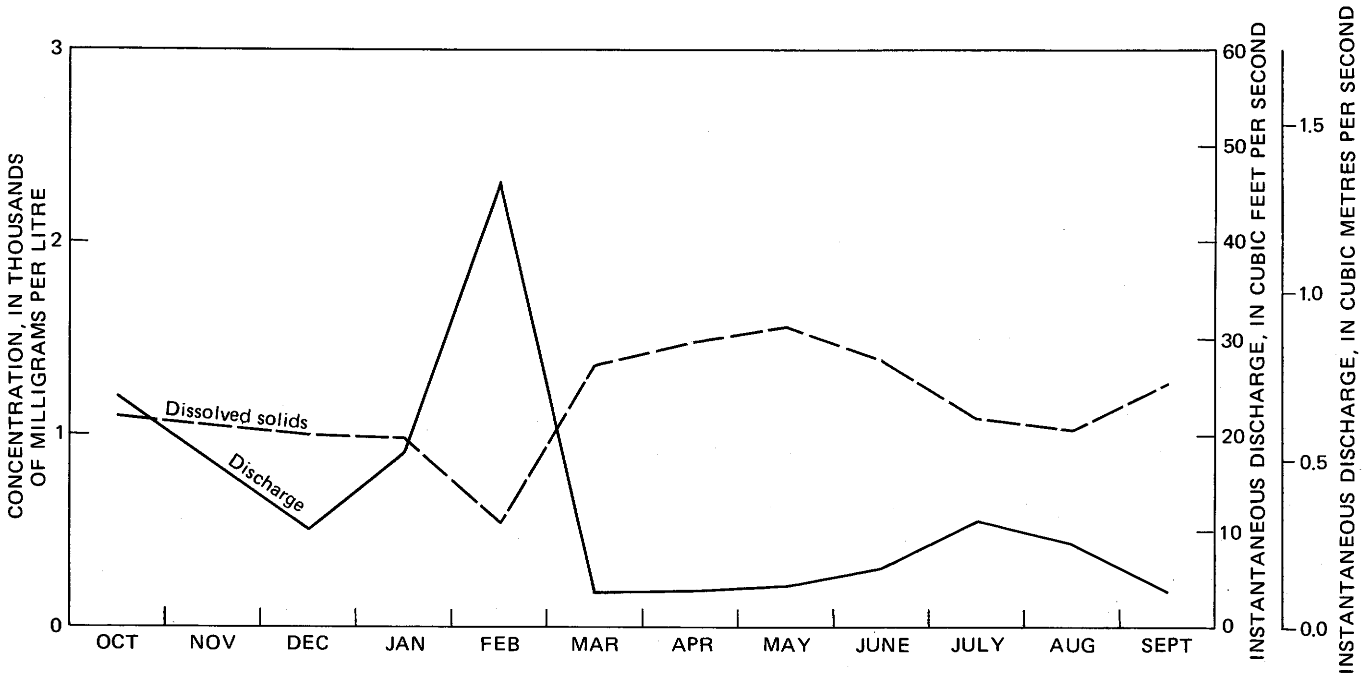


FIGURE 16. — Dissolved-solids concentration and discharge measured in Piceance Creek below Ryan Gulch, 1972 water year.

of aquatic invertebrates occurred in June with a mean of 1,488 organisms per square metre, whereas the low occurred in April with a mean of 140 organisms per square metre. Abundance, composition, and biomass were found to decrease in the downstream direction.

Pettus (1973) made a study of fish population at two sites on Piceance Creek. His samples revealed numerous blue-head mountain sucker (*Catostomus discobolus*) and speckled dace (*Rhimichthyes osculus*) in an upper reach near Story Gulch (fig. 13) but only a few dace and minnows (*Notropis sp.*) in a lower reach near the White River. Two brook trout (*Salvelinus fontinalis*) and one rainbow trout (*Salmo gairdneri*) were also found in the upper reach but were believed to have been planted. Everhart and May (1973) reported finding the same species as Pettus, plus the bonytail chub (*Gila elegans*), black bullhead (*Ictalurus melas*), mountain whitefish (*Prosopium williamsoni*), and two additional species of sucker.

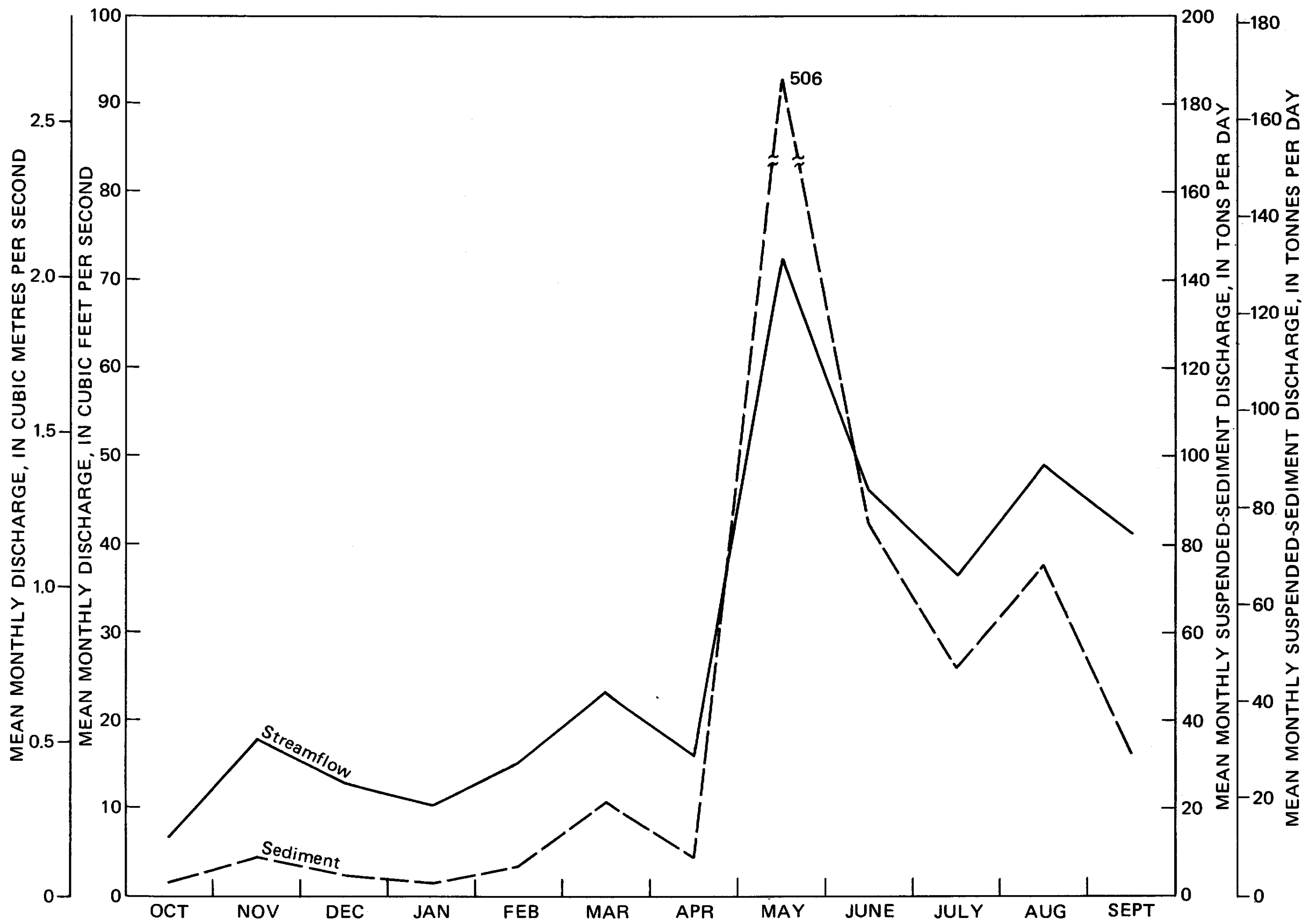


FIGURE 17. — Suspended-sediment discharge and runoff for Piceance Creek below Ryan Gulch, 1973 water year.

SEDIMENT DISCHARGE

Suspended-sediment discharge from Piceance Creek has been monitored at the gage below Ryan Gulch (fig. 13, sta. 4) since October 1972. Samples are automatically collected on a daily basis, and during a rise in stage the sampling frequency is increased. Analysis of the 1973 water-year data gives a total suspended-sediment discharge for the year of about 25,000 tons (22,700 t), or about 0.03 acre-foot per square mile (14.3 m^3/km^2) of drainage area. Figure 17 shows the mean monthly suspended-sediment discharge for the 1973 water year and its relationship to mean monthly runoff. Maximum sediment discharges occured during the high snowmelt runoff period in May, when the mean daily concentrations ranged from 1,000 to 4,000 mg/l. High sediment concentrations were also recorded for thunderstorms during August with maximum concentrations exceeding 1,000 mg/l.

Sediment yields from the Piceance basin and selected areas within the basin were estimated by Frickel, Shown, and Patton (1974) using the Pacific Southwest Inter-Agency Committee (PSIAC) method (Pacific Southwest Inter-Agency Comm., 1968). Sediment yields from 45 sediment-source areas, ranging from 0.5 to 5 mi^2 (1.3 to 13 km^2), were estimated. The sediment-source areas were classified by landform, vegetation, and land-treatment type. Based on the associations of these classifications and the estimated sediment yield, a map of sediment yield for the entire basin was produced. Estimated sediment yields from source areas ranged from less than 0.2 acre-foot per square mile (95 m^3/km^2) to 2.0 acre-feet per square mile (950 m^3/km^2). The total sediment yield to the White River from Piceance and Yellow Creeks was estimated to be about 0.2 acre-foot per square mile (95 m^3/km^2).

Frickel, Shown, and Patton (1974) estimated the sediment yield from the drainage area above the Piceance Creek gage below Ryan Gulch at 0.2 acre-foot per square mile (95 m^3/km^2). Although this estimate includes both suspended and bedload sediment, it is much larger than the 0.03 acre-foot per square mile (14.3 m^3/km^2) suspended-sediment load observed for the 1973 water year. Few conclusions can be drawn from a single year of data, but continued sampling will improve estimates of sediment yield from the basin. Eighteen additional automatic suspended-sediment samplers have been installed in the basin to provide additional data on sediment yield. These stations plus continued analysis of stream-channel cross sections and hillslope erosion transects established by the U.S. Geological Survey in 1972 will provide the necessary information for improved sediment-yield estimates.

GROUND WATER

Ground water occurs throughout the Piceance Basin. The principal water-bearing zones are in the Uinta and Green River Formations. The underlying Wasatch Formation, of Paleocene and early Eocene age, consists of brightly colored clay, shale, and lenticular sandstone. The Wasatch Formation has very little permeability compared with the Green River Formation, owing to a lack of primary and secondary porosity.

The Green River Formation has been divided into several lithologic units based on depositional history. The Garden Gulch Member consists of marlstone and lean oil shale and yields very little water to wells. The Garden Gulch Member is relatively impermeable and forms the lower boundary of the aquifer system in much of the area of the Piceance basin.

The Parachute Creek Member, which overlies the Garden Gulch Member, contains the most permeable rocks in the Green River Formation. Water wells which are open to the Parachute Creek Member yield as much as 1,000 gpm (63 l/s) for short periods although 200 to 400 gpm (13 to 25 l/s) is typical.

The Uinta Formation (the lower part was formerly called the Evacuation Creek Member of the Green River Formation, pl. 1) overlies the Parachute Creek Member and forms the surface rock over most of the basin. Wells completed in the formation yield as much as 300 gpm (19 l/s), although yields of less than 100 gpm (6 l/s) are more common. The depths to the saturated zone may be as much as 500 feet (150 m) on ridges above the stream valleys. However, water can generally be found at an altitude higher than that of perennial streams.

The alluvium is a source of water in the perennial stream valleys, such as Piceance Creek, Yellow Creek, and Black Sulphur Creek. The thickness of the alluvium is as much as 140 feet (43 m) and is generally saturated below stream level. Well yields as large as 1,500 gpm (95 l/s) have been reported by Coffin, Welder, Glanzman, and Dutton (1968). However, the alluvial aquifers are of limited areal extent, generally less than 0.5 mile (0.8 km) in width, and high discharge rates can be maintained only for brief periods of time.

AQUIFER SYSTEM

The principal aquifers in the Piceance basin are in the Uinta and Green River Formation. The principal aquifer system consists of two aquifers separated by a confining layer, as shown in figure 18. Discharge from the bedrock aquifers is mainly to the alluvium along the perennial streams.

Numerous core holes have been drilled in the Piceance basin to obtain data on the occurrence and the kerogen content of the oil shale. In addition, many oil and gas test wells and a few water wells have been drilled. Hydrologic data have been collected from many of these wells. Ficke, Weeks, and Welder (1974) and Weeks and Welder (1974) reported hydrologic data from 97 wells in the basin. The wells for which data have been reported are shown in figure 19. The data contained in the above reports are the basis for the following description and interpretation of the geohydrology of the Piceance basin. To facilitate reference to the basic data, the number assigned to each well in figure 19 is the same as that used in the two data reports.

ALLUVIAL AQUIFERS

DESCRIPTION

The alluvial aquifers are limited to the valley bottoms along the creeks. The aquifers are generally less than 0.5 mile (0.8 km) in width. The thickness of the alluvium is as much as 140 feet (43 m), and the saturated thickness may be as much as 100 feet (30 m). Coffin, Welder, Glanzman, and Dutton (1968) reported a saturated thickness of 100 feet (30 m) in the alluvium of Piceance Creek near well 87 in figure 19. The alluvium is principally composed of sand, gravel, and clay derived from the sandstone and marlstone of the Uinta Formation. Water in the alluvium occurs under both water-table and confined conditions, depending on the occurrence of clay beds.

HYDRAULICS

The transmissivity of the alluvial aquifers is highly variable, depending on the saturated thickness and the occurrence of clay- or silt-size material. Coffin, Welder, and Glanzman (1971) reported that the transmissivity ranges from 2,700 to 20,000 ft^2/day (250 to 1,900 m^2/day) and that the storage coefficient averages 0.20. However, because of the limited areal extent of the aquifer, geologic boundaries greatly influence the drawdown in discharge wells. Aquifer test data presented by Coffin, Welder, Glanzman, and Dutton (1968) clearly show the effects of increased drawdown resulting from the boundaries of the alluvium. Consequently, relatively large pumping rates can be obtained from wells in the alluvium, but the rate can be maintained only for brief periods of time because of the limited areal extent of the aquifers.

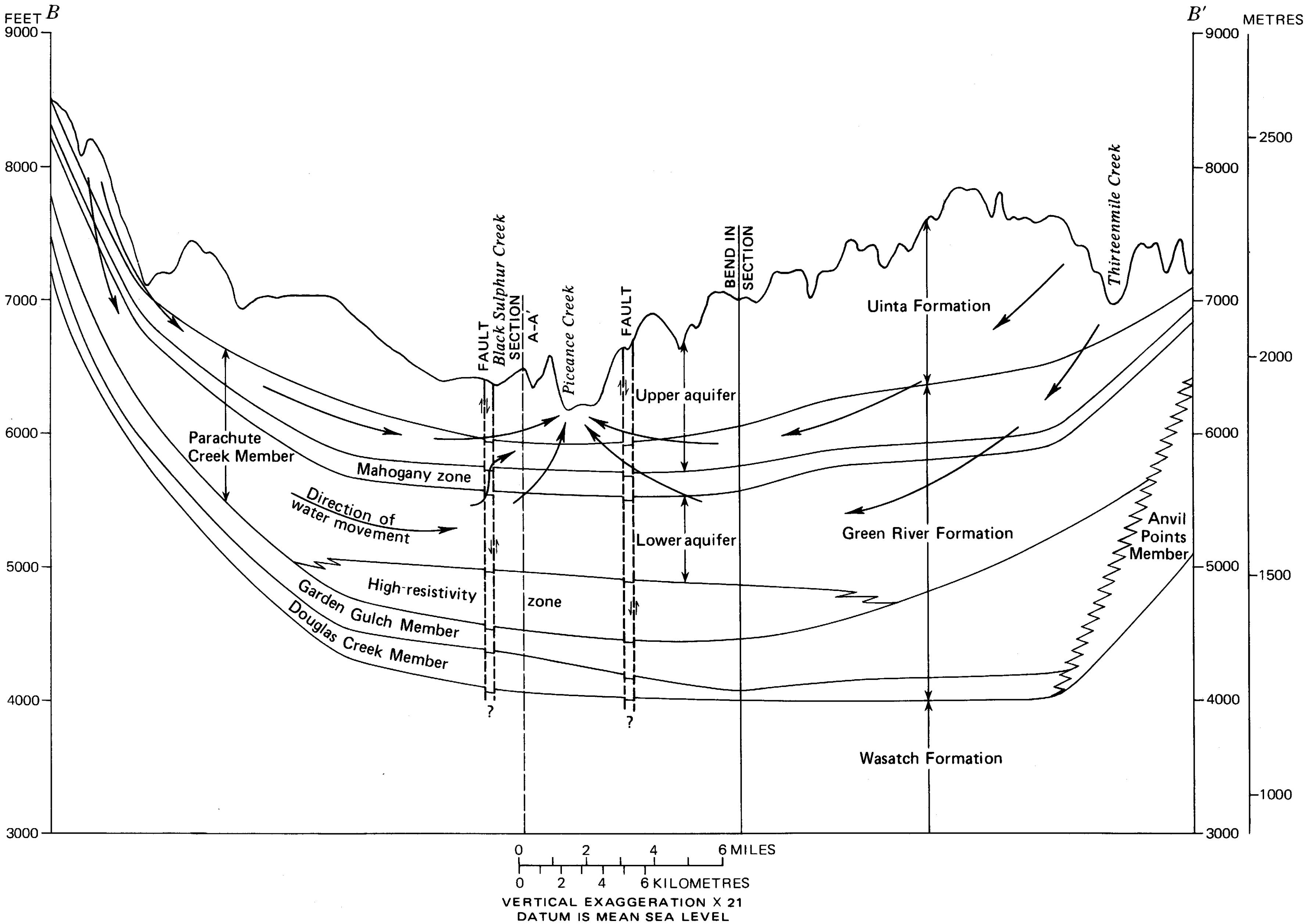


FIGURE 18. — Geohydrologic section through the Piceance basin showing relation of the aquifers to the Green River and Uinta Formations. Section located in figure 1.

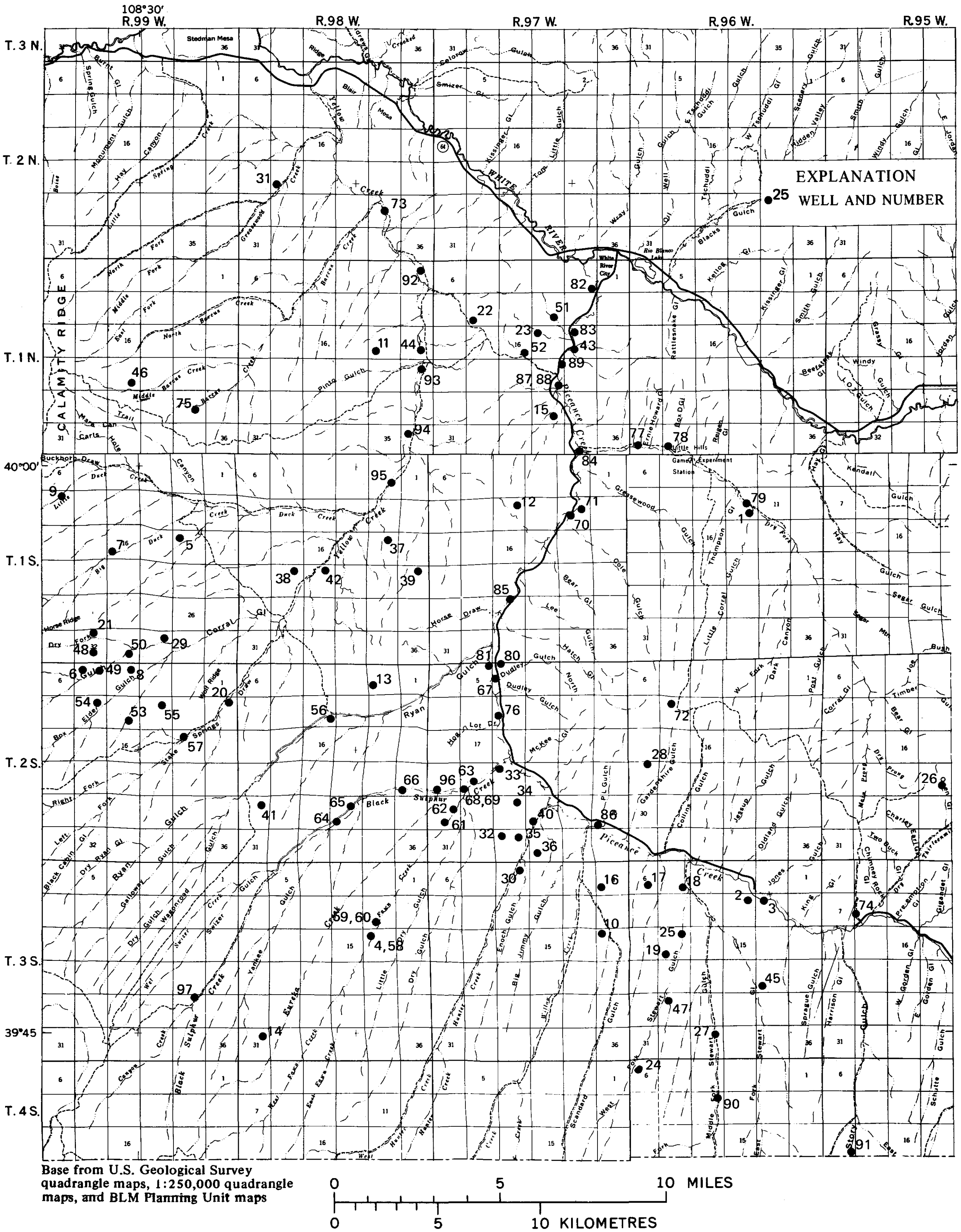


FIGURE 19. — Location of wells in the Piceance basin used by Ficke, Weeks, and Welder (1974) and by Weeks and Welder (1974).

UPPER AQUIFER

DESCRIPTION

The upper aquifer consists of fractured, lean oil shale (marlstone) of the Parachute Creek Member above the Mahogany zone and the fractured marlstone, siltstone, and sandstone of the Uinta Formation (fig. 18). The permeability of the aquifer is mainly due to secondary, or fracture, porosity. The siltstone and sandstone beds of the Uinta Formation have been cemented by precipitates from percolating water resulting in very low primary porosity. Consequently, the marlstone beds are generally better conductors of water because they are more highly fractured than the sandstone beds.

The upper aquifer is complicated by a series of marlstone and sandstone beds with varying permeabilities and degrees of confinement. The aquifer is generally confined by low-permeability sandstones but may be unconfined in many locations, particularly in outcrop areas. Many of the marlstone beds in the Uinta Formation contain perched water-bearing zones that are not part of the upper aquifer. These marlstone beds occur in the ridges between stream valleys. The perched water bodies can usually be identified by the occurrence of springs above the valley bottom in outcrop areas.

HYDRAULICS

The transmissivity of the upper aquifer has been estimated by aquifer test data from 26 wells. The transmissivity values range from 8 to 1,000 ft^2/day (0.7 to 9.0 m^2/day). Figure 20 shows the locations of the 26 wells used to estimate the transmissivity and the values computed from aquifer tests. Most of the data were collected from oil-shale core holes. Consequently, the data are concentrated in the vicinity of the prototype lease tracts (fig. 1) and are not well distributed. The data are highly variable, which is to be expected in a nonhomogeneous fractured-rock aquifer. However, the aquifer is thin on the west side of the basin and thickens eastward, and the transmissivity tends to increase from west to east.

The transmissivity variability probably results from the relatively small area of influence of the well during testing. Locally, in the immediate vicinity of the well, the transmissivity may be very large (or small) compared with the regional value. Thus, aquifer tests having a small area of influence do not, necessarily, result in transmissivity values typical of the region.

Nearly all wells in the basin have been drilled for purposes other than hydrologic testing. Wells are rarely spaced close enough together to be used as observation wells during aquifer testing. Consequently, the aquifer storage coefficient has been determined from aquifer test data at only six sites in the basin. The results of these tests are summarized in table 5. Only one aquifer test was conducted in wells open only to the upper aquifer, two tests were conducted in wells open to both the upper and lower aquifers, and three tests were conducted in wells open only to the lower aquifer. On the basis of these few data, the storage coefficient of the upper aquifer is probably of the order of 10^{-3}. In the outcrop areas where the aquifer is unconfined, the specific yield of the upper aquifer is probably between 10^{-2} and 10^{-1}.

CONFINING LAYER

DESCRIPTION

The upper and lower aquifers are separated by the Mahogany zone (fig. 18), an interval of rich oil shale 100 to 200 feet (30 to 60 m) thick. Within the Mahogany zone, an interval ranging from 3 to 10 feet (1 to 3 m), known as the Mahogany bed, is probably the principal confining layer. Samples of the Mahogany bed have assayed as high as 79 gallons of oil per ton of shale (330 l/t; Donnell, 1961, p. 855). Correlations of fracture density and kerogen content indicate that the oil shale which is rich in kerogen is more resistant to fracturing than the lean shale. Consequently, the Mahogany zone is less permeable than the rocks immediately above or below it. The Mahogany zone persists throughout the basin and effectively separates the upper and lower aquifers both chemically and hydraulically, except in the recharge and discharge areas.

TABLE 5. — *Storage coefficients determined by aquifer tests in the Piceance basin*

Well No.[1]	Aquifer tested	Storage coefficient
3	Lower	1×10^{-4}
4	do	7×10^{-4}
29	Upper and lower	1×10^{-3}
35	do	6×10^{-4}
44	Lower	4×10^{-4}
58	Upper	1×10^{-3}

[1]Well locations shown in figure 19.

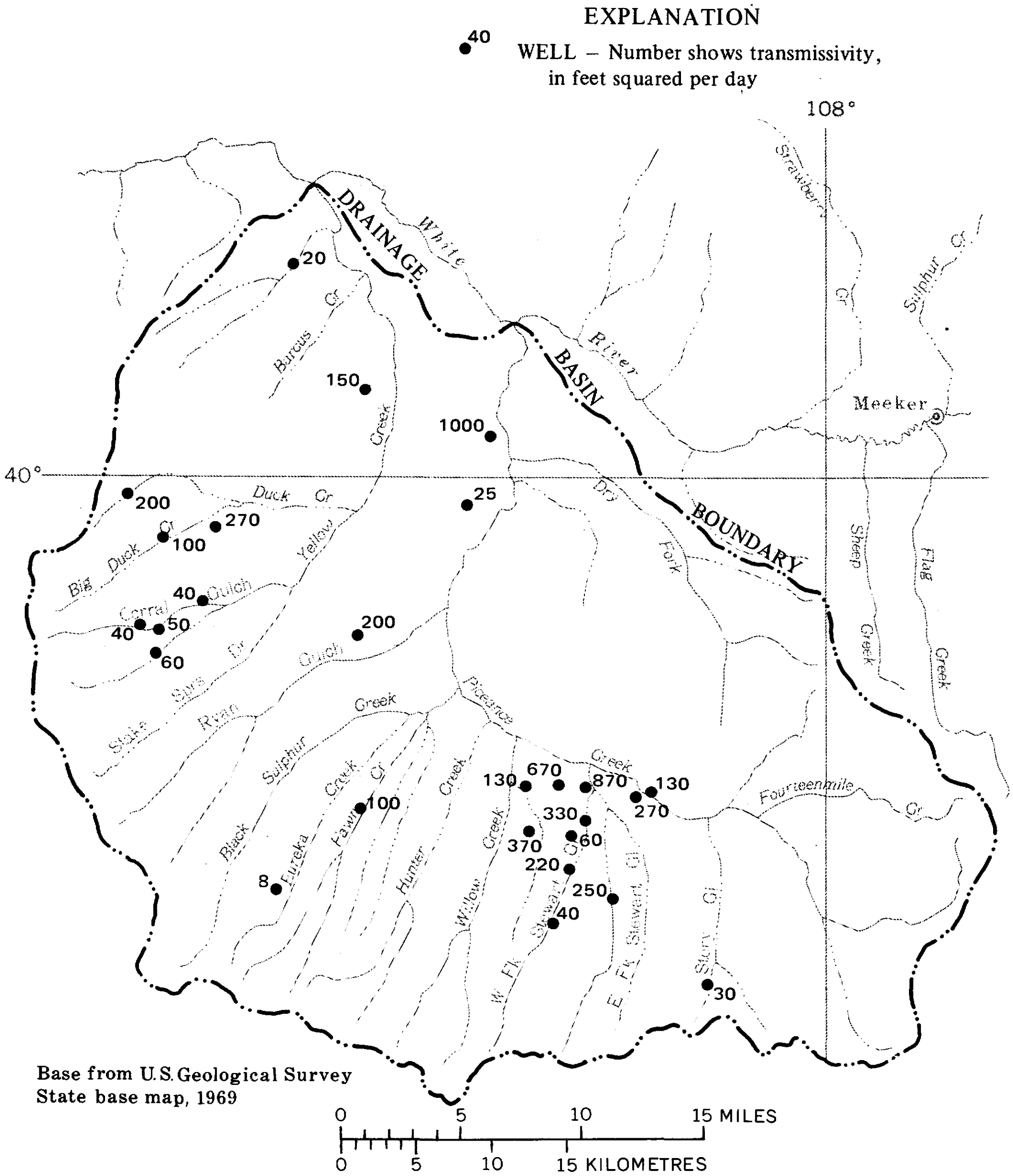


FIGURE 20. — Distribution of transmissivity in the upper aquifer.

HYDRAULICS

The Mahogany confining zone is fractured and permits the vertical exchange of water between the aquifers. The vertical hydraulic conductivity of the Mahogany zone has not been adequately determined.

Ficke, Weeks, and Welder (1974) and Weeks and Welder (1974) reported data from aquifer tests conducted in isolated intervals in the Mahogany zone. The data were collected by the U.S. Geological Survey from wells 6, 7, 10, 12, 13, 14, 29, 30, 43, and 52 in figure 19. The data indicate that the hydraulic conductivity of the Mahogany zone may be as large as 0.37 ft/day (0.11 m/day) at well 7. However, tests in selected intervals of the Mahogany zone in wells numbered 6 and 13 reported by Weeks and Welder (1974) resulted in no measureable hydraulic conductivity. Although the results of these tests are helpful in estimating the hydraulic conductivity, the tests are designed to measure horizontal, not vertical, hydraulic conductivity.

Aquifer tests designed to measure the vertical hydraulic conductivity of the Mahogany zone were conducted at only one site in the Piceance basin. These tests were conducted at wells 4, 58, 59, and 60 (fig. 19) in conjunction with Project Rio Blanco (Knutson and others, 1973). The aquifer tests were repeated several times, using pumping rates of 77 to 135 gpm (4.8 to 8.5 l/s) for periods of about 1 day. No vertical hydraulic conductivity in the Mahogany zone could be measured at the site.

The vertical hydraulic conductivity of the Mahogany zone has not been determined. However, the Mahogany zone is fractured and generally permits the vertical movement of water between the upper and lower aquifers. As will be shown later in this report, there are over 1,200 feet (365 m) of head change in the aquifers between the recharge area and the discharge area, but the head difference between the aquifers rarely exceeds 100 feet (30 m). If the Mahogany zone were impermeable, much larger head differences would be developed between the upper and lower aquifers than have been observed. Consequently, the Mahogany zone must be generally permeable, although the vertical hydraulic conductivity may be small.

LOWER AQUIFER

DESCRIPTION

The lower aquifer consists of the fractured oil shale and marlstone of the Parachute Creek Member underlying the Mahogany zone (fig. 18). The secondary porosity and permeability of the lower aquifer have been enhanced by the solution of minerals—principally nahcolite, a sodium bicarbonate mineral. In the north-central part of the basin, soluble minerals originally may have made up as much as 20 percent of the volume of the lower part of the Parachute Creek Member. This estimate is based on the volume of soluble minerals contained in cores from the high-resistivity zone (fig. 18). The lower aquifer is frequently referred to as the leached zone because of the leaching of soluble minerals by percolating water which results in low resistivity on electric logs (fig. 3).

The lower aquifer is underlain by low-permeability deposits. In the central part of the basin, the high-resistivity zone forms the base of the lower aquifer. Here, the shale is rich in kerogen, the salts are in place, and the fracture density is very low, indicating low permeability. The high-resistivity zone is part of the Parachute Creek Member of the Green River Formation and occurs where the member is thickest. Elsewhere, the Garden Gulch Member, or its equivalent, forms the base of the lower aquifer. The Garden Gulch Member is similar to the Parachute Creek Member except that it is generally much lower in kerogen and carbonate content. The member is characterized by papery to flaky shale beds which are far less permeable than the overlying leached zone of the Parachute Creek Member.

HYDRAULICS

The transmissivity of the lower aquifer has been estimated on the basis of aquifer test data from 20 wells. The areal distribution of the data are shown in figure 21. The data are highly variable, and values are as large as 1,940 ft^2/day (180 m^2/day). Coffin, Welder, and Glanzman (1971) reported that the transmissivity of the leached zone is as much as 2,700 ft^2/day (250 m^2/day). As discussed previously, aquifer test data represent a small area of influence, and the resultant transmissivity may not be typical of the region.

The leached zone is well developed in the north-central part of the basin, and the transmissivity is greatest there. The transmissivity of the lower aquifer is controlled by the structure of the basin and the occurrence of soluble minerals. Fracturing should be greatest along the major structural axis of the basin (Donnell, 1961, p. 860), where the rock stress is greatest. Depending on the concentration of dissolved minerals in the ground water, the solution of minerals should increase in the direction of flow, which is from the basin margins toward the north-central part of the basin. The transmissivity should generally increase from the southeast to the northwest along the major structural axis of the basin.

The storage coefficient of the lower aquifer has been computed from aquifer test data at three sites in the Piceance basin. The results of these tests are presented in table 5. The data indicate that the storage coefficient of the lower aquifer is of the order of 10^{-4}. In outcrop areas where the lower aquifer is not confined, the specific yield of the lower aquifer should be about 10^{-1}.

GEOHYDROLOGY

RECHARGE AREA

Recharge to the aquifer system occurs principally from snowmelt during the spring. During the summer months, rainfall is lost as direct runoff or goes to meet the soil moisture deficiency, which is subsequently evapotranspired. Probably little if any rainfall infiltrates and percolates to the saturated zone of the ground-water system except in the alluvium. On the other hand, several inches of water may accumulate in the winter snowpack. In the spring this water in storage is released slowly, allowing ample opportunity for the melt to infiltrate the soil, increase the soil-moisture content to field capacity, and percolate to the saturated zone. The process is more effective at the higher altitudes, where the most water is in storage as snow. Recharge to the aquifer system is most effective in the areas of the basin which are above an altitude of 7,000 feet (2,130 m), where about 65 percent of the total volume of November to March precipitation occurs.

In the recharge area, water from the upper aquifer moves downward through the Mahogany zone to recharge the lower aquifer. Generally, ground water in both the upper and lower aquifers flows from the recharge areas at the basin margins toward the north-central part of the basin.

DISCHARGE AREA

In the discharge areas, water moves upward from the lower aquifer through the Mahogany zone to the upper

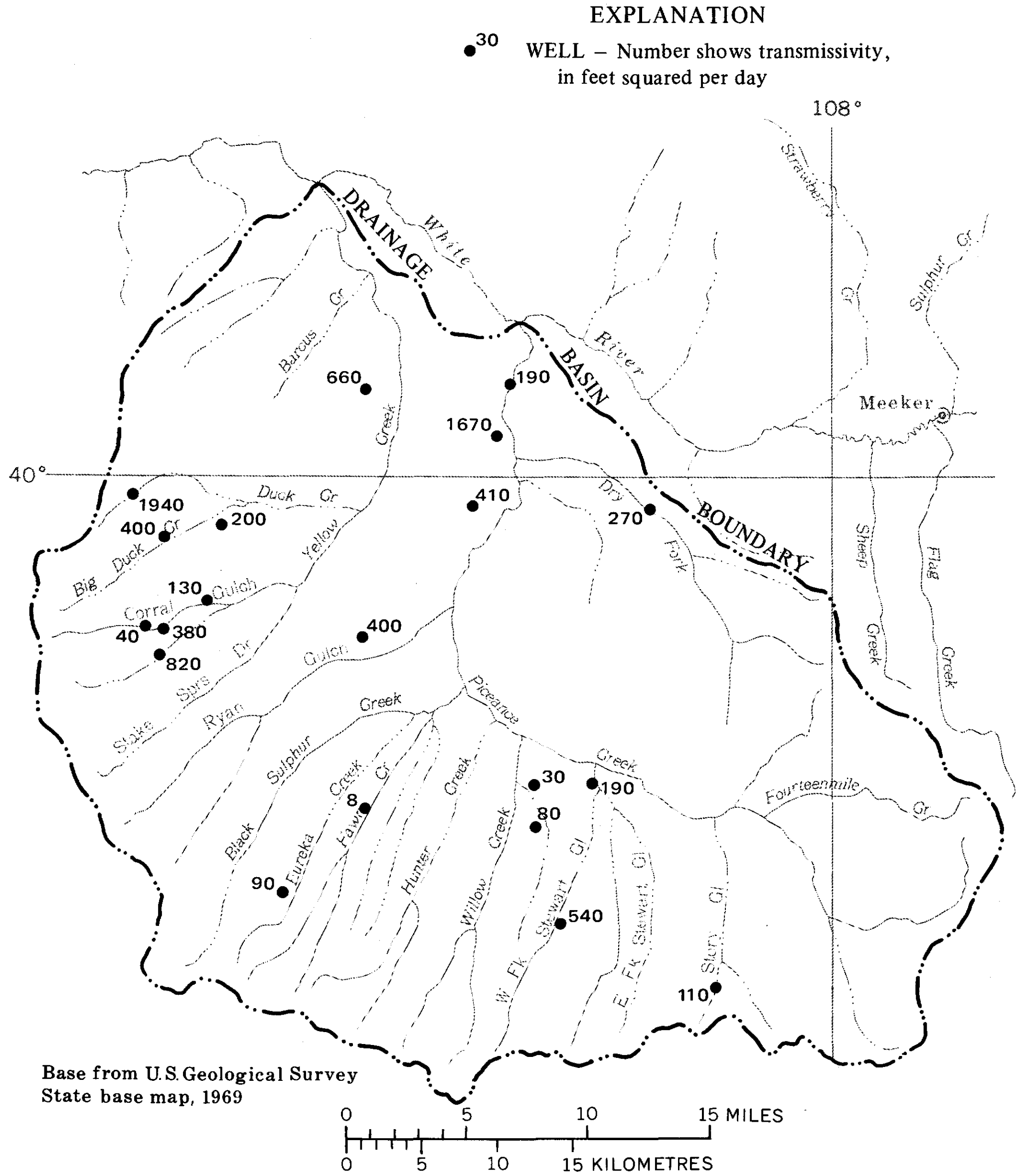


FIGURE 21. — Distribution of transmissivity in the lower aquifer.

aquifer. Water is discharged from the upper aquifer to the alluvium through the valley floors and by springs along the valley walls. The ground water flows through the alluvium to the streams and is lost from the basin by evapotranspiration and discharge to Piceance Creek and Yellow Creek.

Data on discharge and specific conductance have been presented by Ficke, Weeks, and Welder (1974, p. 242) for the White River. A salt balance, based on the data for the reach of the White River from above Piceance Creek to below Yellow Creek, indicates that the entire salt load can be accounted for by surface-water inflow. The result implies that no significant amount of ground-water discharge from the Green River Formation (which has a much greater concentration of dissolved solids than the White River) reaches the White River except through Piceance and Yellow Creeks. As shown on plate 1 and in figure 2, the Wasatch Formation crops out along the White River and prevents ground-water discharge from the Piceance basin to the White River.

GROUND-WATER FLOW

The geohydrology of the Piceance basin is illustrated by figure 22 which is a potentiometric map based on water levels in wells that are open to both the upper and lower aquifers. The altitude of the potentiometric surface varies by more than 1,200 feet (365 m). Because water flows from higher to lower potentiometric levels, flow is from the basin margins to the north-central part

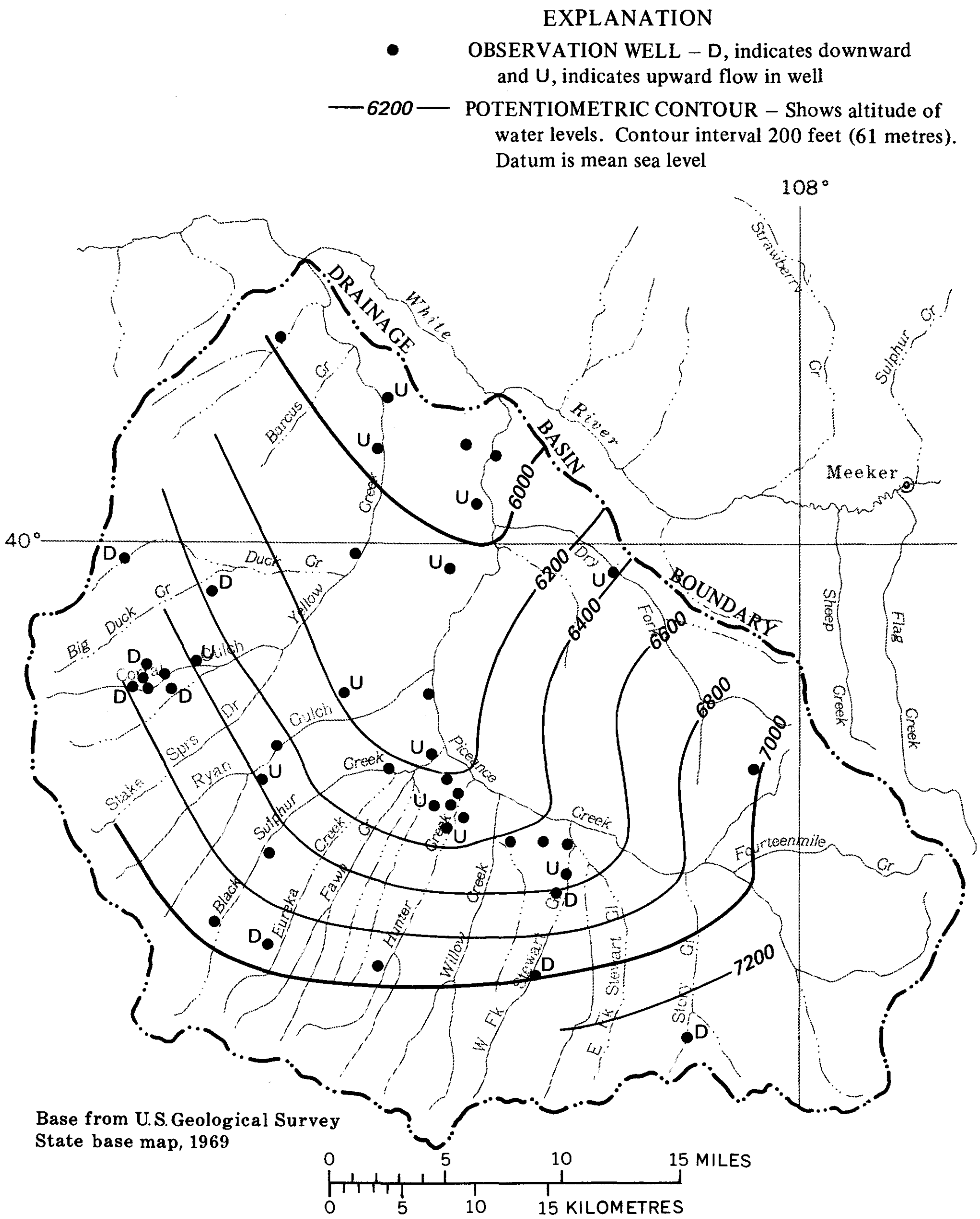


FIGURE 22. — Potentiometric map based on water levels in wells open to both the upper and the lower aquifers, April 1974.

of the basin. The shape of the potentiometric contours shows that Piceance Creek valley is the principal ground-water discharge area in the basin. The results of the digital-model study presented later in this report indicate that about 80 percent of the ground-water discharge occurs in Piceance Creek drainage area and about 20 percent occurs in Yellow Creek drainage area.

The letters at the control points in figure 22 show whether water moves up or down in the well bore. If the hydraulic head is higher in the upper than in the lower aquifer, water will move down the well bore just as it will move downward through fractures in the Mahogany zone to the lower aquifer. If the hydraulic heads in the aquifers are reversed, the flow in the well bore and between the aquifers is reversed. Thus, figure 22 demonstrates the location of the recharge and discharge area, as well as the direction of flow.

The difference in hydraulic head between the upper and lower aquifers is generally less than 100 feet (30 m), and differences of less than 50 feet (15 m) are typical. Figure 23 shows that the change in hydraulic head with depth measured during the drilling of four wells. The locations of the wells are shown in figure 19. Wells 50 and 91 are located in the recharge area. Figure 23 shows that

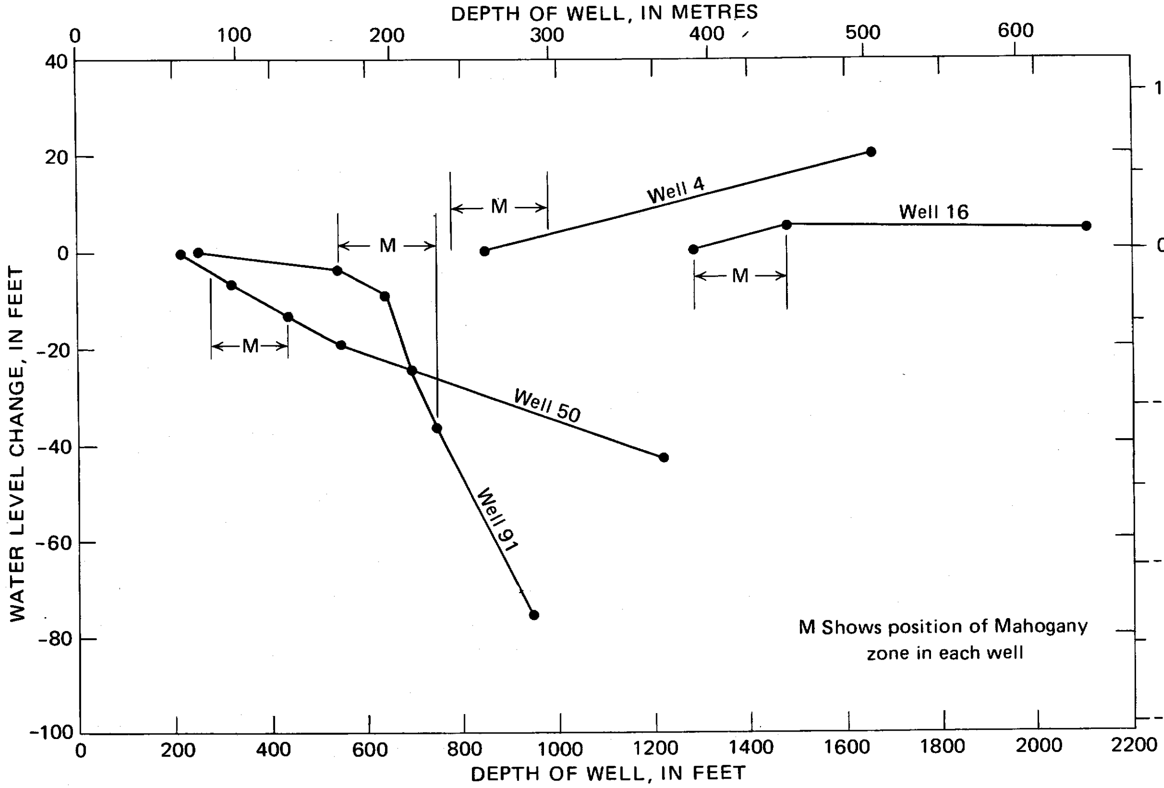


FIGURE 23. — Change in water level during the drilling of four wells.

the water level in wells 50 and 91 decreased as the wells were drilled down to, through, and below the Mahogany zone. This indicates that the potential for flow between the aquifers is downward, through the Mahogany zone. Well 16 shows little change in head with depth. This well is located between the recharge and discharge area, and the head difference between the aquifers is small. Well 4 is located in the Fawn Creek valley, and the potential for flow is upward, through the Mahogany zone. This is a typical condition that exists in the valleys of Piceance Creek and its major tributaries. Comparable data collected during drilling are not available in the northern part of the basin. However, the U.S. Geological Survey has installed a packer in the Mahogany zone in well 44 shown in figure 19. Water-level measurements from above and below the packer have been collected since 1971. Above the packer the well is open to the upper aquifer, and below the packer the well is open to the lower aquifer. The head difference between the aquifers is about 20 feet (6 m), with a few feet of fluctuation. Considering that there are over 1,200 feet (365 m) of head change in the basin, it is doubtful that such small head differences between the aquifers could be maintained unless the Mahogany zone is permeable. The magnitude of the vertical permeability of the Mahogany zone may be very small. However, the cross-sectional area of flow in the vertical direction is very large, and large volumes of water can be transmitted through the Mahogany zone even though the vertical permeability is small.

WATER BUDGET

Very little ground-water development has taken place in the Piceance basin. The principal use of ground water has been for watering stock. Consequently, the ground-water system has not been significantly stressed, and it is in a state of hydrologic equilibrium. Equilibrium, or steady state, implies that the rate of discharge from the ground-water system is equal to the rate of recharge and that no change in ground-water storage takes place. Obviously, there are seasonal fluctuations in discharge, recharge, and storage. However, on an annual average, the water budget becomes balanced—that is, inflow equals outflow with no change in ground-water storage.

Ground water is discharged from the basin in the form of runoff (baseflow) and evapotranspiration. In the semiarid environment of the Piceance basin, ground-water runoff is the major component of the mean annual discharge from the basin. Ground water is evapotranspired mainly in the valley bottoms, where water is discharged from the Unita and Green River Formations to the alluvium. The bottomlands contain phreatophytic sagebrush and irrigated hay meadows and pasture. The water transpired in the bottomland is supplied by surface-water diversion (which is partly ground-water discharge), precipitation, and ground water.

The ground-water budget can be estimated by assuming the steady-state condition that inflow is equal to outflow. The outflow or ground-water discharge, G, is given by the sum of the baseflow runoff from the basin, B, and the evapotranspiration from the bottomlands, E, minus the precipitation on the bottomlands, P, on an annual basis—that is.

$$G = B + E - P. \qquad (1)$$

The mean annual runoff from Piceance and Yellow Creek has been estimated to be 15,650 acre-feet (19.2 hm^3). Assuming that 80 percent of the runoff is ground-water discharge, the baseflow is estimated to be 12,500 acre-feet (15.4 hm^3) per year. The annual volume of evapotransipration from the bottomlands, given in table 1, is 41,200 acre-feet (50.8 hm^3). The average precipitation is estimated to be 14.5 inches (370 mm) on the 22,800 acres (9,230 ha) of bottomland. This is equivalent to 27,600 acre-feet (34 hm^3) per year. Substituting in the above equation, the estimated ground-water discharge from the basin is 26,100 acre-feet per year or 36.1 ft^3/s (1.0 m^3/s). Assuming steady-state conditions, ground water is estimated to circulate through the aquifer system in the Piceance basin at 36 ft^3/s (1.0 m^3/s).

The volume of ground water in storage in the Piceance basin has not been accurately determined. Coffin, Welder, and Glanzman (1971) estimated that the volume of water stored in the leached zone was 2.5 million acre-feet (3,100 hm^3). On the basis of considerably more information, the Department of the Interior (1973, v. 1, p. II–141) estimated that as much as 25 million acre-feet (31,000 hm^3) of water may be stored in the Green River and Uinta Formations in the Piceance basin. A map of the porosity of the permeable section is needed before an accurate estimate of the volume of stored water can be made. The volume of water stored in the aquifers is probably within the range of the above estimates and is believed by the authors to lie closer to the larger estimate

WATER QUALITY

The chemical quality of ground water in the Piceance basin varies both within and among the aquifers. Ground water from the alluvial, upper, and lower aquifers generally does not meet the standards recommended by the U.S. Public Health Service (1962), although ground water is frequently used for stock watering and supplies some ranches. In particular, the concentration of dissolved solids exceeds the recommended limit of 500 mg/l in all but 3 of the 75 water analyses reported by Ficke, Weeks, and Welder (1974) and by Weeks and Welder (1974). The average concentration of constituents in water samples from the alluvial, upper, and lower aquifers is shown in figure 24. Water-quality data for the aquifers is summarized in table 6. The data show that water in the upper and lower aquifers is chemically different, and that water in the upper and alluvial aquifers is chemically similar.

ALLUVIAL AQUIFERS

Analyses of water samples from 30 alluvial wells and springs in the major drainages in the Piceance basin were reported by Weeks and Welder (1974). The locations of the wells and springs from which samples were collected are shown in figure 25. The water in the alluvium is classified as a sodium bicarbonate type. Concentrations of the major cations and anions indicate that the alluvial ground water is similar in quality to that in the upper aquifer (fig. 24). The concentration of dissolved solids averages 1,750 mg/l and generally increases in the downstream direction, with an increase in sodium and bicarbonate, from the recharge areas to the discharge areas. The increase is due to irrigation-return flows, the contribution of ground water discharging to the alluvium from deeper aquifers, and concentration by evapotranspiration.

The concentration of dissolved solids in water samples from the alluvium is shown in figure 26. The concentration ranges from 470 to 6,720 mg/l except at spring S2 where the concentration is 22,100 mg/l. Several sampling sites along Piceance Creek have relatively high concentrations of dissolved solids and reflect the chemistry of the water discharging to the alluvium from the lower aquifer.

Four samples, collected from wells 67, 68, 76, and 81 in figure 25, contain high concentrations of dissolved solids. In addition, the samples from wells 67, 68, and 76 contain very high concentrations of fluoride (9.8–30 mg/l) and the samples from wells 67 and 76 also contain hydrogen sulfide gas. All four wells are located in the vicinity of mapped faults (pl. 1). Water samples with high fluoride content and hydrogen sulfide gas are indicative of water from the lower aquifer. The occurrence of these constituents in the alluvial ground water indicates that water from the lower aquifer is migrating upward along the faults and is discharging to the alluvium. Not all faults mapped in the area display this relation.

Four samples—from wells 82, 83, and 85 and spring S2 (fig. 25), which do not occur near known faults—have high concentrations of dissolved solids. These sample points are located in the discharge area of the basin and reflect the chemistry of the water discharging to the alluvium from the lower aquifer. Near wells 82 and 83, water is discharged to the alluvium directly from the lower aquifer where the Parachute Creek Member crops out. At well 85 and spring S2, the water from the lower aquifer moves through the Mahogany zone and the upper aquifer to reach the alluvium. The vertical

TABLE 6. — *Summary of water-chemistry data from wells in the alluvial, upper, and lower aquifers, Piceance basin*

Chemical constituent	Concentrations, in milligrams per litre, in each aquifer[1]								
	Alluvial[2]			Upper[3]			Lower[4]		
	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum
Potassium----------	0.8	2.5	6.8	0.2	1.5	6.0	0.4	11	78
Sodium-------------	66	490	2,900	55	210	650	230	3,980	16,000
Calcium------------	2.4	57	120	7.4	50	110	2.8	7.4	15
Magnesium----------	3.6	80	160	9.8	60	187	3.0	9.5	26
Bicarbonate--------	336	1,220	3,560	307	550	918	493	9,100	40,000
Chloride-----------	5.2	42	270	3.4	16	63	1.3	690	2,900
Sulfate------------	41	430	1,500	34	320	850	4.2	80	350
Fluoride-----------	.1	4.6	33	0	1.4	12	5.0	28	66
Dissolved solids--	469	1,750	6,720	345	960	2,180	491	9,400	38,900

[1]Data from Ficke, Weeks, and Welder (1974) and from Weeks and Welder (1974).
[2]Based on 27 samples from wells located in figure 25.
[3]Based on 17 samples from wells located in figure 27.
[4]Based on 27 samples from wells located in figure 29.

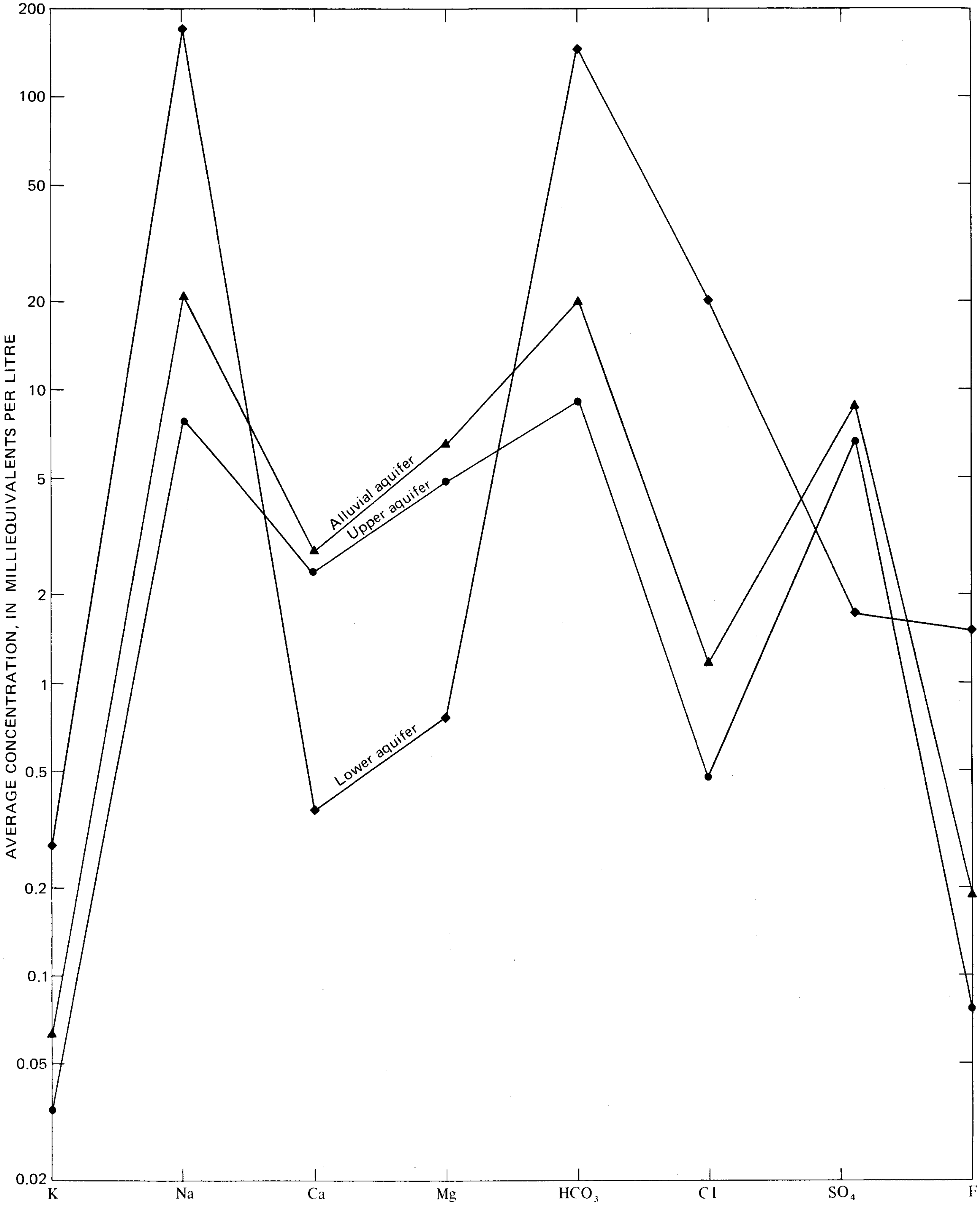


FIGURE 24. — Average concentration of chemical constituents in ground water.

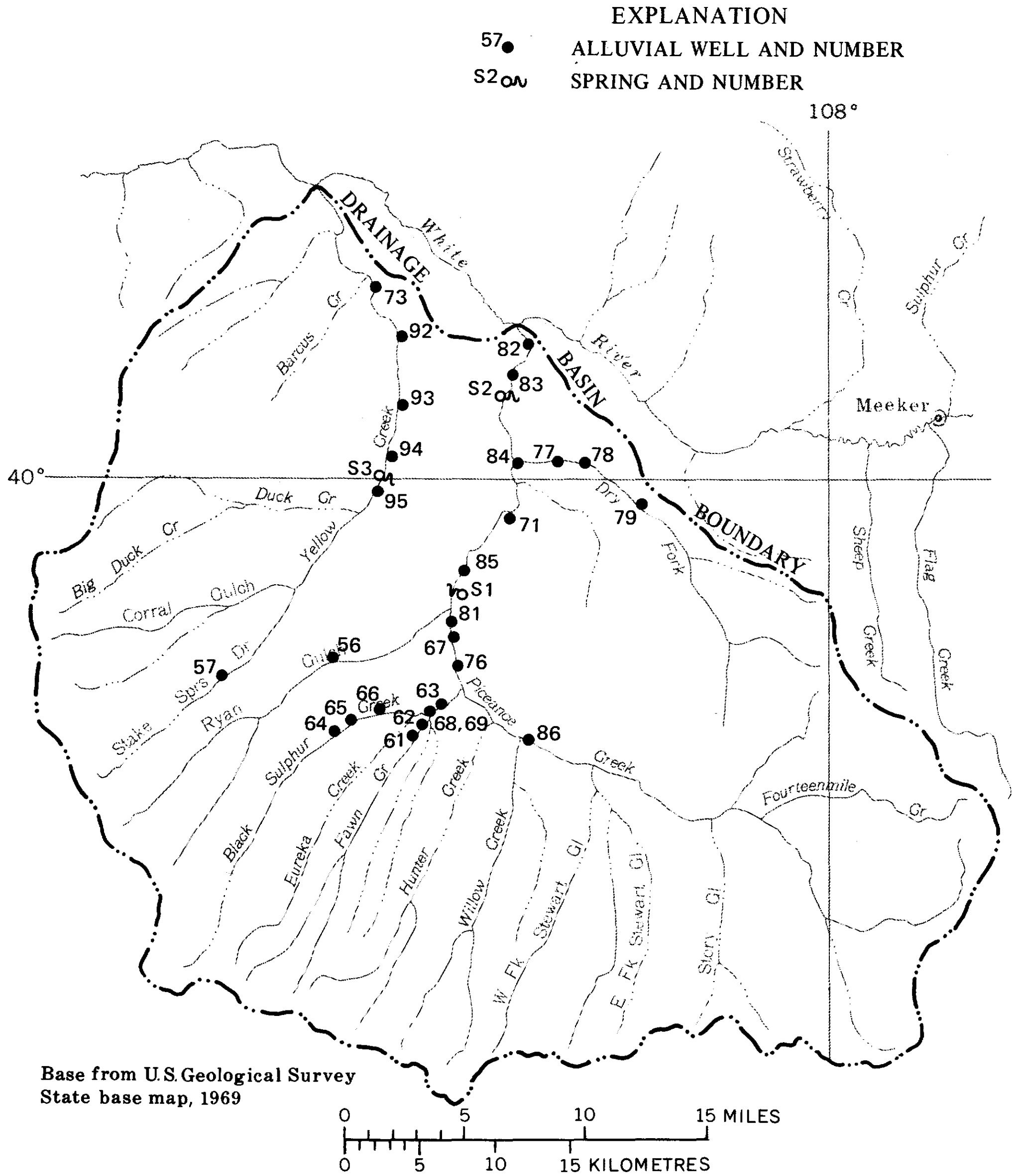


FIGURE 25. — Location of water-quality sampling sites in the alluvial aquifer. Chemical data reported by Weeks and Welder (1974).

permeability of the Mahogany zone may be increased by faulting or fracturing in the vicinity of well 85 and spring S2.

UPPER AQUIFER

Ficke, Weeks, and Welder (1974) and Weeks and Welder (1974) presented 19 chemical analyses of water samples collected from the upper aquifer. The location of the wells and springs from which these samples were collected are shown in figure 27. The data are summarized in figure 24 and table 6.

The water in the upper aquifer can be classified as sodium bicarbonate water. The water generally contains moderate concentrations of sulfate and low concentrations of chloride and fluoride. Figure 24 shows the similarity of the water in the upper and the alluvial aquifers.

The concentration of dissolved solids generally increases in the direction of flow, ranging from less than 400 mg/l to more than 2,000 mg/l. Figure 28 shows the variation of dissolved-solids concentration in the upper aquifer. A potentiometric map was presented in figure

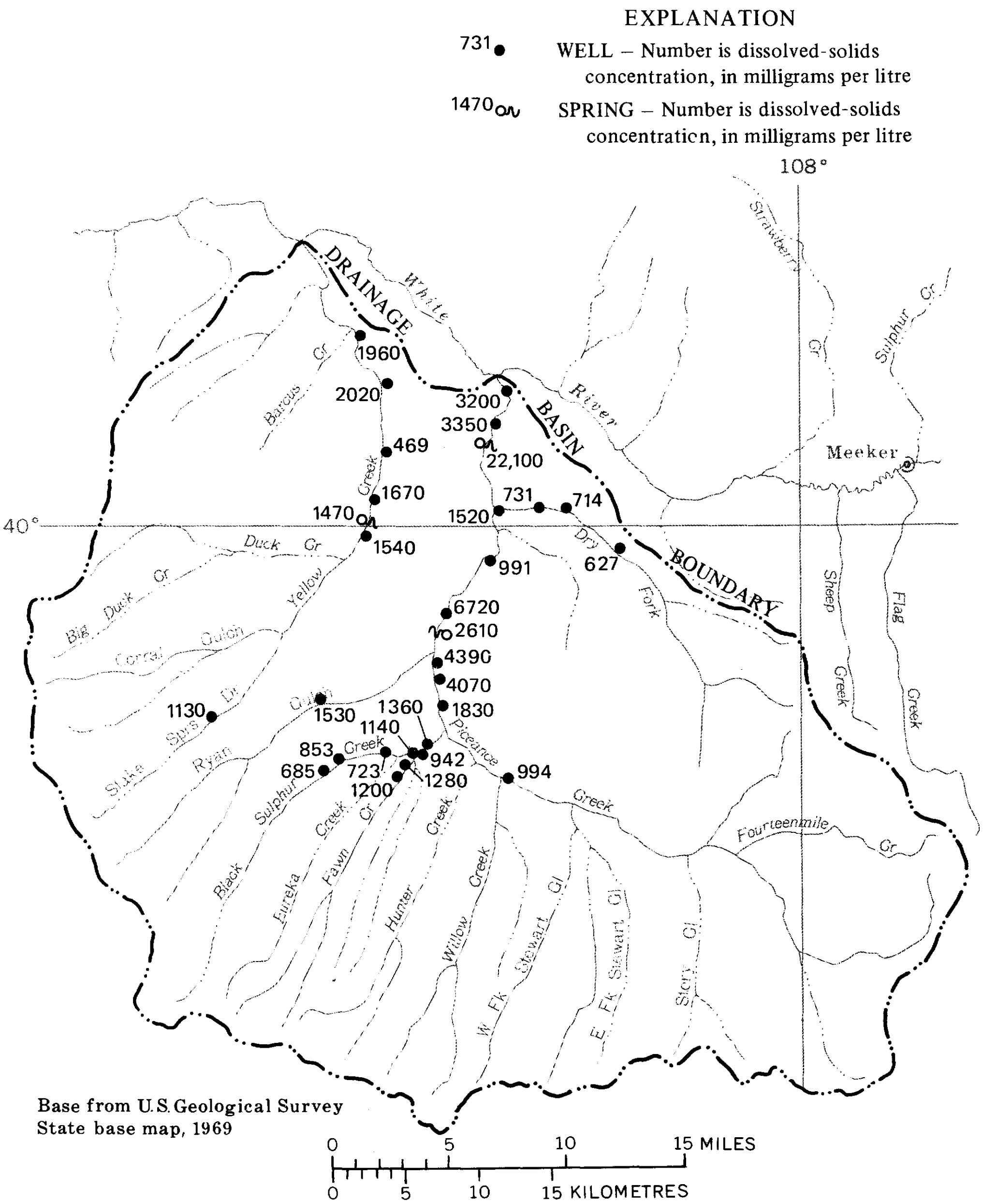


FIGURE 26. — Dissolved-solids concentration in the alluvial aquifer, May–September 1974.

22. The similarities in the shape of the contours between the two maps demonstrates that the dissolved-solids concentration of the water in the upper aquifer increases in the direction of flow. The increase is due to the solution of minerals and to the water moving upward from the lower aquifer. Figure 28 shows that effects of dilution from recharge along the divide between Piceance and Yellow Creeks. Except in the area of the drainage divide, the contours in figures 22 and 28 have the same shape.

The chemical composition of the water in the upper aquifer varies as it moves from the recharge area to the discharge area. In the recharge area, the ground water is generally a sodium-magnesium bicarbonate type, with sulfate making up nearly 50 percent of the anion concentration. As the water moves toward the north-central part of the basin, sodium and bicarbonate increasingly dominate the ionic concentrations.

LOWER AQUIFER

Water-quality data from water samples collected from 27 wells in the lower aquifer are presented by Ficke, Weeks, and Welder (1974) and Weeks and Welder (1974). The locations and numbers of the wells from which these samples were obtained are shown in figure 29. Figure 24 shows how the water chemistry of the lower aquifer differs from that of the upper and alluvial

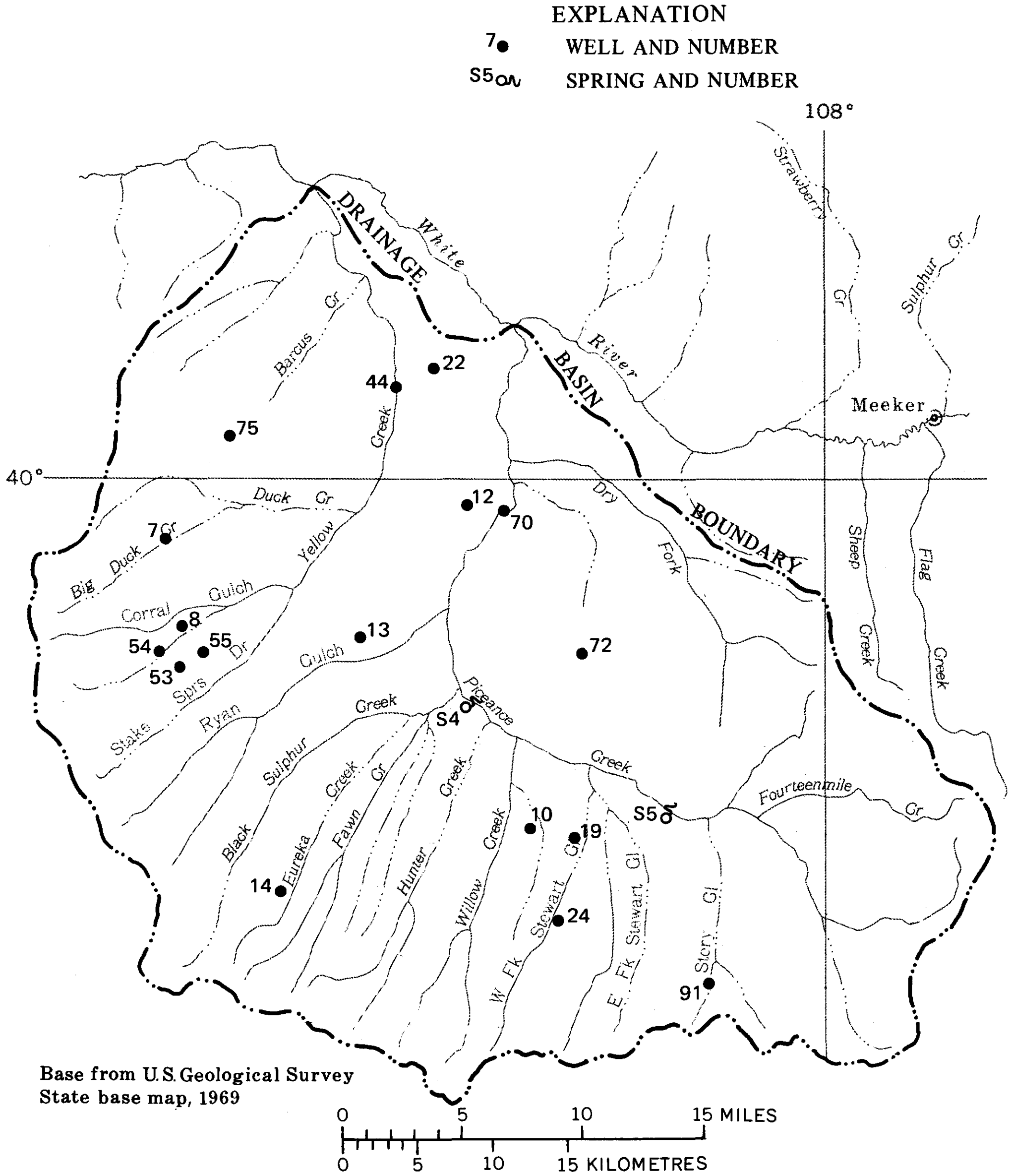


FIGURE 27. — Location of water-quality sampling sites in the upper aquifer. Chemical data reported by Ficke, Weeks, and Welder (1974) and by Weeks and Welder (1974).

aquifers. The graph is calculated from the average concentrations given in table 6. The graph shows that water from the lower aquifer is a definite sodium bicarbonate type with higher chloride and fluoride and lower sulfate concentrations than water from the other aquifers. Water from the lower aquifer is extremely low in calcium and magnesium content. The ratio (calculated from milliequivalents) of calcium plus magnesium to sodium is less than 0.1 in all samples reported by Weeks and Welder (1974). However, the water is generally saturated with respect to calcium carbonate at the prevailing temperature and pH.

The sulfate-ion concentration in the lower aquifer is generally lower than in the other aquifers in the basin. Additionally, hydrogen sulfide gas is present in many samples collected from the lower aquifer (fig. 29, wells 1, 29, 31, 55, 58, 87, 88, and 90). These facts indicate that reducing conditions exist in the lower aquifer preventing oxidation of the sulfide ion.

Fluoride concentration is a noteworthy characteristic of the water in the lower aquifer. This is evident from the data in table 6. The average fluoride concentration is 28 mg/l. The fluoride concentration was found to be more than 10 mg/l in all but one sample (well 1 in fig. 29). The maximum concentration of fluoride found was 66 mg/l. According to Worl, Van Alstine, and Shawe (1973, p.

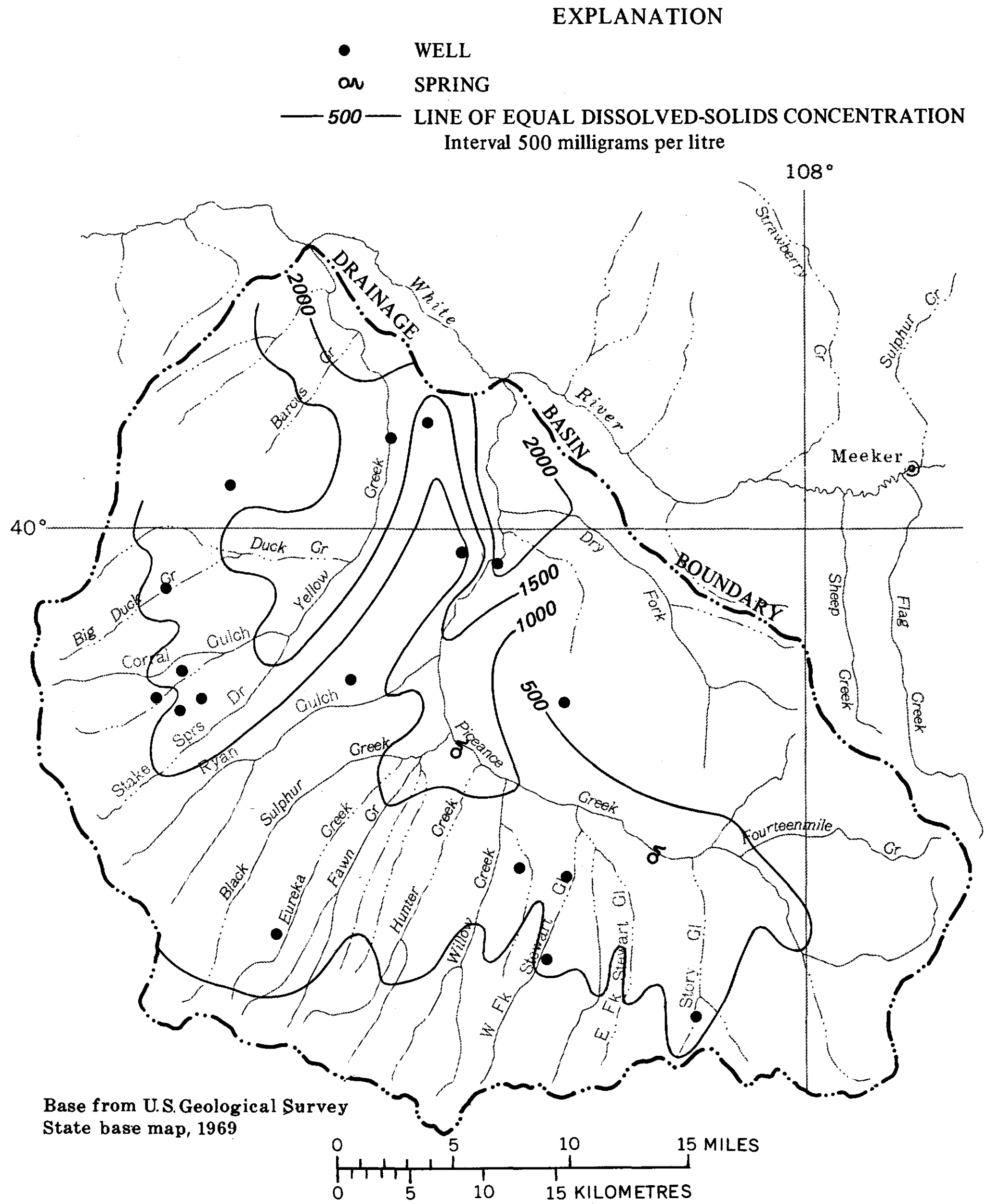


FIGURE 28. — Concentration of dissolved solids in the upper aquifer, May–September 1973.

225), the maximum recorded fluoride concentration in ground water is 67.2 mg/l and few waters contain more than 10 mg/l. Thus, the ground water in the lower aquifer of Piceance Creek basin contains exceptionally high concentrations of dissolved fluoride. The areal distribution of fluoride has no significant pattern, and the fluoride sources are probably disseminated throughout the lower aquifer. The main source of the fluoride is believed to be authigenic fluoride minerals (cryolite and fluorite) found in the rocks of the Parachute Creek Member of the Green River Formation (Desborough and others, 1974).

The concentration of dissolved solids in the water of the lower aquifer is moderate to extremely high. Table 6 shows that the dissolved-solids concentration ranges from less than 500 mg/l to nearly 40,000 mg/l. However, Coffin, Welder, and Glanzman (1971) reported a dissolved-solids concentration of 63,000 mg/l in a water sample obtained from the high-resistivity zone (fig. 18). The variation in the concentration of dissolved solids in the lower aquifer is illustrated in figure 30. The concentration lines are similar in shape to the potentiometric contours shown in figure 22. This is the result of the solution of soluble minerals as the water moves from the basin margins toward the north-central part of the basin. The principal areas of unleached nahcolite (sodium bicarbonate) and halite (sodium chloride) deposits have been mapped by Dyni (1974, fig. 9) and are outlined in

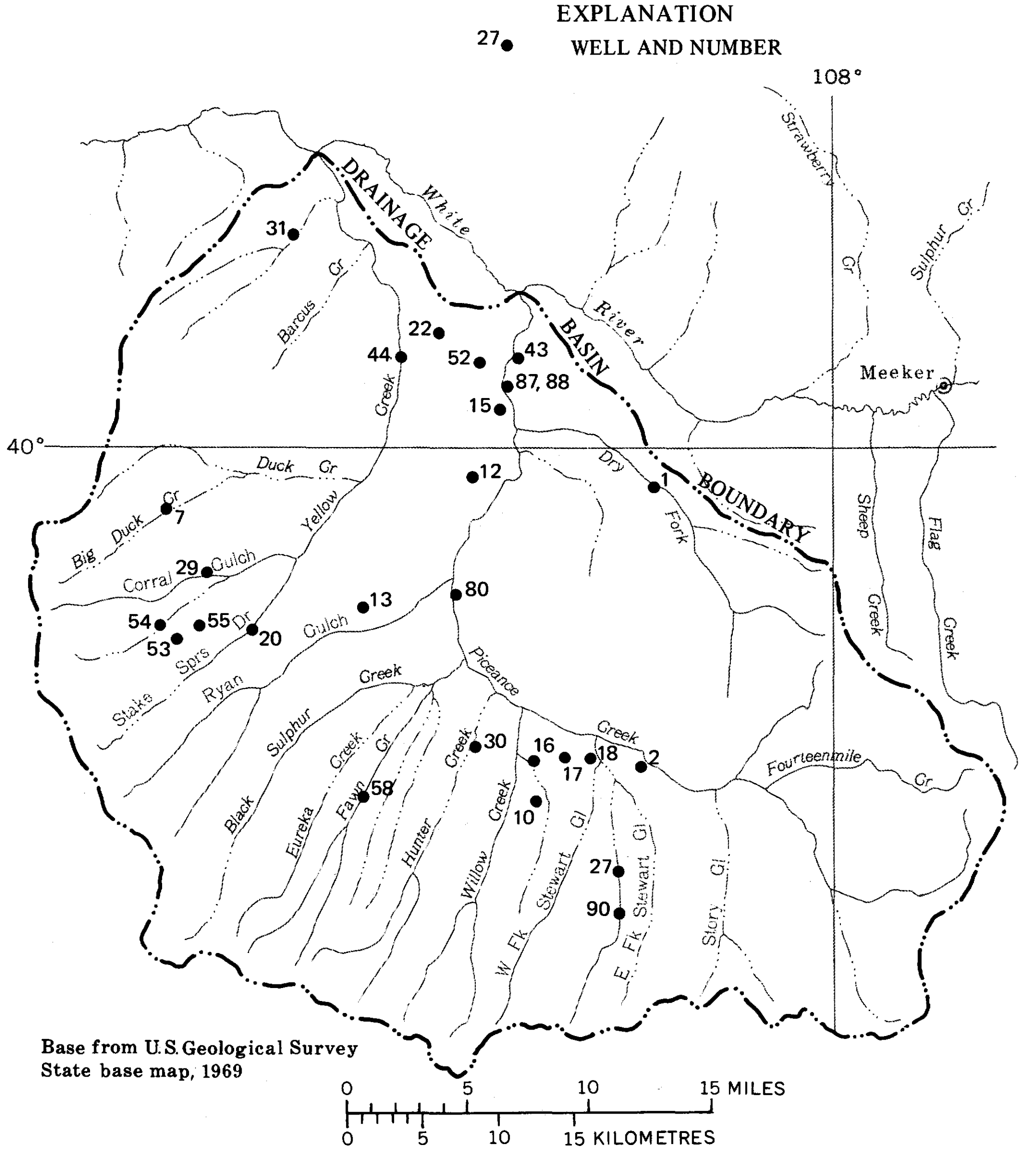


FIGURE 29. — Location of water-quality sampling sites in the lower aquifer. Chemical data reported by Ficke, Weeks, and Welder (1974) and by Weeks and Welder (1974).

figure 31. The sodium minerals are contained in the rocks of the Parachute Creek Member of the Green River Formation below the Mahogany zone. Most of the unleached mineral deposits are in the high-resistivity zone (fig. 18). The high dissolved-solids concentrations are associated with these deposits. Water samples from wells 31 and 43 in figure 29 have lower dissolved-solids concentrations than samples from other wells in the vicinity. This may be the results of dilution due to recharge from the exposed rocks of the Parachute Creek Member, which crops out along the north edge of the basin near the White River.

As discussed in the previous section, the water in the upper aquifer is generally sodium magnesium bicarbonate type in the recharge area, and sulfate generally makes up nearly half of the anions. However, samples collected from the lower aquifer in the recharge area are strongly sodium bicarbonate type with a small sulfate content. The sodium bicarbonate minerals are disseminated throughout the lower aquifer and are not limited to the area shown in figure 31. The change in chemical composition of the ground water between the aquifers in the recharge area indicates that the minerals are actively being dissolved.

The nahcolite and halite deposits shown in figure 31 are also actively being dissolved by ground water. This is demonstrated in figure 32 which shows the difference in water chemistry between wells 7 and 44 in figure 31. As shown by the potentiometric map in figure 22, ground water moves in the direction of well 44 from well 7. The

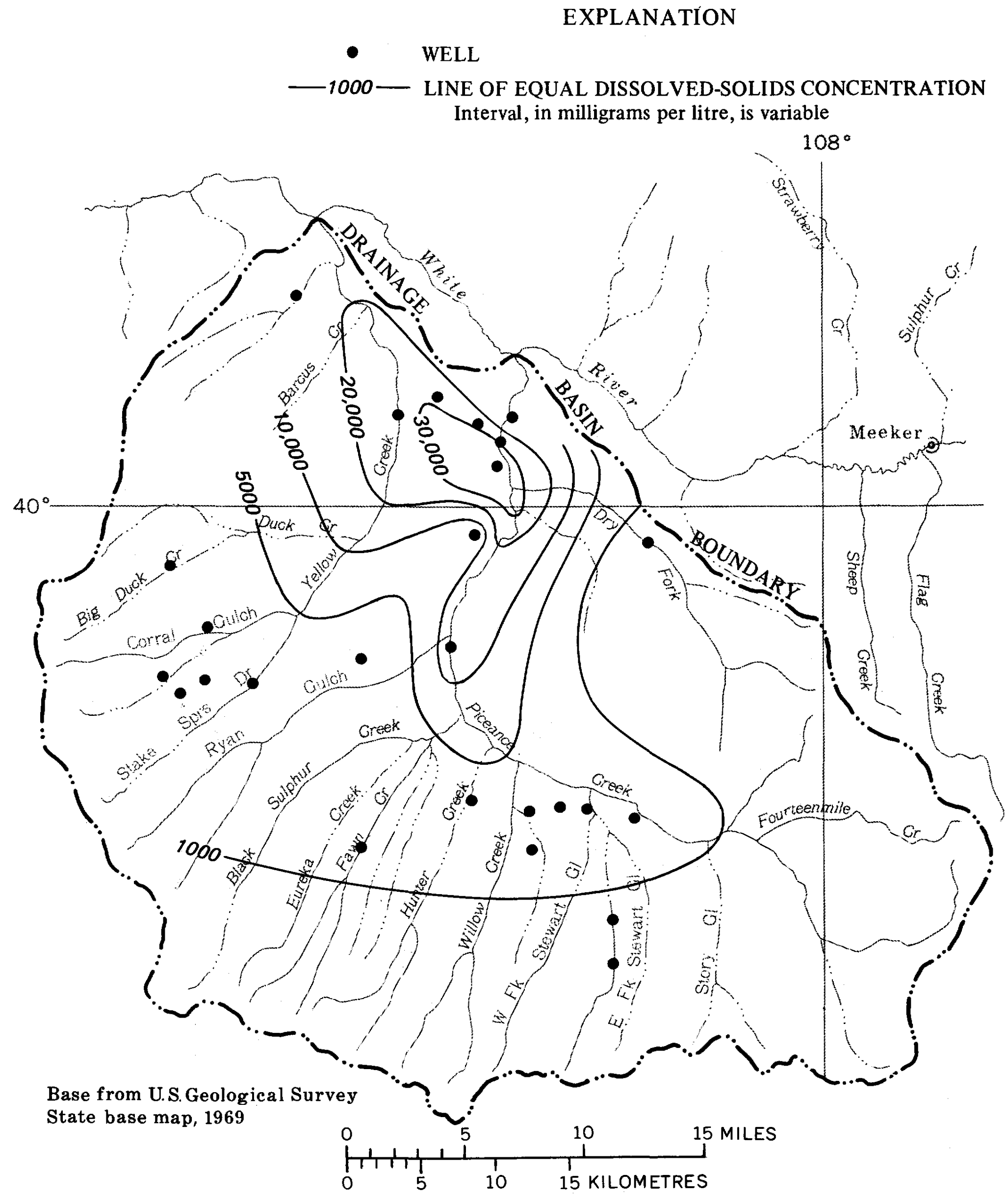


FIGURE 30. — Concentration of dissolved solids in the lower aquifer, May–September 1973.

increase in sodium, bicarbonate, and chloride shown in figure 32 demonstrates that nahcolite and halite are actively being dissolved by ground water as it flows through the lower aquifer.

TRACE ELEMENTS

The ground water in the lower aquifer contains many trace elements and, at some locations, the concentrations of particular elements are great enough to be of environmental concern. Water-quality data presented by Weeks and Welder (1974) show that aluminum, arsenic, barium, boron, iron, lead, lithium, manganese, molybdenum, selenium, and strontium are present in the water in at least trace amounts. Adequate data are not available to determine the occurrence of other elements. The concentrations of barium, boron, and lithium are consistently high in the northern part of the basin, indicating that minerals of these elements may be associated with the occurrence of nahcolite and halite deposits (fig. 31). The concentrations of barium, boron, and lithium in water samples from the lower aquifer are presented in table 7. Most of the sampling sites (fig. 29) yielding high concentrations of barium, boron, and lithium, are in the northern part of the basin.

The toxic effects of barium are discussed by the U.S. Public Health Service (1962). A maximum of 1,000 $\mu g/l$ (micrograms per litre) is recommended as the limit for drinking water. Hem (1970) reported that the concentra-

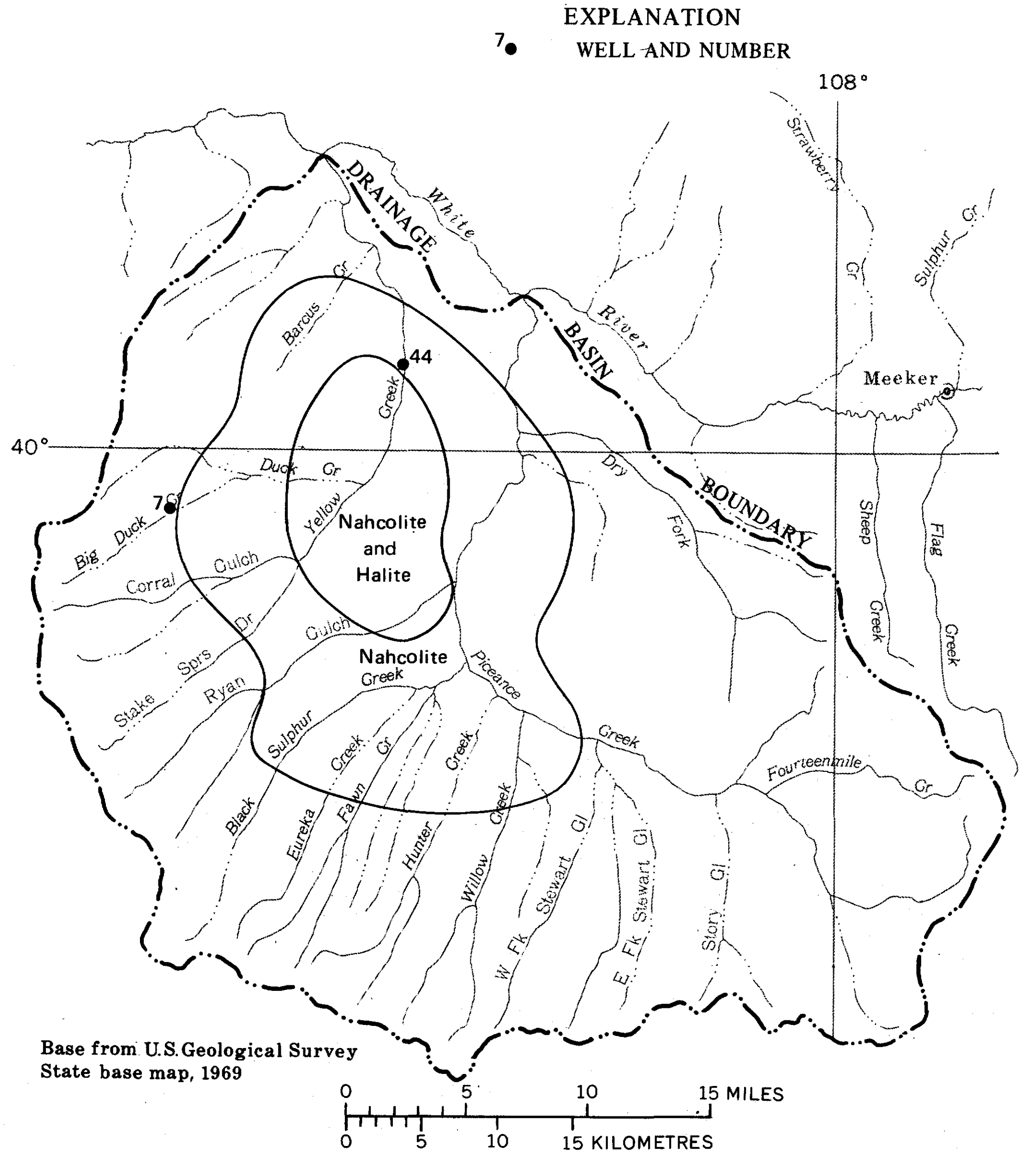


FIGURE 31. — Location of principal halite and nahcolite deposits (from Dyni, 1974).

tion of boron in excess of 3,000 μg/l or lithium in excess of 5,000 μg/l is toxic to most plants. It is evident from table 7 that the water in the northern part of the lower aquifer is generally not suitable for consumption or irrigation. The concentration of dissolved soilds shown in figure 30 supports this conclusion.

OIL-SHALE LEASE TRACTS

Chemical data from one well in each of the oil-shale lease tracts indicate the presence of very poor quality water. The wells (10 and 29) are shown in figure 29 and the chemical analyses are presented in tables 8 and 9. In both wells, sodium bicarbonate brines similar to those in the northern part of the basin were found near the base of the Parachute Creek Member of the Green River Formation.

The samples from well 10 in tract C-b were collected by pumping water from the intervals listed in table 8. The well was being constructed when the January 1972 samples were collected. A large increase in dissolved solids occurred below a depth of 1,456 feet (444 m). The base of the Parachute Creek Member is at a depth of 2,200 feet (670 m). The water in the lower part of the Parachute Creek Member in this well is a sodium bicarbonate brine containing 30,000 mg/l dissolved solids and high concentrations of boron, lithium, chloride, and fluoride. The well was left open-hole until August 1972 when additional samples were collected. It is evident from the data in table 8 that the brine has migrated uphole and is contaminating the overlying aquifers. The well was pumped open-hole to obtain the sample dated February 1972. The dissolved-solids concentration was

TABLE 7. — *Concentrations of barium, boron, and lithium in water samples from the lower aquifer, Piceance basin*

[Dash leaders (---) indicate no data available]

Well No.[1]	Concentration, in micrograms per litre[2]		
	Barium	Boron	Lithium
1	300	920	60
2	------	-------	110
7	300	520	30
15	------	7,300	-----
20	1,900	4,100	-----
22	4,900	7,300	2,100
27	------	450	-----
30	900	570	10
31	13,000	6,500	6,500
43	4,300	120,000	1,200
44	------	1,500	-----
52	6,100	12,000	2,100
80	------	2,600	-----
88	5,000	3,500	-----
90	400	260	30
S2[3]	6,300	5,500	1,200

[1]Wells located in figure 29.

[2]Data from Ficke, Weeks, and Welder (1974) and from Weeks and Welder (1974).

[3]Spring located in figure 25.

only 1,790 mg/l, indicating that there was little contribution to flow from the zone containing the brine and that the permeability of the zone is probably small.

Two wells, 16 and 24 in figure 19, near well 10, were drilled to the same stratigraphic level. Specific conductance data presented by Ficke, Weeks, and Welder (1974) for each of these wells show a significant increase in fluid conductance near the base of the Parachute Creek Member, indicating that the brine may be present.

Water-quality analyses from well 29 in tract C–a are presented in table 9. The well was completed open-hole at a depth of 1,808 feet (551 m) in August 1972, and the samples were obtained a year later. The base of the Parachute Creek Member is at a depth of 1,540 feet (470 m). An increase in specific conductance of the water from 1,000 to 3,000 μmhos/cm (micromhos per centimetre) at 25°C was noted during drilling below 1,400 feet (427 m). The sample in table 9 collected at 1,650 feet (503 m) was obtained using a point sampler. The water sampled is a sodium bicarbonate brine and contains 52,000 mg/l dissolved solids and high concentrations of boron and fluoride.

The two samples collected August 9, 1973, were obtained by pumping water from the intervals listed in table 9. The chemical composition of the water obtained from the 125- to 617-foot (38- to 188-m) interval is about the same as that from the 577- to 1,808-foot (176- to 551-m) interval. Therefore, the contribution to flow from the zone containing the brine must be very small, and the permeability of the zone is probably small.

Specific conductance data given by Ficke, Weeks, and Welder (1974) for several nearby wells indicate an increase in dissolved solids near the base of the Parachute Creek Member. Specifically, wells numbered 5, 7, 20, 29, 48, and 49 in figure 19 show a significant increase in fluid conductance at about the same stratigraphic level. However, water samples have not been obtained from the base of the Parachute Creek Member in these wells to confirm the presence of the brine.

Lateral extensions of the high-resistivity zone (fig. 18) may be present at both oil-shale lease tracts. If so, the brine probably results from water in contact with soluble minerals in a zone of very low permeability. However, adequate data are not available to determine the distribution of the brine or the permeability of the zones

TABLE 8. — *Chemical analyses of water samples from well 10 in tract C–b*

[Data by U.S. Geological Survey]

Date	Depth of interval open to well (feet)	Specific conductance (micromhos)	Dissolved solids (sum of constituents) (mg/l)	Alkalinity as $CaCO_3$ (mg/l)	Dissolved silica (SiO_2) (mg/l)	Total aluminum (Al) (μg/l)	Dissolved aluminum (Al) (μg/l)	Total barium (Ba) (μg/l)	Total beryllium (Be) (μg/l)	Total bismuth (Bi) (μg/l)	Total boron (B) (μg/l)
Jan. 1972											
11------	126- 717	1,140	758	334	27	--	--	--	--	--	--
15------	126-1,060	866	530	399	15	--	10	--	--	--	--
21------	1,040-1,458	2,800	1,830	1,510	14	--	10	--	--	--	--
26------	1,456-1,984	24,200	30,100	18,569	23	--	0	--	--	--	--
Feb. 1972											
1------	127-2,530	2,740	1,790	1,150	16	--	--	--	--	--	--
Aug. 1972											
17------	127- 673	2,250	1,340	886	18	--	--	--	--	--	--
18------	633-1,420	1,480	857	611	8.3	--	--	--	--	--	--
18------	127-1,074	36,000	24,200	12,500	14	2,700	--	6,800	<110	<500	320,000
18------	1,034-1,420	39,000	31,000	18,700	16	7,700	--	8,300	<100	<500	310,000

Date	Dissolved boron (B) (μg/l)	Total cadmium (Cd) (μg/l)	Dissolved calcium (Ca) (mg/l)	Total chromium (Cr) (μg/l)	Total cobalt (Co) (μg/l)	Total copper (Cu) (μg/l)	Total gallium (Ga) (μg/l)	Total germanium (Ge) (μg/l)	Total iron (Fe) (μg/l)	Dissolved iron (Fe) (μg/l)	Total lead (Pb) (μg/l)	Total lithium (Li) (μg/l)
Jan. 1972												
11------	--	--	40	--	--	--	--	--	--	--	--	--
15------	350	--	11	--	--	--	--	--	--	9	--	--
21------	990	--	7.7	--	--	--	--	--	--	9	--	--
26------	250,000	--	21	--	--	--	--	--	--	3,300	--	--
Feb. 1972												
1------	--	--	18	--	--	--	--	--	--	--	--	--
Aug. 1972												
17------	7,700	--	7.7	--	--	--	--	--	--	1,000	--	--
18------	--	--	8.4	--	--	--	--	--	--	120	--	--
18------	--	<7,500	18	<500	<500	340	<210	<750	6,000	600	<500	38,000
18------	--	<7,000	18	<500	500	1,000	<200	<700	12,000	1,800	<500	42,000

Date	Dissolved magnesium (Mg) (mg/l)	Total manganese (Mn) (μg/l)	Dissolved manganese (Mn) (μg/l)	Total molybdenum (Mo) (μg/l)	Dissolved molybdenum (Mo) (μg/l)	Total nickel (Ni) (μg/l)	Dissolved potassium (K) (mg/l)	Dissolved sodium (Na) (mg/l)	Total silver (Ag) (μg/l)	Dissolved selenium (Se) (μg/l)	Total strontium (Sr) (μg/l)	Total tin (Sn) (μg/l)
Jan. 1972												
11------	41	--	--	--	--	--	0.3	160	--	--	--	--
15------	7.2	--	0	--	16	--	.4	190	--	4	--	--
21------	15	--	0	--	130	--	1.2	720	--	6	--	--
26------	14	--	200	--	74	--	7.6	12,000	--	40	--	--
Feb. 1972												
1------	12	--	--	--	--	--	3.7	670	--	--	--	--
Aug. 1972												
17------	4.1	--	20	--	7		3.2	520	--	--	--	--
18------	3.6	--	10	--	--	--	1.7	340	--	--	--	--
18------	4.8	<500	60	<250	--	--	73	10,000	<50	--	3,900	<500
18------	4.1	<500	60	<220	--	<500	89	13,000	<50	--	5,100	<500

Date	Total titanium (Ti) (μg/l)	Total vanadium (V) (μg/l)	Dissolved vanadium (V) (μg/l)	Total zinc (Zn) (μg/l)	Total zirconium (Zr) (μg/l)	Dissolved arsenic (As) (μg/l)	Bicarbonate (HCO_3) (mg/l)	Bromide (Br) (mg/l)	Carbonate (CO_3) (mg/l)	Dissolved chloride (Cl) (mg/l)	Dissolved fluoride (F) (mg/l)	Dissolved sulfate (SO_4) (mg/l)
Jan. 1972												
11------	--	--	--	--	--	3	407	0.040	0	6.5	3.3	280
15------	--	--	0.8	--	--	20	487	.040	0	4.2	13	49
21------	--	--	2.1	--	--	19	1,370	.060	231	8.0	16	140
26------	--	--	85	--	--	70	20,000	39	1,300	6,200	47	330
Feb. 1972												
1------	--	--	--	--	--	0	1,250	1.0	77	250	14	110
Aug. 1972												
17------	--	--	3.7	--	--	--	1,080	--	0	210	13	23
18------	--	--	--	--	--	--	745	--	0	100	14	14
18------	<500	<500	--	<23,000	<750	--	14,000	--	634	6,200	39	320
18------	<500	<500	--	<22,000	<700	--	20,300	--	1,260	6,400	44	150

TABLE 9. — *Chemical analyses of water samples from well 29 in tract C–a*

Date	Depth to top of sample interval (ft)	Depth to bottom of sample interval (ft)	Specific conductance (micromhos)	Dissolved solids (sum of constituents) (mg/l)	Alkalinity as $CaCO_3$ (mg/l)	Dissolved silica (SiO_2) (mg/l)	Dissolved aluminum (Al) (µg/l)	Dissolved iron (Fe) (µg/l)	Dissolved manganese (Mn) (µg/l)	Dissolved calcium (Ca) (mg/l)	Dissolved magnesium (Mg) (mg/l)	Dissolved sodium (Na) (mg/l)	Dissolved potassium (K) (mg/l)	Bicarbonate (HCO_3) (mg/l)
Aug. 1973														
8-------	1,650	1,651	46,300	52,000	49,500	7.4	0	--	30	3.3	2.9	22,000	9.2	60,400
9-------	117	617	3,880	2,890	2,590	12	--	190	10	4.3	4.4	1,200	2.4	3,160
9-------	577	1,808	4,080	2,900	2,610	15	0	110	10	3.6	3.4	1,200	1.9	3,180

Date	Carbonate (CO_3) (mg/l)	Dissolved sulfate (SO_4) (mg/l)	Dissolved chloride (Cl) (mg/l)	Dissolved fluoride (F) (mg/l)	Bromide (Br) (mg/l)	Dissolved nitrite plus nitrate (N) (mg/l)	Dissolved orthophosphorus (P) (mg/l)	Dissolved arsenic (As) (µg/l)	Total barium (Ba) (µg/l)	Dissolved boron (B) (µg/l)	Total lead (Pb) (µg/l)	Total lithium (Li) (µg/l)	Total molybdenum (Mo) (µg/l)	Dissolved selenium (Se) (µg/l)	Total strontium (Sr) (µg/l)
Aug. 1973															
8-------	0	120	53	28	2.5	0.00	1.3	17	1,400	5,500	300	640	10	--	110
9-------	0	7.9	59	30	.300	.24	.04	2	1,000	5,600	<50	40	0	5	230
9-------	0	19	52	34	.070	.33	.06	16	--	5,600	50	30	1	5	--

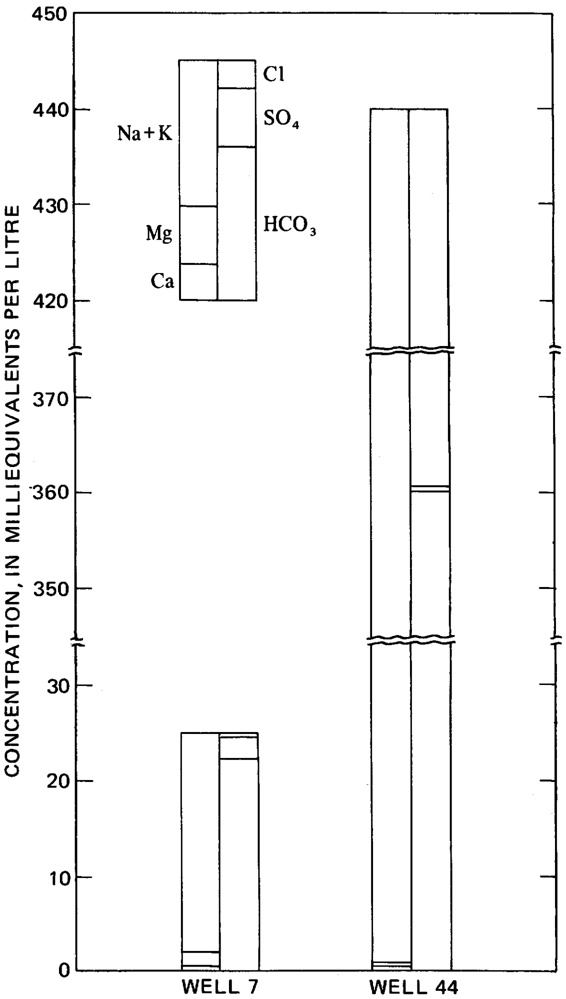


FIGURE 32. — Chemical composition of water from two wells in the lower aquifer.

containing the brine. Mine-dewatering operations for oil-shale development will create large hydraulic gradients in the lower aquifer. If the saline zones are permeable enough, the brine could move into the lower aquifer and greatly alter the water quality in the vicinity of the lease tracts. Additional data are needed to determine the extent and permeability of the zones containing the brine.

HYDROLOGIC MODELS

The response of the hydrologic system to applied stresses, such as pumping from wells or changes in precipitation, can best be evaluated by the use of models. Models provide the hydrologist with the ability to integrate the many interrelated components of the hydrologic system in response to changes in the system. In all but the simplest hydrologic systems, equations governing the hydraulics of these systems are either too numerous or too complicated to be solved by direct mathematics. Digital models are computer programs which utilize the high-speed computation capability of computers to solve the governing equations. The following sections of this report describe two digital models—a watershed model and a ground-water hydraulics model—which were used to simulate the hydrologic system in the Piceance basin.

WATERSHED MODEL

DIGITAL MODEL DESCRIPTION

The watershed model used to simulate the Piceance basin hydrologic system was developed by George Leavesley at Colorado State University and is documented in a doctoral dissertation entitled "A Mountain Watershed Simulation Model." Copies are available through the University's Department of Earth Resources. The model is capable of predicting the response of the hydrologic system resulting from modifications of system input and modifications of the system itself. Total system response is measured in terms of mean daily runoff and is computed under the conditions of no irrigation. For the purpose of this report, basin response in the absence of irrigation will be termed "natural" basin response.

MODEL CONCEPTS

The model used to simulate the surface-water system of the Piceance Creek drainage basin is a deterministic physical-process model. It is applicable to basins where snow is the major form of precipitation input and the primary source of annual runoff. The variables that drive the model are daily temperature, precipitation, and solar radiation. The model is designed around the concept of partitioning the basin into subunits on the basis of measurable climatic, physiographic, vegetative, and soils features. The resulting subunits are each considered homogeneous with respect to its hydrologic response and, thus, are termed "hydrologic response units" (HRU's). A daily water balance is calculated for each HRU, and the sum of the responses of all HRU's, weighted on a contributing area basis, produces the overall system response and runoff from the basin.

WATERSHED PARTITIONING

The watershed is partitioned into HRU's on the basis of slope, aspect, vegetation type, soil type, and snow distribution. Partitioning attempts to account for the temporal and spatial variations of basin physical and hydrologic characteristics, climatic variables, and total system response.

The vertical structure of an HRU is shown in figure 33. It consists of an upper soil zone, a lower soil zone, and a ground-water zone. The upper soil zone is considered to be equal to the average rooting depth of the major form of vegetation in the HRU. The water-storage capacity of this zone is expressed in terms of available water for plant uptake. The maximum storage capacity of the upper soil zone is considered to be the water stored between 0.33 bar and 15 bars tension. The uppermost part of the upper soil zone is termed the recharge zone. Evapotranspiration losses from the upper soil zone occur first from the recharge zone until its storage is depleted; then water is removed from the lower part of the upper soil zone. Likewise, all available storage deficits in the recharge zone must be filled before water will move down to the lower depths of the upper soil zone. Evapotranspiration from the recharge zone always occurs at the potential rate, whereas evapotranspiration from the lower depths occurs as a function of soil texture and soil water availability. The lower soil zone is below the upper soil zone. The lower

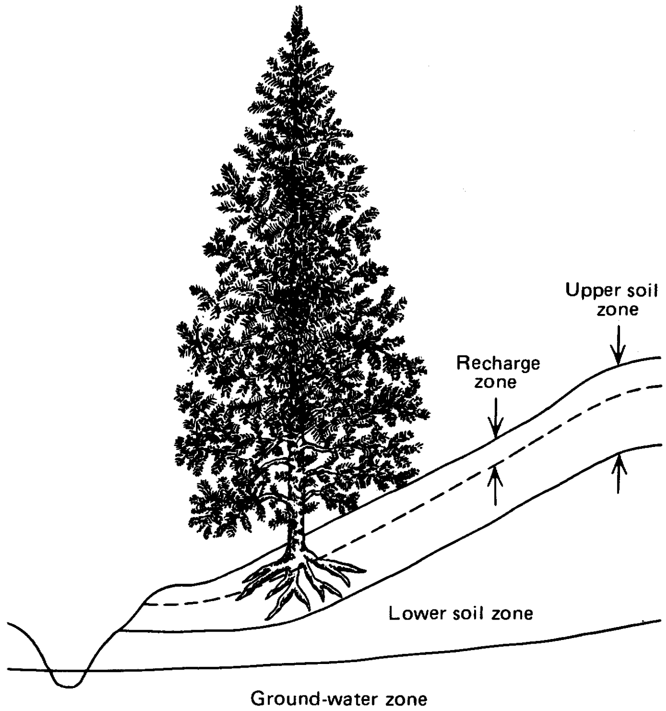


FIGURE 33. — Vertical structure of a hydrologic-response unit.

soil zone has no evapotranspiration losses and is assumed to always have its retention storage capacity satisfied. Excess soil water moving down from the upper soil zone percolates through the lower soil zone to the ground-water zone. The ground-water zone is assumed to have no upper limit on its storage capacity, and it is the source of baseflow.

HYDROLOGIC SYSTEM

To reproduce the physical reality of the hydrologic system as closely as possible, each component of the hydrologic cycle is expressed in the form of known physical laws or empirical relationships which have physical interpretation and measurable watershed characteristics. The watershed system used in this model can be visualized as a series of linear and nonlinear reservoirs whose outputs combine to produce total system response. This system is depicted schematically in figure 34. The upper soil zone reservoir is representative of the upper soil zone depicted in figure 33. This zone is a linear reservoir whose storage is increased by rainfall and snowmelt and depleted by evapotranspiration. Seepage to ground water (S_1) and flow to the subsurface reservoir (S_2) occur only after the upper soil zone reaches field capacity. Surface runoff (Q_1) takes place only when rainfall occurs on a snowfree soil surface or when snowmelt exceeds a maximum daily infiltration value. The subsurface reservoir is representative of the saturated parts of the upper and lower soil zones and is the source of all subsurface flow (Q_2). Subsurface flow

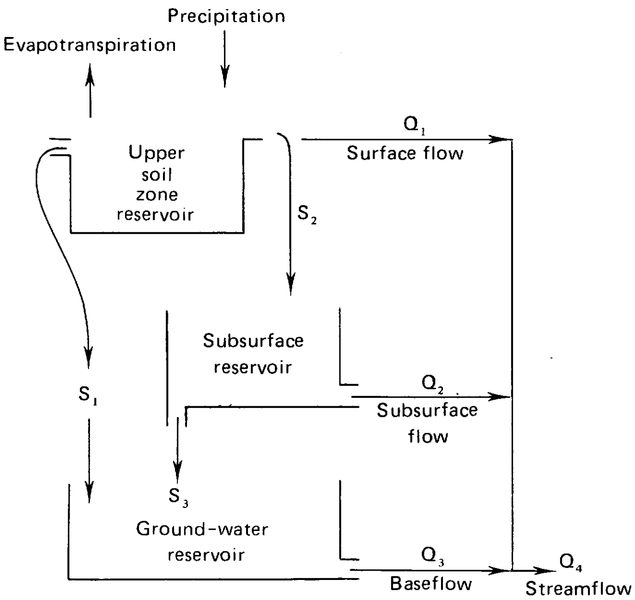


FIGURE 34. — Schematic diagram of the watershed model. S_1, S_2, and S_3 denote movement of water between the reservoirs.

is the movement of water through the soil mantle from the point of infiltration to some point of discharge. The subsurface reservoir is conceptually the routing function for soil-water excess not percolating to ground water. This reservoir can be delineated as either linear or nonlinear and S_2 is its only source of input. The subsurface reservoir includes the saturated parts of the upper soil zone and the entire lower soil zone (fig. 33), and is the source of all subsurface flow (Q_2). Seepage from the subsurface reservoir to ground water (S_3), is assumed to occur as long as a melting snowpack exists. The ground-water reservoir is assumed to be a linear reservoir whose inputs are S_1 and S_3 and is the source of all baseflow (Q_3). Each HRU has its own upper soil zone. However, the subsurface and ground-water reservoirs may be associated with one or several HRU's.

Outputs Q_1, Q_2, and Q_3 are combined to produce the total daily streamflow Q_4. No channel routing is done because the traveltime for the basin is much less than 1 day, and the watershed model simulates daily streamflow.

MODEL COMPONENTS

General model structure and operation are shown in the flowchart in figure 35. Model initialization occurs at flowchart step Input A. Then for each day of simulation, flowchart steps from Input B to Evapotranspiration are performed for each HRU. Upon completion of a day's accounting of all HRU's, routing is performed on the subsurface and ground-water reservoirs. The reservoir outputs, weighted by area, plus any surface runoff from the HRU's, weighted by their respective contributing areas, are summed to produce the model output expressed as

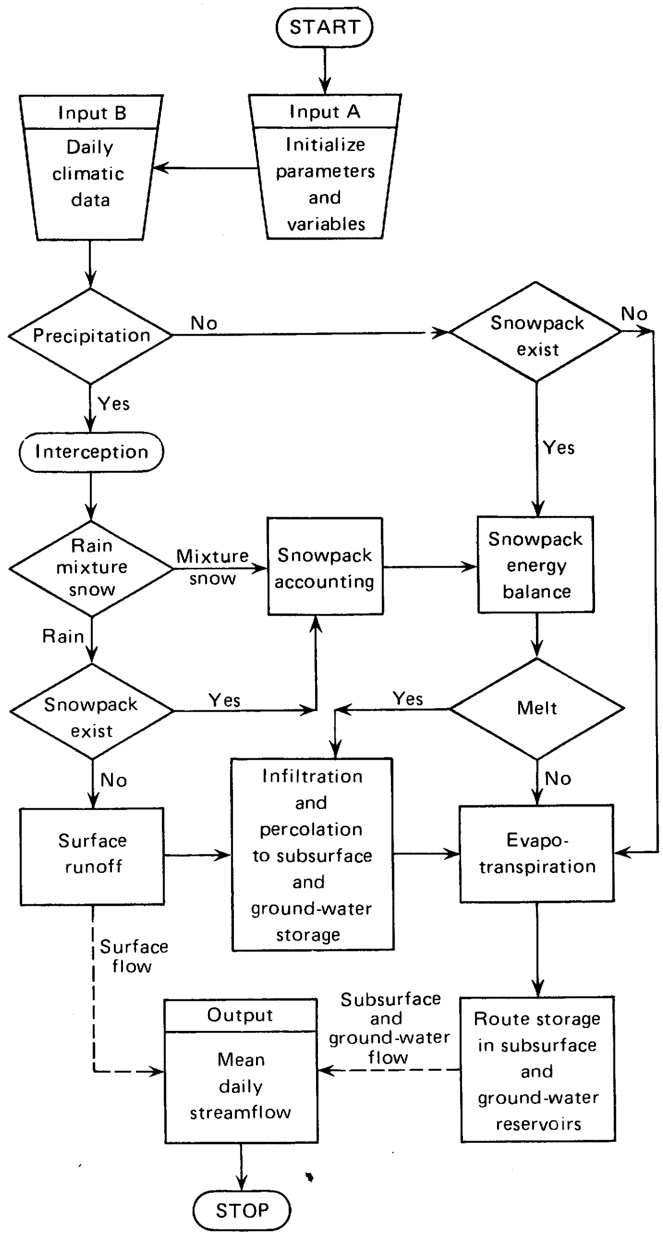


FIGURE 35. — Flow chart of the digital watershed model.

mean daily streamflow. Discounting the initialization and general accounting routines, the model structure can be divided into three general areas of emphasis with regard to the hydrologic cycle. These are the climatic components, the land phase components, and the snow components.

CLIMATIC COMPONENTS

The climatic components are those functions and subroutines which handle and adjust the input climatic data to better define the climate of each HRU. Variations in climate occur with changes in slope, aspect, altitude, and time. To account for these variations, measured climatic data are corrected for each

HRU, using adjustment factors which are functions of the HRU's median altitude, slope, and aspect. Precipitation is adjusted to account for its increase with altitude, and its form (rain or snow) is determined on the basis of the maximum and minimum daily air temperatures. Daily air temperature is adjusted to account for both its decrease with increasing altitude and its variation with aspect. Daily solar radiation is adjusted to account for its variations with slope and aspect.

LAND-PHASE COMPONENTS

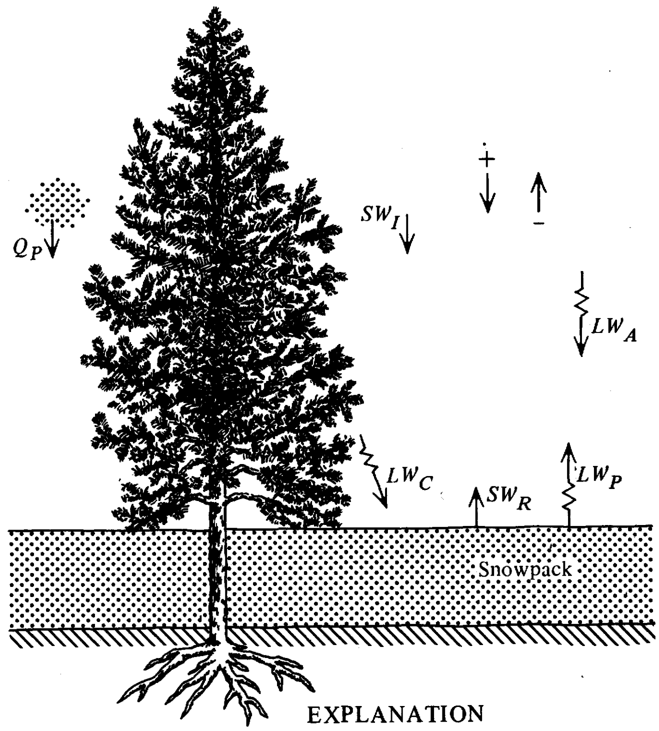
The land-phase components are those functions and subroutines which simulate the effects, responses, and interactions of the vegetation, soil, and geology of an HRU. This includes the accretion, depletion, storage, and routing of water through these elements.

Precipitation enters the land-phase components as rain or snow and is initially reduced in amount by the interception component. Interception amounts are a function of vegetation type and density and of precipitation form and amount. That part of rainfall or snowmelt reaching the soil surface is handled by the soil-water accounting component. Determination is made of any direct surface runoff, and the remaining water infiltrates the upper soil zone surface to satisfy any available soil-water storage capacity. Once the upper soil zone reaches field capacity, all remaining water is delivered to the subsurface and ground-water reservoirs for routing to streamflow by the routing components. Routing from each reservoir is a function of the volume of water stored.

Depletion of soil water from the upper soil zone is computed by the evapotranspiration component. Potential evapotranspiration is computed daily, based on climatic data. Actual evapotranspiration is estimated by adjusting the potential value, using a correction factor that is a function of vegetation type, available water in the upper soil zone, and time.

SNOW COMPONENTS

The snow components are those functions and subroutines which simulate the initiation, accumulation, and depletion of the snowpack on each HRU. A snowpack is maintained and modified on both a water-equivalent basis and as a dynamic-heat reservoir. An energy balance in terms of caloric heat is computed daily for each HRU snowpack. The resulting gain or loss of heat energy is used to modify the existing snowpack conditions. The general energy-balance equation used considers the net shortwave radiation absorbed by the snowpack(Q_{SWN}), the net longwave radiation exchange between the snowpack and its environment (Q_{LWN}), and the energy input through the heat content of precipitation (Q_P). The components of this energy-balance equation are shown in figure 36.



EXPLANATION

Q_{SWN} = Shortwave in (SW_I)-Shortwave reflected (SW_R)

Q_{LWN} = Longwave canopy (LW_C) + Longwave air (LW_A)-Longwave snowpack (LW_P)

Q_P = Heat content of precipitation

FIGURE 36. — Components of the snowpack energy-balance equation used in the watershed model.

BASIN CONFIGURATION

Basin configuration refers to the conceptualization of the Piceance basin in terms of numbers and locations of HRU's, subsurface reservoirs, and ground-water reservoirs. The model was applied only to the 485-square-mile (1,256-km^2) drainage area above the gage on Piceance Creek below Ryan Gulch. This limitation is based principally on the considerations of adequate data and length of continuous streamflow record. The gage below Ryan Gulch has 9 years of continuous streamflow record, whereas the gages on Piceance Creek at White River and Yellow Creek near White River have only 3 and 1 years, respectively.

Figure 37 shows the initial subdivision of the Piceance Creek drainage above the gage below Ryan Gulch. The seven subdivisions shown were determined on the basis of slope, aspect, altitude, and snow distribution. Each of these was subdivided further, on the basis of vegetation and soils, to produce a total of 22 HRU's. Table 10 lists the numbered subdivisions shown in figure 37, the HRU's associated with each, and a general description of each HRU.

TABLE 10. — *Characteristics of the hydrologic-response units used in the digital watershed model*

Area No.[1]	HRU No.	Area (acres)	Aspect	Slope (percent)	Median altitude (feet above mean sea level)	Vegetation[2]	Available soil-water capacity (inches)
1---	1	8,860	NW.	10	6,600	SAGE	5.4
	2	21,730	NW.	10	6,600	P-J	3.0
	3	8,860	SE.	10	6,600	SAGE	5.4
	4	21,730	SE.	10	6,600	P-J	3.0
2---	5	10,685	NW.	10	7,500	SAGE-MB	4.5
	6	11,690	NW.	20	7,500	P-J	3.5
	7	10,685	SE.	20	7,500	SAGE-MB	4.5
	8	11,690	SE.	20	7,500	P-J	3.5
3---	9	32,800	EW.	10	7,500	SAGE-MB	4.5
	10	34,800	EW.	20	7,500	P-J	3.5
4---	11	20,240	NW.	30	8,200	MB-SAGE	4.5
	12	20,240	SW.	30	8,200	MB-SAGE	4.5
5---	13	12,800	NW.	20	8,200	MB-SAGE	4.5
	14	6,900	NW.	30	8,200	FOREST	4.5
	15	12,800	SE.	20	8,200	MB-SAGE	4.5
6---	16	9,550	SE.	20	7,400	SAGE	4.5
	17	4,770	SE.	20	7,400	P-J	3.5
	18	7,800	NW.	20	7,400	SAGE	4.5
	19	3,910	NW.	20	7,400	P-J	3.5
7---	20	5,570	SE.	10	7,000	SAGE	5.4
	21	22,290	SE.	10	7,000	P-J	3.0
1-7--	22	10,000	HOR[3]	0	6,800	SAGE	7.0

[1]Numbers refer to major subdivisions shown in figure 37.
[2]SAGE = sagebrush, P-J = Pinon-Juniper, MB = mountain browse.
[3]Horizontal surface with bottomlands in areas 1 through 7.

Subsurface flow from the study area was simulated using two subsurface reservoirs. The high-altitude HRU's (11-15) are routed through one subsurface reservoir and the remaining lower altitude HRU's are routed through the second. All flow from the lower altitude subsurface reservoir is routed to bottomland areas and is used by bottomland vegetation. Consequently, this reservoir has no contribution to basin streamflow. The use of supplemental water by bottomland vegetation was reported in the basin water-balance study by Wymore (1974) and was found to be a necessary assumption in model application. All flow from the high-altitude subsurface reservoir is routed to streamflow. The high-altitude HRU's compose the headwaters of most of the major tributaries of Piceance Creek. Drainages within these HRU's are relatively steep and narrow and have little bottomland alluvium for the storage of subsurface flow. Snowmelt is the primary source of subsurface flow and, because of their altitude, HRU's 11–15 receive more snow than the other HRU's. In addition, winter winds, primarily from the southwest, redistribute much of this snow into large drifts in the heads of the drainages. In March 1974 these drifts were observed by the U.S. Geological Survey to range in depth from 30 to 50 feet (10 to 14 m) and to have a density of about 0.3 gram per cubic centimetre. The concentration of water in the heads of drainages in the form of snow, and the small storage available in the valley bottoms of these HRU's support the assumption that only HRU's 11–15 contribute subsurface flow to streamflow. Because infiltration rates in the basin are assumed adequate to handle most daily snowmelt volumes, snowmelt runoff is managed primarily as subsurface flow. Consequently, HRU's 11–15 are the only sources of snowmelt runoff.

The ground-water system of the basin is described by a single ground-water reservoir to which all HRU's may contribute. Perched aquifers in the upper reaches of the basin tributaries and the upper and lower aquifers are all

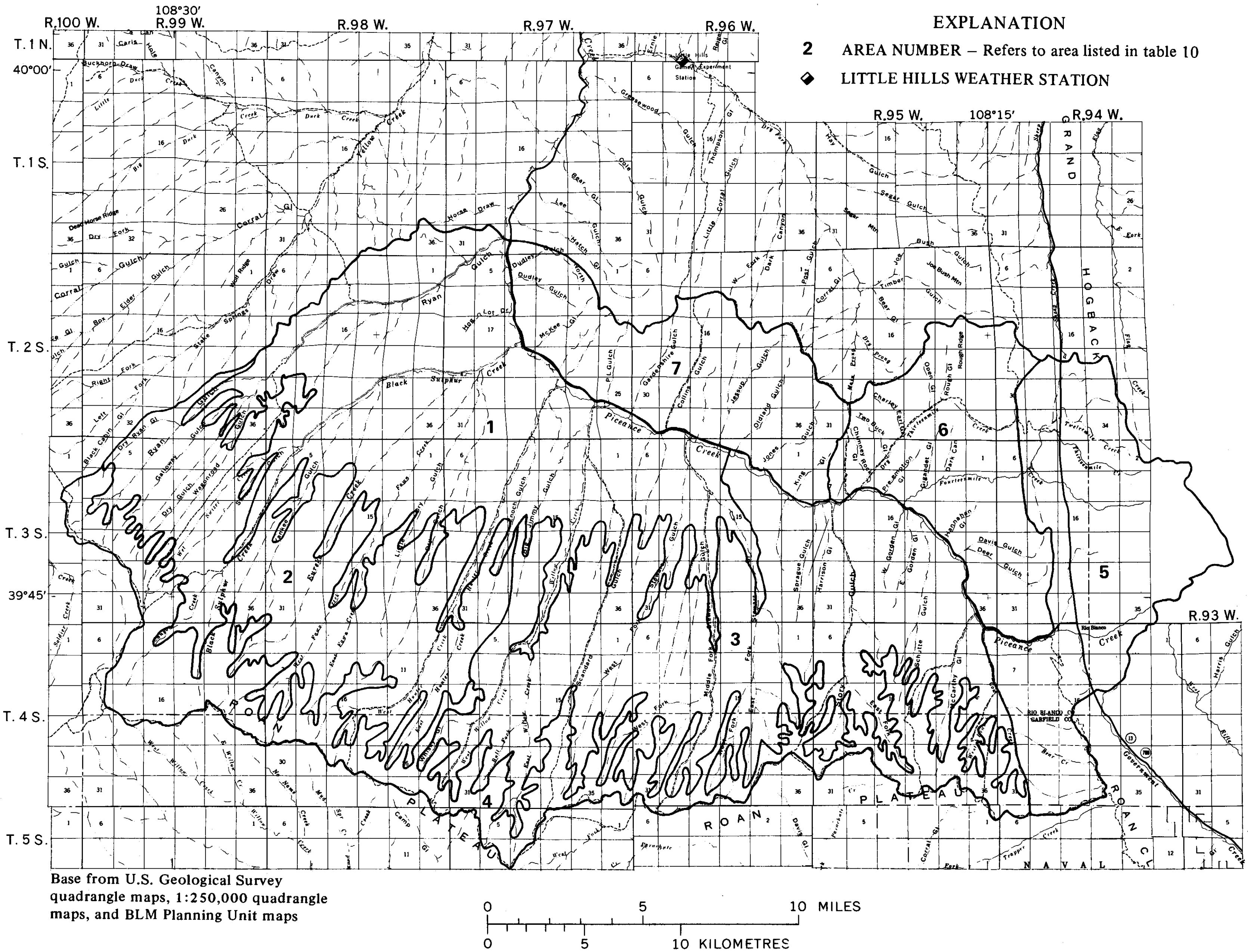


FIGURE 37. — Location of major subdivisions and weather stations used in the watershed model.

sources of ground-water discharge. However, sufficient data are not available to permit the simulation of each of these ground-water zones as distinct discharge sources.

MODEL PARAMETERS AND PARAMETER FITTING

A total of 10 parameters are available for fitting the model to historic streamflow records. Because the model is designed to simulate regions where snowmelt is of prime importance, the 10 parameters are the factors most significantly affecting snow accumulation and melt and the resultant volume and timing of basin runoff. Each parameter is associated with a physical hydrologic property of the watershed and has some physical significance in the hydrologic system.

The model is normally fitted using an objective parameter-fitting procedure developed by Rosenbrock (1960). The procedure is a direct-search algorithm which permits the constraining of all parameters to a range of realistic values. The objective function used for parameter optimization is

$$MIN \ \Sigma_i |P_i - O_i|, \tag{2}$$

where

i = the ith day,

P_i = predicted mean daily streamflow on the ith day,

O_i = observed mean daily streamflow on the ith day.

Equation 2 is the minimization of the sum of the absolute differences between the predicted mean daily flow and the observed mean daily flow.

Application of this procedure to the Piceance basin, however, is impossible with the data currently available on streamflow and irrigation diversions. Streamflow data for the snowmelt period does not reflect "natural" basin response because of diversions, and the records on irrigation diversions are not adequate to permit the estimation of "natural" basin response on a daily basis. Therefore, to accommodate available data, a change was made in both the fitting procedure and the fitting criterion.

The fitting procedure was changed to a manual method, thus adding some subjectivity to the procedure, so that known data shortcomings could be taken into account in the "best fit" determination. In addition, the number of parameters used to fit the model was limited to three—two which influence snowpack accumulation and melt, and one which affects snowmelt routing to ground-water recharge. Two of the remaining seven parameters are subsurface reservoir routing parameters which affect only the shape of the runoff hydrograph during the snowmelt period. These two parameters were estimated using hydrographs from the streamflow records of the U.S. Geological Survey gaging station Willow Creek above diversions, near Ouray, Utah. The Willow Creek drainage basin is about 60 miles (77 km) west of the Piceance basin and is hydrologically similar. The remaining five parameters were estimated from basin characteristics. Initial application of the model to a forested mountain watershed indicates that these five parameters can be reasonably estimated from basin characteristics (Leavesley, 1973).

The fitting criterion was changed and expanded to the following:

1. The minimization of the difference between predicted and observed mean daily flows for the period November through February.
2. The minimization of the difference between the predicted and estimated annual volume of discharge. Estimated annual discharge is considered to be the "natural" basin discharge and is computed as the sum of the annual measured discharge, irrigation diversion bypassing the gage, and streamflow depletions due to irrigation above the gage.
3. The proper timing of runoff during the spring snowmelt period.

Criterion 1 was used to fit the ground-water recharge parameter and criteria 2 and 3 were used to fit the snowpack accumulation and melt parameters. The application of these criteria will be discussed further in the model-calibration section of this report.

DATA REQUIREMENTS

Model data requirements are the basin descriptive, climatic, and hydrologic information necessary to define the physical characteristics, daily inputs, and hydrologic response of each HRU. Most of the currently available data is point-source data defining a few specific areas of the basin. To define the total basin system, these data were extrapolated to undefined areas, using general soils, vegetation, and altitude relationships. The extrapolation procedure provides the total basin description necessary for initial model application. However, it also provides an additional source of data error to be accounted for in model calibration. Hydrologic and environmental data to be collected during preliminary oil-shale development will provide additional information necessary to better define the basin and improve its simulation.

BASIN DESCRIPTIVE DATA

The basin descriptive-data requirements are the physiographic, soil, vegetative, and hydrologic characteristics of each HRU. Several of these characteristics are listed in table 10. The physiographic data are area, slope, aspect, and altitude obtained from topographic maps. These play a primary role in basin subdivision. The soils data describe the physical properties of the soil mantle and consist of soil type, water-storage capacity, and infiltration characteristics. Information on soils was obtained from a description of the soils of the Piceance Creek and Yellow Creek drainage basins by Campbell, Berg, and Heil (1974) and from a water-balance study for the same region by Wymore (1974). Vegetation data required are type, density, interception storage, and transpiration characteristics. These data were obtained from a vegetation analysis of the Piceance and Yellow Creek basins by Ward, Slauson, and Dix (1974), from a vegetation map prepared by Terwilliger and Threlkeld (1974), from available aerial photographic coverage, from field observations, and from pertinent literature on the characteristics of the vegetation communities in the region.

CLIMATIC DATA

The climatic data required are daily precipitation, maximum and minimum air temperature, and solar radiation. In addition, estimates of the variation of these variables with changes in slope, aspect, and altitude are also needed. Daily precipitation and air-temperature data are available from Little Hills climatic station which is located on Dry Fork Piceance Creek at an altitude of 6,148 feet (1,874 m; fig. 37). These climatic data were corrected for differences in slope, aspect, and altitude between Little Hills and each HRU, using correction factors derived in a regional climate analysis by Wymore, Striffler, and Berg (1972).

Solar radiation data are collected at Grand Junction, Colo., located about 60 miles (97 km) south of Little Hills. Grand Junction is the nearest solar radiation station with records concurrent with discharge records at Piceance Creek below Ryan Gulch. Examination of these data indicated that they were not representative of solar radiation received on concurrent days at Little Hills. Therefore, daily solar radiation received at Little Hills was estimated from daily potential solar radiation and daily maximum air temperature, using a technique reported by Leaf and Brink (1973). A monthly linear relationship was developed relating daily maximum air temperature at Little Hills and percent potential solar radiation estimated to be received at Little Hills. Daily potential solar radiation is primarily a function of latitude, time of year, slope, and aspect and is easily computed for the basin, using data reported by Frank and Lee (1966). Multiplying this potential value by the percent correction factor obtained from the appropriate monthly temperature-radiation relationship, an estimate of the actual solar radiation received at Little Hills is obtained. This estimate is for a day with no precipitation. For days with precipitation the estimate is further reduced by a straight percentage that is also a function of the month of the year. Comparing computed estimates with daily solar radiation measurements—collected by Colony Development Operation at Grand Valley, Colo. (approximately 15 miles (24 km) south of the basin), for the period February through April 1973—showed that the empirical technique described above gives reasonable daily solar radiation estimates.

An optional feature of the model provides for the adjustment of snowpack depths on each HRU on the basis of snow distribution relationships between each HRU and an available index snow course. Precipitation gage catch of snowfall is strongly affected by wind. Gage catch deficiency can range from 0 to 73 percent depending on the wind velocity associated with a given storm (U.S. Army, 1956). Therefore, snow-course data may provide a better estimate of precipitation received during the winter than the gage at Little Hills. Snow distribution on the Piceance Creek drainage basin was determined by the U.S. Geological Survey for the 1974 water year. This distribution was related the Burro Mountain snow course located approximately 32 miles (51 km) east of Little Hills in the White River basin at an altitude of 9,000 feet (2,743 m). The Burro Mountain snow course is measured monthly and reported annually by the U.S. Soil Conservation Service. Using the data from Burro Mountain and the snow distribution relationships for the 1974 water year, the snowpack on each HRU was adjusted on the first day of February of each year simulated.

HYDROLOGIC DATA

Hydrologic data required for the model are primarily streamflow records from which snowmelt-runoff and rainfall-runoff relationships can be derived. These data were obtained from streamflow data reported annually by the U.S. Geological Survey (1961–73) and streamflow and springflow data reported by Ficke, Weeks, and Welder (1974).

The November through February streamflow records provide the data from which the ground-water storage-reservoir volume and routing coefficients were determined. The March through October streamflow records should provide the data from which the snowmelt and subsurface-reservoir routing coefficients can be determined. However, the effects of irrigation diversions from March through October mask the snowmelt- and rainfall-runoff relationships for the basin. To estimate the irrigation effects, additional data on diversions and irrigated acreage in the basin were obtained from the Colorado Division of Water Resources.

Streamflow depletion resulting from irrigation was computed as the sum of the daily differences between evapotranspiration from irrigated areas and evapotranspiration from the same acreage under natural conditions. Evapotranspiration from irrigated lands was computed daily as a function of the number of acres irrigated, an average monthly crop coefficient, seasonal water availability, and a constant 20-percent increase for incidental losses. The daily irrigated acreage was computed from the Colorado Division of Water Resources data. The crop coefficients and seasonal water availability were taken from Wymore (1974). Evapotranspiration under natural conditions is computed by the evapotranspiration component of the model. Although the depletion estimates are computed daily, they cannot be used to reconstruct "natural" basin daily discharge. The loss computed for a specific day is not necessarily the result of water applied on that day. However, the sum of these depletions is a reasonable estimate of the annual streamflow loss.

CALIBRATION

Calibration of the watershed model involves the fitting of predicted discharge to recorded discharge and irrigation data. The measures of the goodness of fit are the three criteria discussed in the previous section on model parameters and parameter fitting. The use of these specific criteria was necessitated by the effects of irrigation on the "natural" basin discharge.

The effects of irrigation diversions can be seen in the measured discharge records. Figure 38 shows the measured daily discharge hydrographs for the 9 years of record at the Piceance Creek below Ryan Gulch gage. The decline in daily discharge, usually in March, indicates the start of irrigation diversions, and the rise in the hydrograph in late October or early November indicates the end of diversions. The only part of the measured hydrograph that is representative of "natural" basin discharge is the winter period of mid-November through February. Also shown in figure 38 are the predicted daily discharge hydrographs for the corresponding water years of record. These hydrographs are the predicted "natural" basin discharges for the entire period of simulation.

Figure 38 is used in the examination of each of the three fitting criteria. When using this figure for comparing measured and predicted discharges, the only part of the two hydrographs directly comparable is the winter period of mid-November through February. During the remainder of the year, irrigation reduces measured discharge below "natural" basin discharge. Therefore, predicted discharge over this period should be somewhat larger than measured discharge. This is an important distinction between the two hydrographs which must be remembered when using figure 38 as a measure of model fit.

MODEL FIT

CRITERION 1

The first criterion is the minimization of the differences between predicted and observed daily discharge for the winter period of mid-November through February. During this period there are normally no irrigation diversions, and measured discharge records reflect "natural" basin response. Simulation of the winter-period discharge from the Piceance basin requires a correct simulation of the volume of ground-water recharge during the previous snowmelt season. The volume of ground-water recharge is a function of the complex association among water availability, antecedent soil-water conditions, and the physically limiting percolation rate to ground water. Under dry antecedent conditions, ground-water recharge will be limited by water availability. With moist antecedent conditions or high precipitation, the percolation rate will limit recharge. Because the water available for recharge is stored as a snowpack, the rate of snowmelt will also affect the volume of recharge. The minimization of the differences between predicted and observed daily discharge during the winter is a measure of the fit of the ground-water recharge parameter.

Figure 38 shows the measured and predicted daily discharge hydrographs for the period of record. With the exception of the 1970 and 1971 water years the model predicted the winter-period discharges reasonably well. Daily differences between predicted and measured discharges generally range from 0 to 3 ft^3/s (85 l/s) with a few periods having differences as large as 10 ft^3/s (283 l/s). The underestimate of the winter-period discharges for the 1970 and 1971 water years is the result of inadequate ground-water recharge during the 1969 and 1970 water years. An overestimate of ground-water recharge for the 1971 water year produces a compensating error and brings the ground-water system back to a good fit for 1972 and 1973.

As stated above, ground-water recharge is a function of the total volume of water available for recharge and of the soil-water-storage deficit which must be satisfied before recharge can occur. In the Piceance basin the summer evapotranspiration far exceeds summer precipitation and the available soil-water-storage capacity of the basin. Consequently, the soil-water-storage deficit is normally at a maximum at the beginning of each fall. Evapotranspiration demands for the fall and winter drop far below those of the summer; thus, fall precipitation plus some winter snowmelt become the controlling factors in determining antecedent soil-water conditions for the spring snowmelt period. The prediction of October through May precipitation volume and distribution are one of the primary sources of error in the simulation of ground-water recharge.

Extended periods of extremely cold weather are sources of errors in the measured discharge record during the winter. These periods produce an ice-affected discharge record in which intermittent periods of record are completely lost. Periods of estimated daily discharge due to ice effect appear in the measured daily discharge hydrographs of figure 38. For example, the daily discharges from December 11 to January 5 and January 17 to January 29 for the 1973 water year, and from December 13 to January 15 for the 1972 water year, were estimated using available hydrologic and climatic information. The model does not simulate ice effects and, therefore, this possible source of error in predicted winter discharge must be considered when examining the winter-period fit.

The average measured discharges for the winter periods of record ranged from approximately 10 ft^3/s (283 l/s) for the 1968 water year to approximately 22 ft^3/s (620 l/s) for the 1970 water year. The accuracy of the measured daily discharges for the winter period are classified by the U.S. Geological Survey as "fair." This means that about 95 percent of the daily discharges are within 15 percent of the measured value. With this size error range in the measured daily discharges, the predicted daily discharges are reasonable estimates of the winter-period discharges for 7 of the 9 years of record. The poor fits for the other 2 years of record are the result of inadequate precipitation input. The degree of fit obtained under the winter-period-discharge criterion indicates that the model is reasonably simulating the ground-water system of the basin for the period of record.

Criterion 2

The second fitting criterion is the minimization of the difference between predicted annual discharge and estimated annual "natural" basin discharge. Estimated "natural" basin discharge was computed annually as the sum of measured discharge, estimated irrigation diversions around the gage, and estimated streamflow depletions due to irrigation above the gage. Table 11 lists the annual measured, estimated "natural"-basin, and simulated discharge volumes for the 9 water years of record. The proportion of the estimated volumes made up by the measured volumes ranges from 65 percent for 1967 to 83 percent for 1973.

The difference between the simulated and estimated annual volumes is shown in table 11 as both a volume error and a percentage error in terms of the estimated discharge. In both relative and absolute error sizes, the 1968, 1970, and 1972 water years have the largest errors. Examination of the simulated hydrographs for these 3 water years in figure 38 indicates that the 1970 error is the result of a poor baseflow fit, explained under the previous criterion, and too little snowmelt runoff in the spring. The 1968 and 1972 water-year errors result from too much spring snowmelt runoff. Likewise, the smaller errors for the remaining water years are primarily the result of an error in snowmelt-runoff volume.

The size of the discharge volume errors is an inherent problem in the modeling of large basins that yield only a small part of their total precipitation input to streamflow. The average annual estimated "natural" basin yield for the 9 years of record was 0.63 inch (16 mm), and the average annual basin precipitation adjusted for altitude was 18.22 inches (463 mm). Consequently, small precipitation errors occurring over large basin areas result in relatively large volume errors.

Another source of possible volume error is the definition of HRU's 11–15 (table 10) as the only surface and subsurface runoff areas for snowmelt. Snowmelt runoff areas are a function of precipitation volume and distribution and may vary in size from year to year from the fixed boundaries of HRU's 11–15. However, the determination of this variation can be made only with additional precipitation and discharge data.

Considering the problems associated with fitting annual discharges discussed above and given the limited

TABLE 11. — *Measured, estimated, and simulated annual discharge and associated error for the period of record at Piceance Creek below Ryan Gulch*

[Data are in acre-feet except as indicated]

Water year	Measured discharge	Estimated "natural" discharge	Simulated "natural" discharge	Error	Percent error
1965-----	11,200	15,040	13,960	-1,080	7
1966-----	9,950	13,900	12,780	-1,120	8
1967-----	6,000	9,210	7,950	-1,260	14
1968-----	9,450	14,090	19,220	+5,130	36
1969-----	13,770	19,440	15,280	-4,160	21
1970-----	16,800	22,150	12,050	-10,100	46
1971-----	11,880	17,620	16,030	-1,590	9
1972-----	7,870	11,820	19,020	+7,200	61
1973-----	21,060	25,290	29,930	+4,640	18

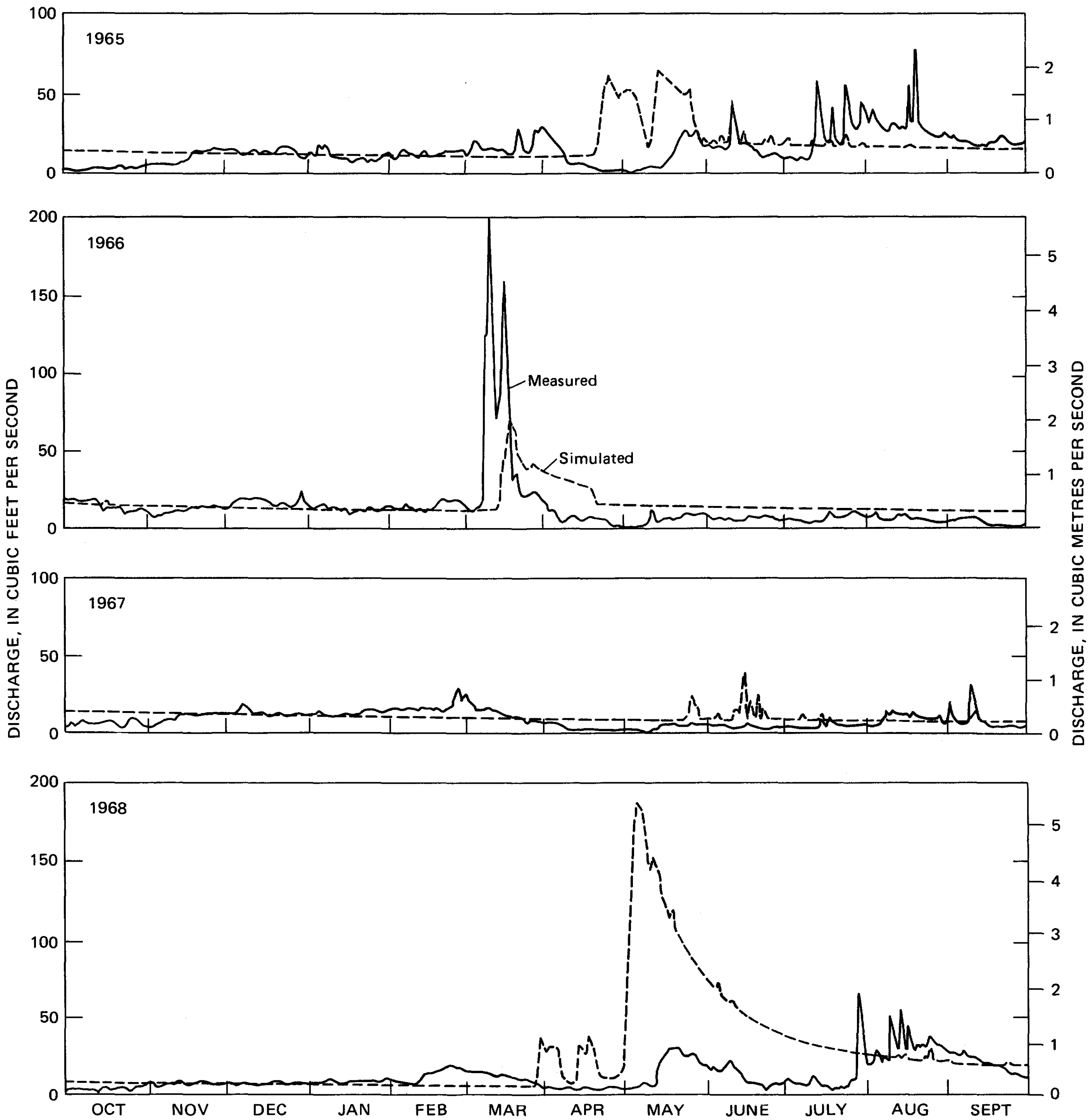


FIGURE 38 (above and facing page). — Measured daily discharge and simulated daily "natural" basin discharge for the period of record at Piceance Creek below Ryan Gulch.

precipitation and discharge data, the errors shown in table 11 are the best fit obtainable, given the current data constraints.

CRITERION 3

The third criterion is the correct simulation of snowmelt-runoff timing. This entails the fit of the start of the snowmelt-runoff period and the reproduction of fluctuations in daily discharge volumes over this period. Due to irrigation, the daily discharge fluctuations for spring and summer are considerably damped. However, the change in daily discharge in the spring is usually large enough to reasonably estimate the start of snowmelt runoff. Likewise, the larger changes in daily discharge over the snowmelt period can be detected in the measured discharge records.

Errors in the correct start of spring runoff result

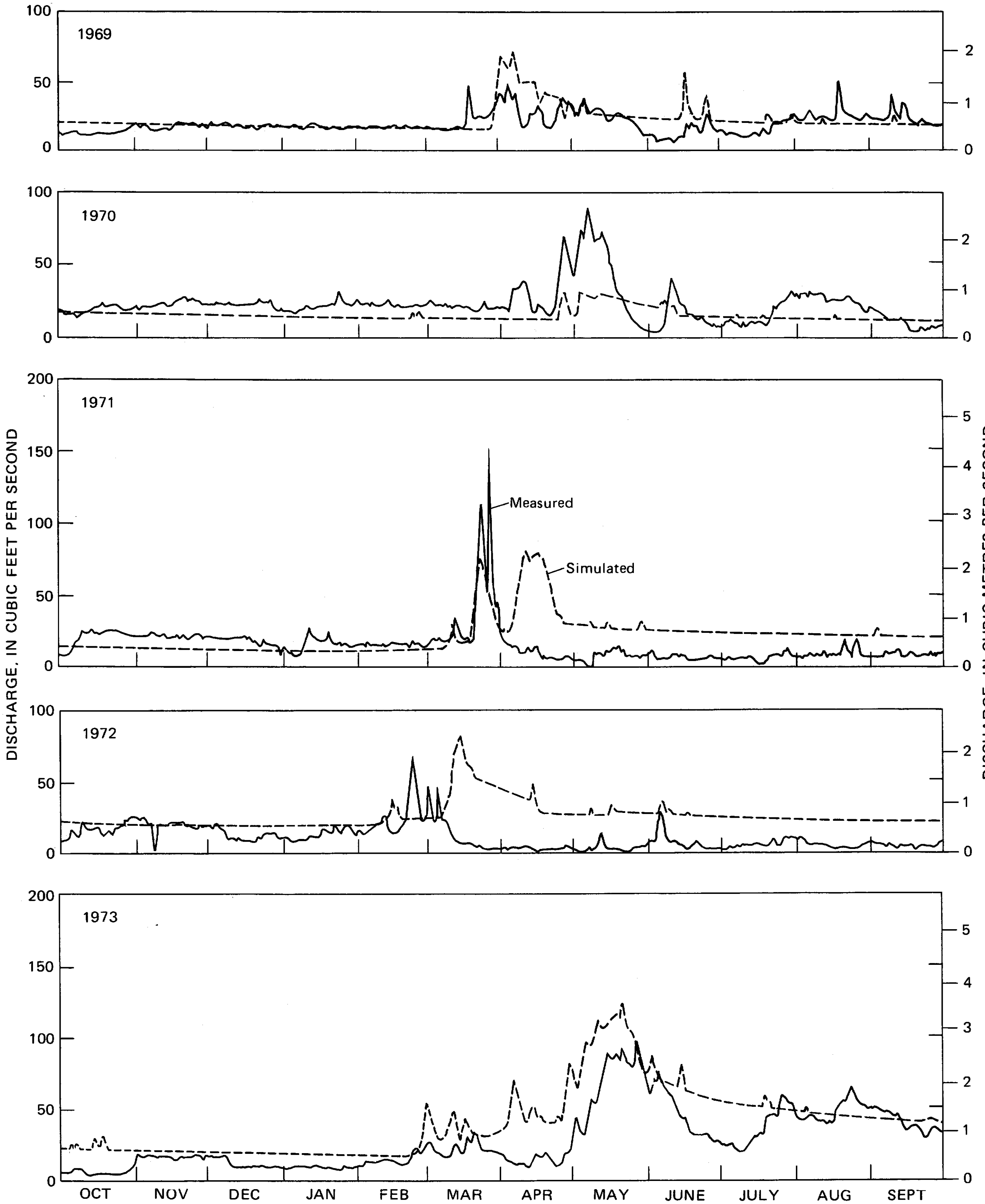


FIGURE 38. — Continued.

primarily from improperly defined antecedent soil-water conditions and errors in the snowpack energy-balance computations. The problems of antecedent soil-water conditions were discussed in the previous criteria of fit and were related to precipitation input errors. Errors in the snowpack energy-balance result primarily from errors in air temperature and solar radiation. The lack of data on temperature distribution and the estimation of daily solar radiation from maximum daily air temperatures are both sources of error large enough to influence the start of snowmelt. Proper fitting of discharge fluctuations once snowmelt has begun is primarily a function of the energy-balance computations and adequate precipitation.

The fit of this criterion is more subjective than the preceding two and is based on the comparison of the measured with the predicted daily discharge hydrographs shown in figure 38. Again, it should be emphasized that the fit is relative because the measured hydrograph reflects the influence of irrigation while the predicted hydrograph does not.

The start of snowmelt runoff has subjectively been defined as a significant change in measured daily discharge between February and April. Examination of the measured discharge hydrographs of figure 38 indicates that, with the exception of 1967 and 1968, all years have a significant change in discharge during this period. Selection of an exact date is not possible. However, comparison of the dates of significant change for the predicted and measured hydrographs indicates that, for all water years but 1965 and 1970, the predicted rise occurs within about a week of the measured rise. The 1965 water year is the first year of simulation. Consequently, an error in the initial condition estimates of the basin soil-water-storage deficit could cause the late start shown in figure 38. The poor fit in 1970 is due to insufficient precipitation input which has been discussed in the previous two criteria.

Some snowmelt runoff is evident in the 1967 and 1968 water years. However, the magnitude of the change indicates only a small volume of runoff. The failure of the model to predict the start for both of these years may be the result of inadequate precipitation input or inadequate definition of the source area for surface and subsurface runoff.

Comparison of the snowmelt parts of the predicted and measured hydrographs in figure 38 indicates that the timing of major discharge fluctuations are reasonably well simulated. Even when large errors exist in the magnitude of the fluctuation, their timing is very good.

Given the present limitations on precipitation, temperature, and solar-radiation data, the fitting of snowmelt timing is considered to be reasonable.

DISCUSSION

The model fit, based on the three established criteria, can be characterized as good, given the present data constraints. The two greatest constraints on fit are the inadequate definitions of precipitation input and daily discharge. The causes of a poor definition in precipitation are the availability of only one precipitation gage for a 485-square-mile (1,256-km^2) basin area and the wind-associated problems of gaging snowfall accurately. The use of an index snow course can reduce precipitation errors. However, the only snow course available lies outside the basin and is climatically more typical of mountain regions receiving larger snowfalls. The problems with discharge data are the influences of irrigation on daily records and the lack of discharge data for the major tributaries of Piceance Creek.

The ground-water component of the hydrologic system is somewhat better simulated than the surface-subsurface runoff component. This is due to the greater sensitivity of model estimates of surface-subsurface runoff to errors in precipitation input. The limit on daily ground-water discharge and the satisfying of daily ground-water recharge, before routing additional snowmelt or rainfall to surface-subsurface runoff, accounts for this sensitivity in the model. Consequently, an underestimate of precipitation can result in adequate ground-water recharge but underestimated surface and subsurface runoff. Conversely, an overestimate of precipitation can result in adequate ground-water recharge but overestimated surface and subsurface runoff. This sensitivity is shown by comparing the total error size of each water year listed in table 11 with the fit of the winter-flow period of the following water year shown in figure 38. For example, the large overestimate of the 1968 volume of discharge (table 11) had little effect on the winter discharge in 1969 water year (fig. 38).

The model fit provides sufficient definition of the basin's hydrologic system to permit a general examination of system characteristics and the prediction of relative changes in basin response resulting from modifications to the system and its inputs. However, the resulting determinations and predictions must be qualified as being the best initial estimates, on the basis of limited data and current model assumptions. Improved model fit and predictive capabilites will result from a better measure of precipitation input and improved definition of the basin hydrologic system. The data necessary to make these improvements will be available from a basic-data network being established by the Department of the Interior to monitor the effects of oil-shale development.

SIMULATED EFFECTS OF DEVELOPMENT ON THE HYDROLOGIC SYSTEM

The effects of oil-shale development on the hydrologic system will result primarily from land-surface modifications and possible weather and climate modifications. Both of these modifications will produce changes in the basin water balance and in the quality of basin discharge. Prediction of water-quality changes is beyond the scope of the watershed model and therefore will not be considered. One change in the basin water balance will result from increased ground-water discharge due to mine dewatering. The effects of mine dewatering are best examined with the ground-water model and will be discussed later in this report.

LAND-SURFACE MODIFICATION

The effects of changes in infiltration and evapotranspiration characteristics will be a function of the type of land-surface modification and the location and size of the area modified. On the basis of data in the Preliminary Development Plans for tracts C–a and C–b, land-surface modifications will entail the development of minesites and plantsites, the establishment of spent-shale disposal piles, upgrading of existing roads, construction of new roads, and the construction of a service corridor for transporting power, water, and petroleum products. With the exception of the service corridor and the upgrading of existing roads, all changes that have hydrologic significance will be limited to the lease tracts and areas immediately adjacent to the tracts. The service corridor may pose some erosional problems until vegetation is reestablished on it but should have minimal effects on runoff. The upgrading of existing roads will also have little effect on the hydrology of the basin.

The area of land influenced by the development of tract C–a is about 15 square miles (39 km^2). This includes an open-pit and underground mine on the tract and proposed spent-shale disposal areas off tract. The area that will be influenced by the development of tract C–b is about 10 square miles (26 km^2). This includes an underground mine and proposed spent-shale disposal areas on the tract. The total area of possible disturbance for both tracts is about 25 square miles (65 km^2) or about 3 percent of the total basin area of 887 square miles (2,297 km^2). Both areas are located outside the regions of significant ground-water recharge and, therefore, will have little effect on this part of the basin water balance.

The major effect of tract development will be an increase in surface runoff resulting from minesite and plantsite development and the establishment of spent-shale disposal areas. Precipitation from summer thunderstorms on the tract will produce larger runoff volumes than they would under natural, undeveloped conditions. The effects of development on snowmelt will be less significant and will vary primarily as a function of accumulated snowpack water-equivalent and daily-snowmelt rates.

The major source of increased surface runoff will be from the spent-shale disposal areas. The physical and hydrologic properties of the disposal piles are a function of the oil-shale retorting process used, the degree of vegetative cover established on the piles, and the degree of pile compaction (Striffler and others, 1974). J. R. Meiman (written commun., 1974) reported that the infiltration rates for spent-shale piles were a function of both the type of retorting process used and the condition of the spent-shale pile surface. Meiman reported that the average 1-hour infiltration rate for TOSCO II-processed spent shale ranged from 2.5 cm/hr for a moist or mulched surface to 0 cm/hr for a surface which had been allowed to dry and become powdery and salty.

The lessees of tract C–b have proposed the use of the TOSCO II process for shale retorting while the lessees of tract C–a have not specified a process. However, regardless of the process used, the compaction of the disposal piles will significantly affect their infiltration and percolation characteristics. During development, compaction and wetting and drying may produce a virtually impermeable surface. Consequently, until vegetation is established on the disposal piles most of the precipitation on the piles could run off. If impermeability is assumed, the estimated average annual precipitation for the tracts of about 17 inches (430 mm) would produce an annual runoff of about 1.4 acre-feet per acre (7 m^3/km^2) of disposal-pile surface. This unit runoff is the maximum average annual yield possible and is an overestimate of actual yield.

To meet the lease stipulations of avoidance or minimization of damage to the environment, water-control structures for both tracts are proposed. The Preliminary Development Plans for both tracts state that diversion and control structures will be used to handle runoff and store it for use in either shale processing or disposal. These storage facilities will also prevent the pollution of surface waters resulting from surface runoff from the disposal areas. The intention of the lease stipulations is to limit the effects of development to the tracts and prevent significant impacts on the environment of the Piceance basin.

With respect to the area simulated by the watershed model (fig. 37), changes in the infiltration and evapotranspiration characteristics of tract C–b will have significant hydrologic effects only within the tract. Therefore, the effects of these changes will not be considered in this study.

WEATHER AND CLIMATE MODIFICATION

Weather and climate modifications may result from the introduction of industrial pollutants into the atmosphere (Hobbs and others, 1974). The oil-shale industry will be a source of atmospheric pollutants and, therefore, the potential exists for changes in the climatic variables of temperature, solar radiation, and precipitation over the basin. In addition, consideration may be given to intentional attempts at cloud seeding to increase basin precipitation. Changes in the climate would affect the total basin water balance and influence the hydrologic response of the basin. The possibility of modifying basin precipitation is an important consequence of weather modification because of the water requirements for industrial processing of oil-shale and the revegetation of spent-shale waste. Therefore, the watershed model was used to simulate the effect of precipitation modification on the hydrology of the Piceance basin.

Precipitation modification can occur with both winter and summer storms. Changes in precipitation from winter orographic and frontal storms will affect the entire basin. However, modification of summer thunderstorms which are limited in areal extent may have only local effects. Also, the large evapotranspiration demands during the summer period would consume any additional water which did not immediately run off. Therefore, only changes in precipitation for winter storms were simulated. Summer precipitation was simulated without change.

Hobbs, Harrison, and Robinson (1974) have reported that the introduction of ice nuclei from industrial pollution sources into cold clouds may either cause an increase or a decrease in precipitation. The magnitude and sign of the change in precipitation was stated to be a function of the number of nuclei introduced. In a discussion on the intentional seeding of winter storms, Kahan (1972) also noted precipitation increases and decreases. He states that a key factor in determining the effects of seeding is cloud-top temperatures.

The magnitude and sign of changes in natural precipitation resulting from oil-shale development is unknown. However, for discriminate seeding of winter storms, Kahan (1972) states that the potential increase for mountain areas is about 10 to 20 percent. To cover all reasonable estimates of changes in precipitation, the watershed model was used to simulate the effects of a 0, 10, and 20 percent increase and a 10 percent decrease in natural precipitation occurring from October through May. These changes in precipitation were simulated by changing, by the appropriate percentage, the 9 years of precipitation data used in the model calibration. The 0 percent increase represents the natural precipitation conditions for the months October through May.

The effects of precipitation modification on ground-water recharge are shown in table 12. Listed are the natural precipitation for the period October through May for each water year simulated and the predicted annual ground-water recharge resulting from the precipitation modifications. The table shows that ground-water recharge under natural precipitation conditions ranged from 0 to about 2 inches (51 mm) for the 9 years simulated. Variations in recharge reflect the effects of antecedent soil-water conditions and the percolation rate to ground water. The lack of recharge for the 1967 water year until a 20-percent increase was applied reflects the strong influence of antecedent soil-water conditions resulting from 2 consecutive years of low winter precipitation.

Comparison of the average recharge values shown in table 12 indicates that there is about a 0.25-inch (6-mm) change in recharge for each 10-percent change in precipitation. Relative to the average ground-water recharge from natural precipitation, the average increase or decrease in recharge represents about 40-percent change in recharge for each 10-percent change in precipitation.

The effects of precipitation modification on ground-water recharge are a function of both antecedent soil-water conditions and the limiting percolation rate to the ground-water reservoir. Figure 39 shows the relationship between predicted ground-water recharge and precipitation received for the period October through May for the four precipitation changes simulated. The large variation in recharge associated with the lower precipitation amounts reflects the effects of antecedent soil-water conditions on total recharge. However, as precipitation increases, antecedent soil-water storage increases and the rate of percolation to ground water controls recharge. This reduces the variation in ground-water recharge as precipitation increases. The envelope line drawn through the largest recharge values is an estimate of the maximum recharge obtainable for a given precipitation input. This maximum is based on the assumptions that little or no soil-water storage deficits exist prior to recharge and that the percolation rate for the basin is reasonably well defined. The slope of this line indicates that under the above assumptions the maximum ground-water recharge obtainable is about 0.3 inch (7.6 mm) over the basin from each 1-inch (25-mm) increase in precipitation.

The effects of precipitation modification on annual basin discharge are shown in table 13. Listed are the natural precipitation for the period October through May for each water year simulated and the predicted annual discharges resulting from precipitation modifications. Variations in annual discharge reflect the effects of antecedent soil-water conditions and total water input during the October through May period.

Comparison of the annual discharges and their changes with respect to the 0-percent-precipitation increase (table 13) indicates that discharge increases associated with precipitation increases are larger than the discharge decrease occurring with decreased precipitation. Relative to the average 0-percent increase, the 10-percent decrease in precipitation resulted in a 30-

TABLE 12. — *Computed ground-water recharge resulting from simulated changes in precipitation*

Water year	Natural precipitation (inches)[1]	Ground-water recharge (inches)[2]			
		Percent change in precipitation			
		-10	0	10	20
1965------	13.50	0.27	0.50	0.78	1.14
1966------	10.37	.14	.26	.41	.59
1967------	10.49	0	0	0	.03
1968------	14.18	.58	.93	1.39	1.83
1969------	10.81	.30	.45	.59	.82
1970------	10.95	.12	.21	.29	.50
1971------	14.14	.61	.95	1.23	1.56
1972------	13.14	.41	.68	.97	1.31
1973------	16.80	1.41	1.96	2.51	3.05
Average recharge--------		0.43	0.66	0.91	1.20
Change in average[3]------		-.23	0	.25	.54

[1]October to May for drainage above gage on Piceance Creek below Ryan Gulch.
[2]Annual recharge for drainage above gage on Piceance Creek below Ryan Gulch.
[3]With respect to zero precipitation change.

TABLE 13. — *Computed discharge at Piceance Creek below Ryan Gulch resulting from simulated changes in precipitation*

Water year	Natural precipitation (inches)[1]	Annual discharge (inches)			
		Percent change in precipitation			
		-10	0	10	20
1965------	13.50	0.47	0.54	0.70	0.94
1966------	10.37	.38	.49	.67	.85
1967------	10.49	.22	.31	.41	.54
1968------	14.18	.49	.75	1.04	1.35
1969------	10.81	.38	.59	.88	1.21
1970------	10.95	.28	.47	.68	.92
1971------	14.14	.39	.61	.90	1.19
1972------	13.14	.47	.74	1.03	1.40
1973------	16.80	.75	1.16	1.62	2.10
Average discharge-------		0.43	0.63	0.88	1.17
Change in average[2]------		-.20	0	.25	.54
Percentage of average occurring as ground-water discharge------------		83	82	79	78

[1]October to May.
[2]With respect to zero precipitation change.

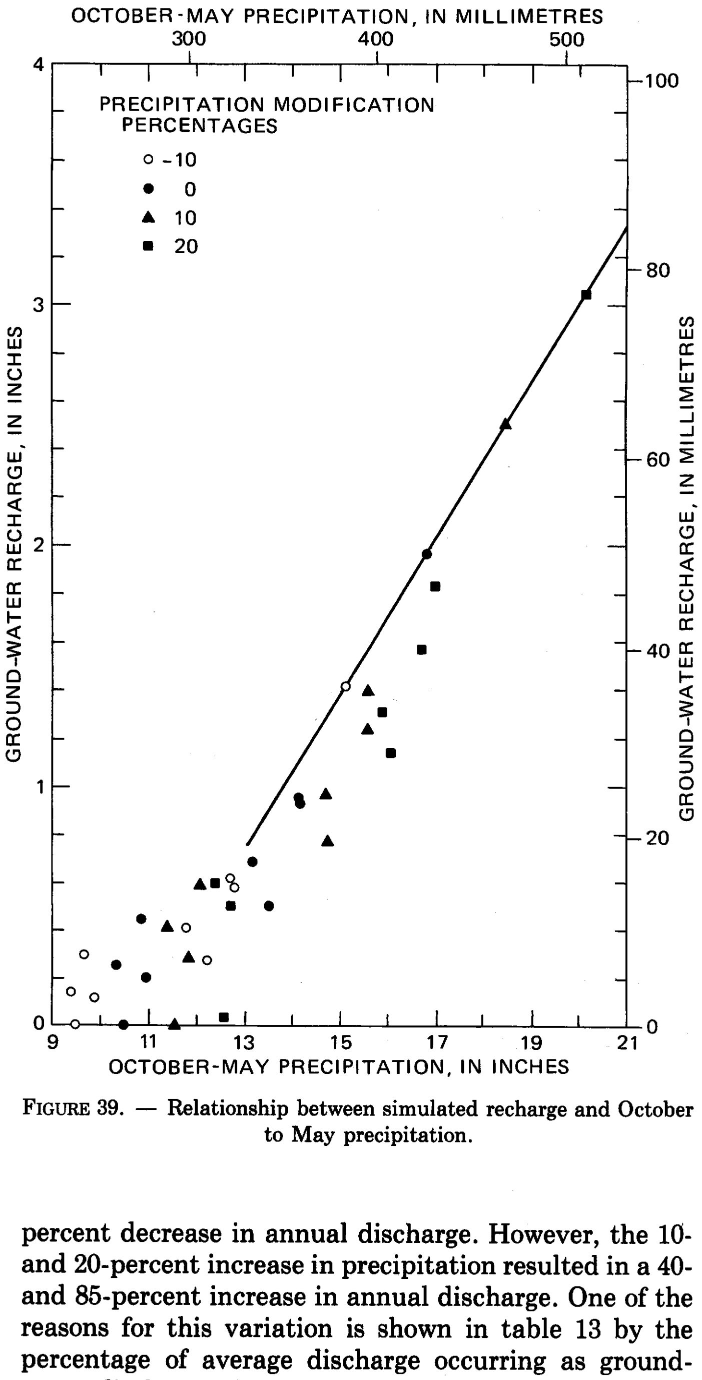


FIGURE 39. — Relationship between simulated recharge and October to May precipitation.

percent decrease in annual discharge. However, the 10- and 20-percent increase in precipitation resulted in a 40- and 85-percent increase in annual discharge. One of the reasons for this variation is shown in table 13 by the percentage of average discharge occurring as ground-water discharge. As precipitation and annual discharge increase, the percentage of the total discharge contributed by ground water decreases. The percentage of change is small but it does reflect the increased contributions from surface and subsurface runoff during the spring-snowmelt period. In the model the rate at which snowmelt recharges ground water is limited by the percolation rate. Therefore, estimated additional water in excess of the daily ground-water recharge will appear as surface or subsurface discharge. The small change in the ground-water contributions for the 10-percent decrease in precipitation indicates that, even though annual discharge is reduced, the ratio of surface and subsurface discharge to ground-water discharge remains the same.

DISCUSSION

Simulation results indicate that precipitation modification of winter storms can have a significant effect on the ground-water system and the annual discharge from the Piceance basin. Changes in ground-water recharge resulting from precipitation modification were directly proportional to the precipitation change. However, changes in annual discharge depend on the magnitude and sign of the precipitation change. For all precipitation modifications simulated, ground-water discharge remained the major source of annual discharge; consequently, the resulting change in discharge was distributed over the entire year.

The simulation produces a reasonable estimate of relative size changes and trends in basin recharge and discharge as the result of precipitation modification. However, the specific recharge and discharge values predicted must be qualified by the period of record used and by the procedure used to generate precipitation changes. The 9 years of record used may not be representative of either the long-term climate of the basin or the shorter term climate that will exist during oil-shale development and operation. Therefore, the average basin response predicted from the 9-year record may not be representative of future periods. In addition, the computation of a specific percentage change in annual precipitation by assuming a constant percentage change in all precipitation events is not realistic. As reported by Kahan (1972), the seeding of all winter storms produces an increase in percipitation in some and a decrease in others. Therefore, it is the percentage of seeded storms which produces increases and the size of these increases in relation to the size of the decreases that determines the annual change in precipitation. Consequently, the basin response will be affected by the pattern of occurrence of precipitation changes throughout the year.

The use of a stochastic approach to the simulation of storms over a much longer period of time is not possible at this time. Adequate precipitation data are not available to determine the statistical distributions or distribution parameters for storm occurrence, magnitude, and seedability. Therefore, the procedure used to simulate precipitation modification in this report is limited by the existing data constraints.

The results presented in this section are for the drainage area above the gage on Piceance Creek below Ryan Gulch. They cannot be directly extrapolated to the entire Piceance basin because the runoff characteristics of the area not simulated are difficult to define from available data. The area that has been modeled, however, is the major source of total basin discharge, producing about 80 percent of the estimated "natural" basin discharge.

The simulated effects of precipitation modification on the hydrology of Piceance Creek are initial estimates based on several broad assumptions. Improvement of these estimates will depend not only on a better definition of basin precipitation and hydrologic characteristics but also on an analysis of the weather-modification potential of the basin. Information on the physical characteristics of basin storms and the weather-modification potential of air pollutants by oil-shale development is required. Data from which this information can be obtained will be available from the basic data network being established by the Department of the Interior, the Colorado River Water Conservation District, and the developers of the lease tracts. These data will permit improved model-prediction capabilities and the expanded application of the model to the entire Piceance basin.

GROUND-WATER HYDRAULICS MODEL

DESCRIPTION

The digital model of ground-water hydraulics used in this study was developed by Bredehoeft and Pinder (1970). The model is quasi-three-dimensional in that it models a three-dimensional multiaquifer system by assuming horizontal flow in the aquifers and vertical flow through the confining layers which separate the aquifers. These assumptions reduce the mathematical problem to one of solving coupled two-dimensional equations for each aquifer in the system. An iterative, alternating-direction-implicit scheme is used to solve the system of simultaneous finite-difference equations which describe the response of the aquifer system to applied stresses.

The quasi-three-dimensional model has been developed by Bredehoeft and Pinder to simulate a ground-water system having any number of aquifers. The aquifers may have confined or unconfined (water-table) hydraulic conditions. The aquifers are assumed to be horizontal, nonhomogeneous, and isotropic (or anisotropic under special conditions). The confining layers separating the aquifers are assumed to permit one-dimensional vertical flow with or without storage in the confining layers.

The general equation which governs the flow of water in a two-dimensional isotropic confined aquifer is

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right)=S\frac{\partial h}{\partial t}+W(x,y,t), \quad (3)$$

where T is the transmissivity of the aquifer, h is the hydraulic head in the aquifer, S is the storage coefficient of the aquifer, and $W(x,y,t)$ is the flux of a source or sink. The transmissivity and storage coefficients are both functions of the space variables x and y. The source term is a function of the space variables and may also be a function of time, t.

The source term, W, incorporates the effects of natural recharge, of discharge or recharge from wells, and of leakage from adjacent aquifers. For the case of leakage without storage in the confining bed, the vertical flow through the confining bed from an adjacent aquifer is given by

$$q=-\frac{K'}{L}(h_a-h), \quad (4)$$

where q is the flow rate per unit area, h_a is the hydraulic head in the adjacent aquifer, and K' and L are the vertical hydraulic conductivity and the thickness of the confining layer, respectively. Substitution of q for W in equation 3 couples the equations describing the head distribution in adjacent aquifers. The finite-difference approximation to equation 3 and the resultant iterative alternating-direction-implicit computational algorithm are given by Bredehoeft and Pinder (1970).

The digital model was used to simulate the existing geohydrologic conditions in the Piceance basin. As shown by equations 3 and 4, the transmissivity, storage coefficient, and leakance (ratio of vertical permeability to thickness) (K'/L) functions must be defined. The solution of the equations yields the distribution of hydraulic head (potentiometric surface) in the aquifers. The computed potentiometric surface will be compared to head measurements from wells in the field. The comparison will provide a measure of the accuracy of the concepts used to derive the model. The comparison will also provide the only measure of the accuracy of model response to hypothetical changes in the system. Finally, the model will be used to predict the effects of mine-dewatering operations on the hydrologic system.

CONCEPTS

The ground-water system in the Piceance basin is well suited to be modeled by the quasi-three-dimensional model of Bredehoeft and Pinder (1970). As previously described, the ground-water system in the Piceance basin consists of two confined aquifers separated by the Mahogany zone confining layer. The upper and lower aquifers are assumed to be horizontal and isotropic. The Mahogany confining layer is assumed to permit vertical connection between the aquifers without storage in the confining layer. Figure 40 illustrates the flow model assumed for the Piceance basin aquifer system. The figure shows a generalized east-west cross section through the model aquifer system. In the model, water enters the aquifer system by recharge from precipitation in the recharge areas at a specified rate. Ground water circulates through the upper and lower aquifers in response to differences in potentiometric heads. The ground water is finally discharged to the stream valley as baseflow and evapotranspiration. The lateral and lower

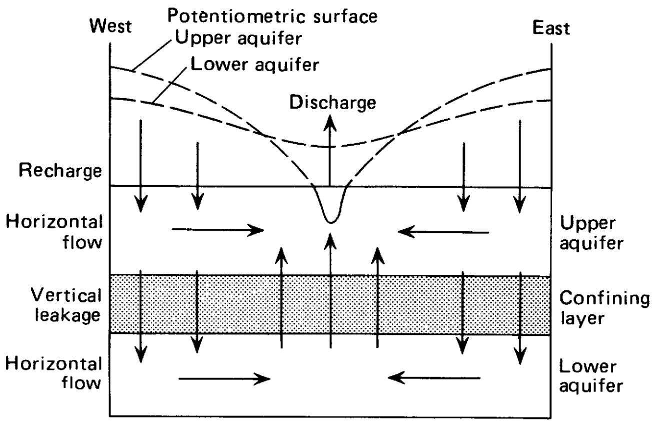


FIGURE 40. — Flow model of the aquifer system.

boundaries of the aquifer model are impermeable, so no water can enter or leave the system by crossing the boundary. Thus, under steady-state conditions, the rate of recharge must equal the rate of ground-water discharge to the stream valleys.

The lateral boundaries of the aquifer model are shown in figure 41. The lateral boundaries of the model are assumed to be impermeable (fig. 41) and coincide with the outcrop of the Green River Formation on the north, east, and west (pl. 1). To the south, the model boundary is assumed to be impermeable and coincide with the ground-water divide on the Roan Plateau. The modeled area of about 900 square miles (2,330 km²) was discretized by dividing the area into a rectangular grid of about 800 nodes. The spacing between grid points is

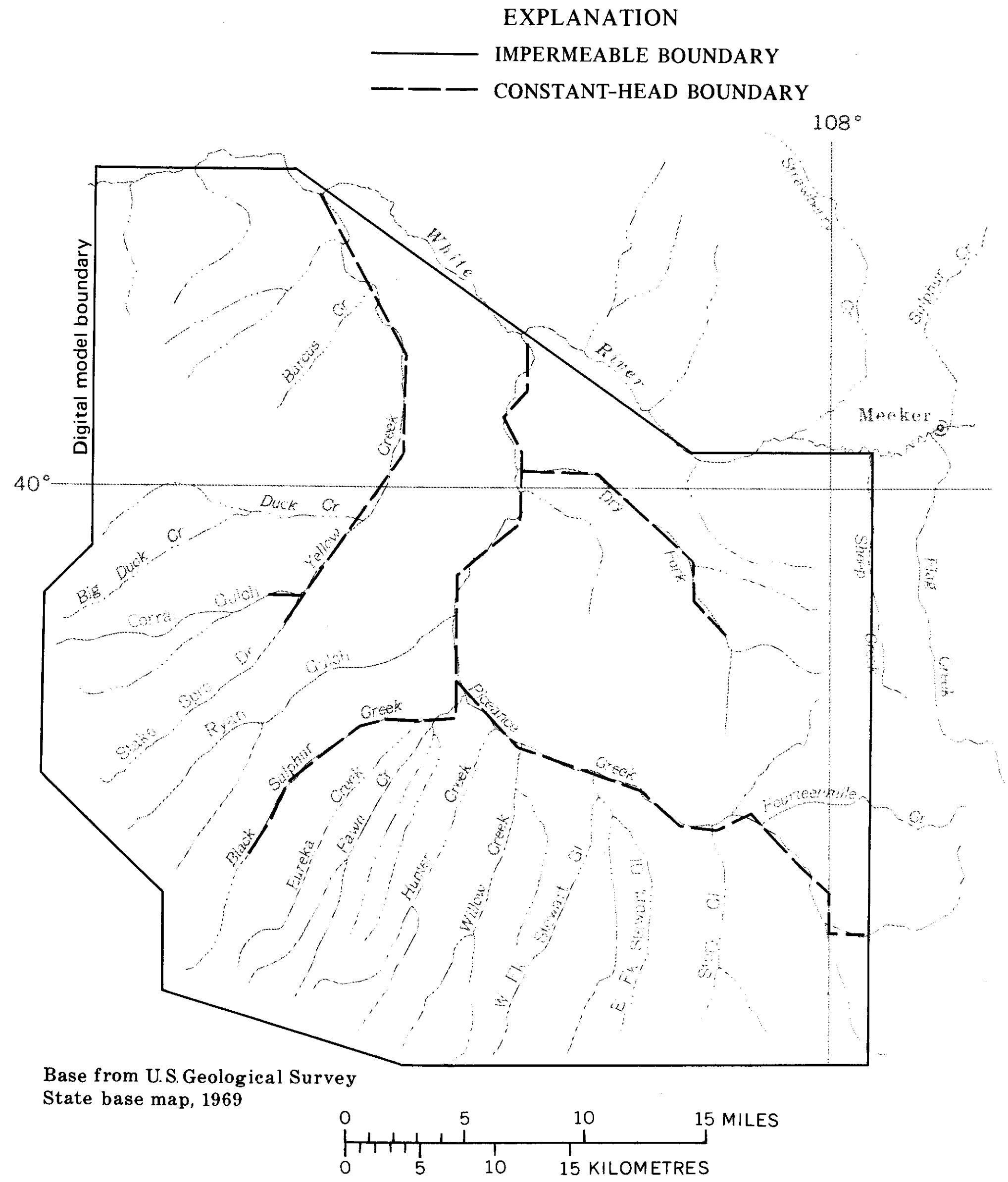


FIGURE 41. — Aquifer boundaries used in the digital model of the ground-water system.

variable and represents a minimum of 1 mile (1.6 km). The stream valleys of Piceance Creek, Yellow Creek, Dry Fork Piceance Creek, and Black Sulphur Creek (fig. 41) are assumed to be constant-head boundaries in the upper aquifer. The altitudes of the streams were assigned to the nodes in the upper aquifer which represent points on the streams. These altitudes become constant potentiometric heads in the model and represent points where ground water is discharged to the stream valleys from the upper aquifer.

COMPONENTS

A simplified flow chart for the digital ground-water model is shown in figure 42. The input data consist of control parameters, hydraulic parameters, and initial conditions. The number of time steps and the head-change tolerance are the two principal control parameters. The number of time steps is used to control the duration of the modeled time period and the head-change tolerance is used to test for the convergence of the iterative solution. A tolerance value of 0.1 foot (0.03 m) was used for steady-state solutions and 1 foot (0.3 m) was used for transient solutions. Thus, when the potentiometric heads calculated by the digital model between two successive iterations do not change at any node in the system by an amount greater than the tolerance, the computation is terminated, and the head values are assumed to be the solution for that time step. When solution has been achieved for the last time step to be modeled, a mass balance is calculated and printed out along with the potentiometric maps (fig. 42), representting the solution at specific times. The mass-balance computation provides a check on the validity of the computations by verifying that inflow minus outflow is equal to the change in storage in the model.

DATA REQUIREMENTS

The data requirements for the ground-water model are the hydraulic parameters and the initial conditions listed in figure 42. The transmissivity, storage coefficient, and initial potentiometric head at each node in the upper and lower aquifer must be specified. The leakance, or ratio of vertical permeability to thickness, of the Mahogany zone confining layer must be specified at each node. The rate of recharge to the upper aquifer must be specified at each node. In total, about 6,400 items of input data must be supplied.

HYDRAULIC PARAMETERS

Maps of the transmissivity data used in the model for the upper and lower aquifers are shown in figures 43 and 44. The control points are the transmissivity data given in figures 20 and 21. The data have been extrapolated to cover the entire study region. The regionalization is based on the geologic structure of the aquifers, correlations between geophysical logs, data trends, and data averages. The areal coverage of the data is poor, and the variability is large; thus, as previously dis-

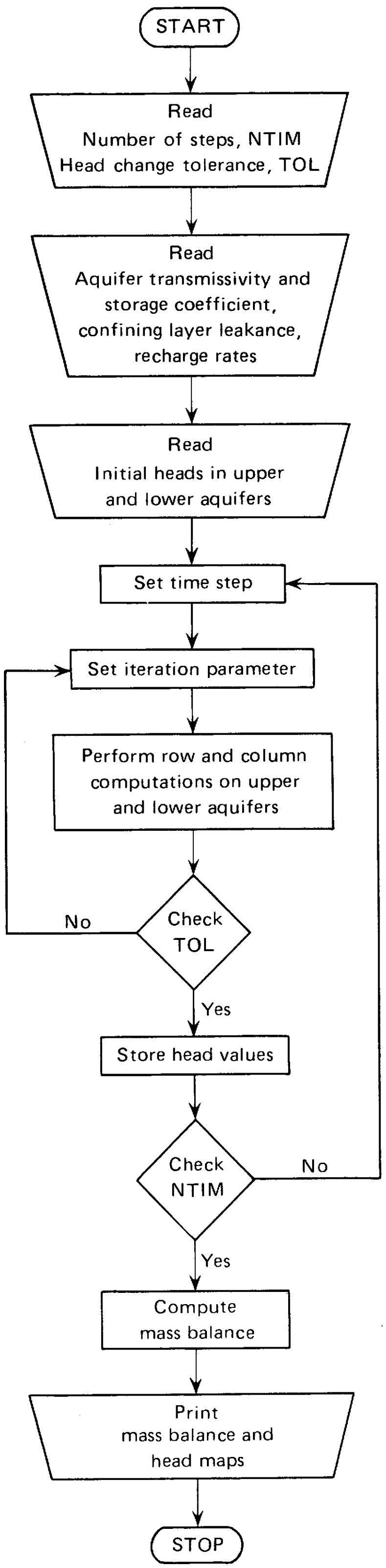


FIGURE 42. — Flow chart of the digital ground-water model.

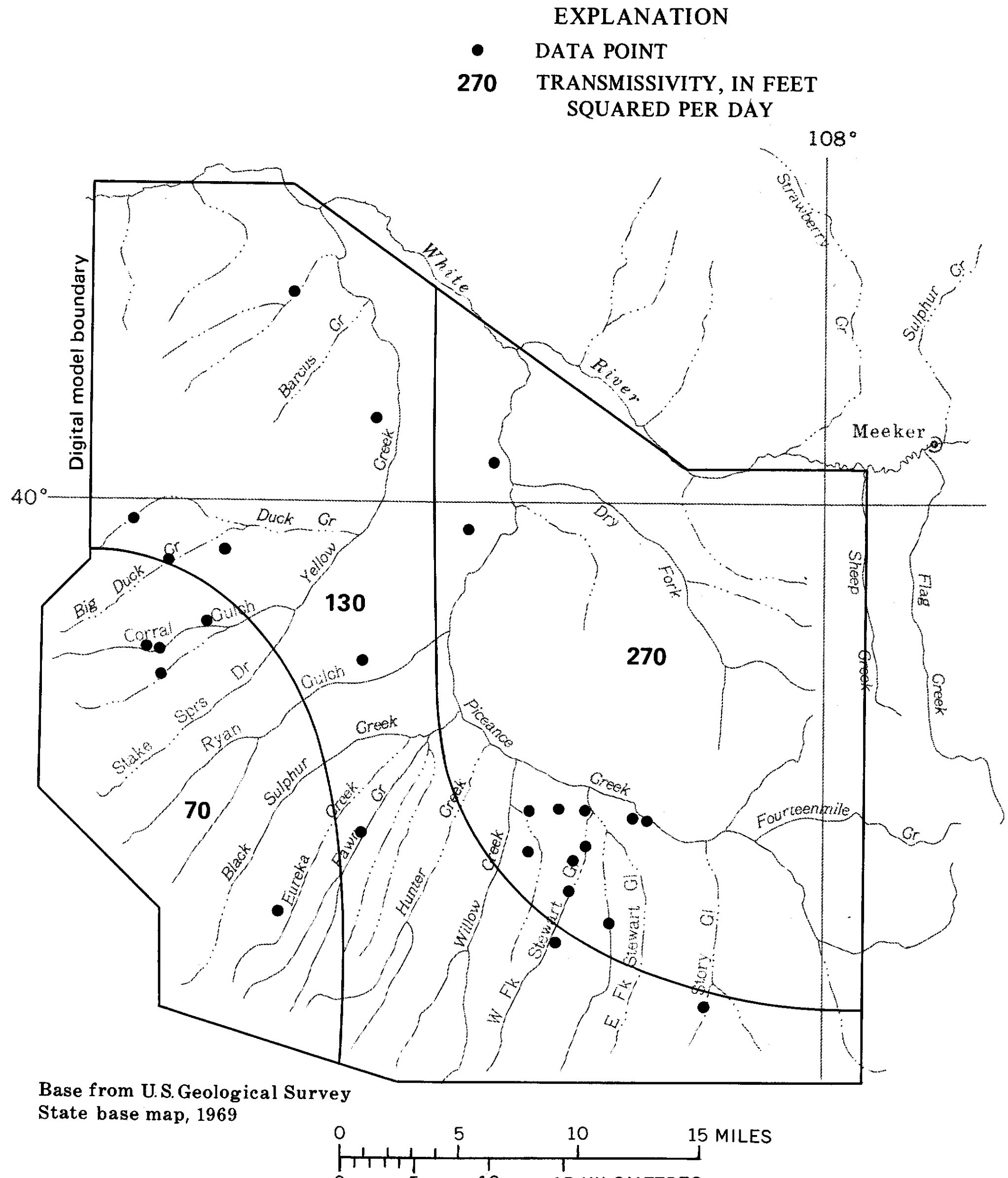


FIGURE 43. — Transmissivity of the upper aquifer used in the digital model.

cussed, the point values may not be representative of the regional transmissivity. As a consequence, the accuracy of the transmissivity distribution shown in figures 43 and 44 is highly uncertain.

Storage coefficients determined by aquifer tests were presented in table 5. The data are not adequate to determine the variation of the storage coefficient in each aquifer. Consequently, a uniform value was assigned to each aquifer on the basis of the data in table 5. Storage coefficients of 10^{-3} and 10^{-4} were used in the model for the upper and lower aquifers, respectively.

The areal distribution of vertical hydraulic conductivity in the Mahogany zone confining layer has not been adequately defined to permit its description. Therefore, the leakance of the confining layer used in the digital model was assumed, based on the available data presented by Weeks and Welder (1974). The assumption was tested by simulating the natural steady-state conditions of the basin. It was determined that the head differences between the upper and lower aquifers were extremely sensitive to the assumed value of the leakance. A leakance value equal to 1.35×10^{-5} day^{-1} was found to result in head differences between the aquifers comparable to those measured in the field, which are generally less than 50 feet (15 m) (fig. 23). If the Mahogany zone is 100 feet (30 m) thick, the vertical hydraulic conductivity of the confining layer is 1.35×10^{-3} ft/day (4×10^{-4} m/day). This is small and

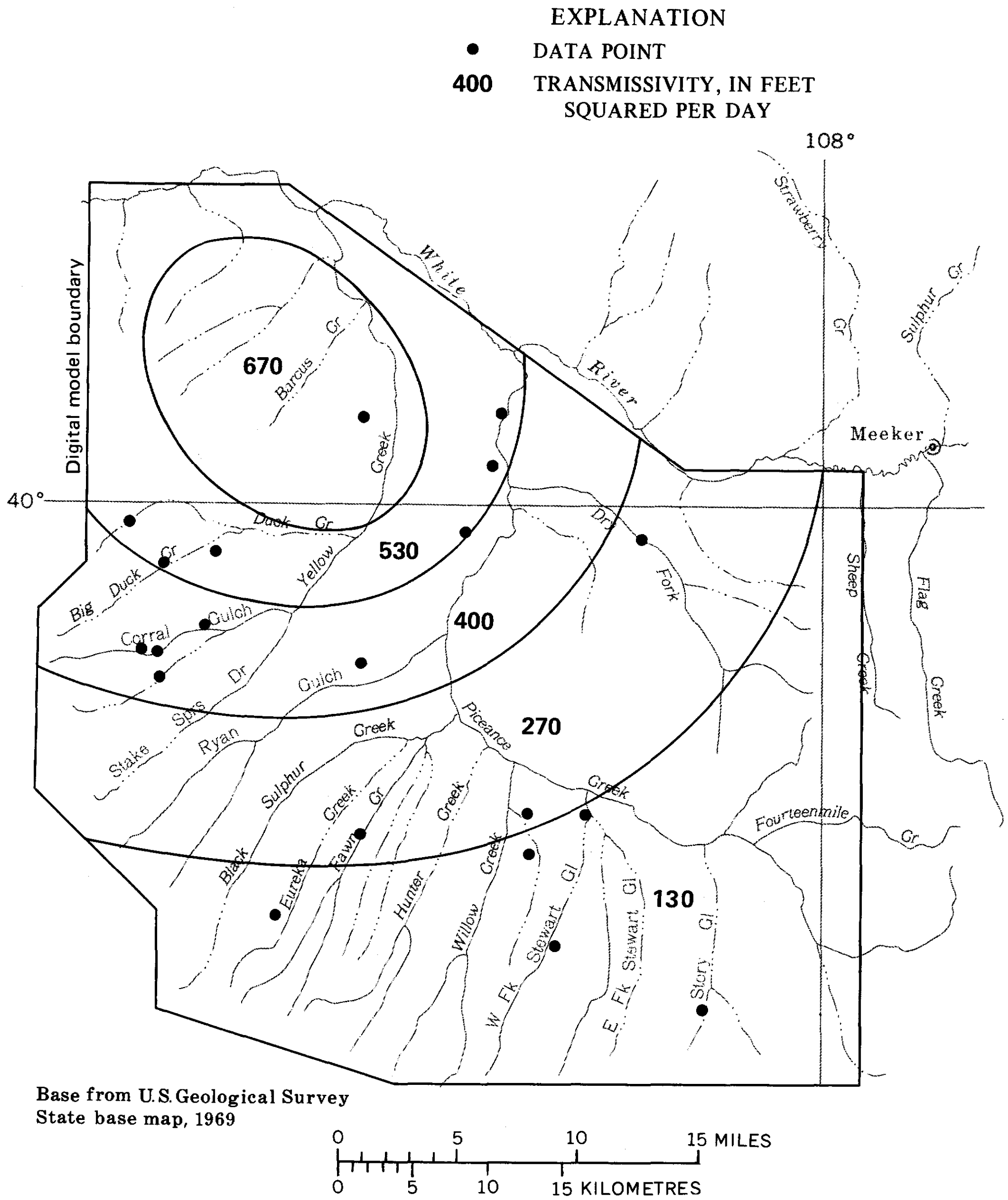


FIGURE 44. — Transmissivity of the lower aquifer used in the digital model.

comparable to the hydraulic conductivity of silty clay, which is a very poor aquifer.

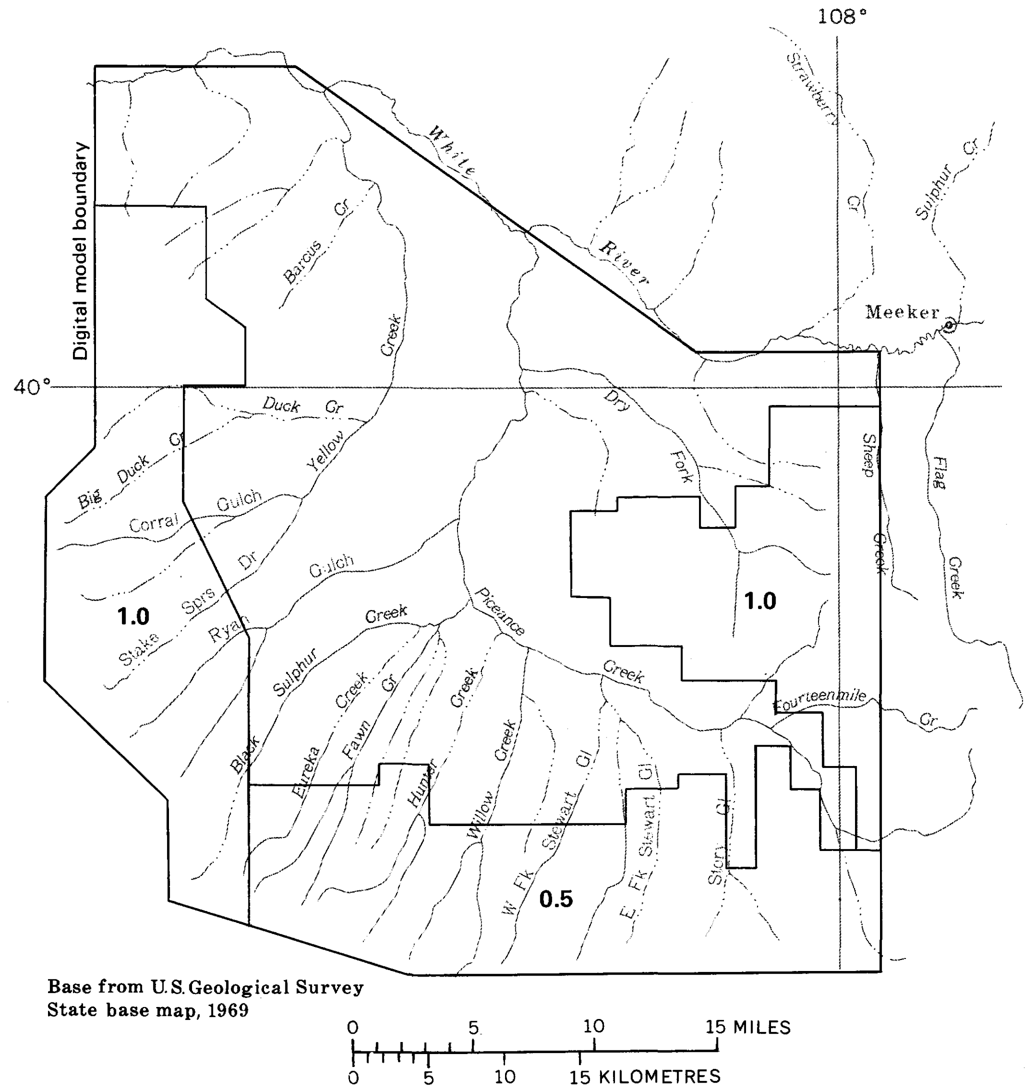
Recharge to the aquifer system was estimated to be 36 ft^3/s (1.0 m^3/s). As previously discussed, the recharge rate was estimated on the basis of a water-budget analysis. The recharge was distributed over the area of the model above 7,000 feet (2,134 m) in altitude to be consistent with the geohydrologic description of the basin. Preliminary modeling results indicated that the rate of recharge required to simulate the steady-state potentiometric surface was slightly less than that estimated. The recharge rate required for the digital model to simulate the steady-state potentiometric surface was 33.4 ft^3/s (0.94 m^3/s) or 24,100 acre-feet (29.7 hm^3) per year. Initially, the recharge was distributed uniformly over the recharge area, but it was found that the simulation was improved by varying the recharge rate based on the distribution of winter precipitation. The distribution of recharge to the upper aquifer was based on the variation in the normal winter (October to April) precipitation map published by the U.S. Weather Bureau (1960). Figure 45 shows the distribution of recharge used in the ground-water digital model. Both recharge and precipitation are less in the southern part of the basin than in the western and eastern parts.

INITIAL CONDITIONS

The initial potentiometric head must be assigned to each node in each aquifer in the digital model. The

EXPLANATION

1.0 RECHARGE AREA – Shows annual recharge, in inches, applied uniformily to the area



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

FIGURE 45. — Distribution of recharge used in the ground-water digital model.

initial-head distribution can be arbitrary when modeling a steady-state solution. The steady-state solution is independent of initial conditions. However, transient solutions depend on the initial conditions, and an accurate initial-head distribution must be specified.

The ground-water system in the Piceance basin is in a steady-state condition, and an arbitrary head distribution was assigned to each aquifer. As discussed in the following section, the digital model generates the steady-state head distribution in both the upper and lower aquifers. The steady-state solution then becomes the initial conditions required for the solution of transient mine-dewatering problems.

CALIBRATION

The only method of measuring the accuracy of a digital model is to simulate historical conditions and compare the response of the model to that measured in the field. This process is known as calibration.

Virtually no ground-water development has taken place in the Piceance basin, and the geohydrologic system is in a steady-state condition. This implies that recharge is equal to discharge and that the hydraulic head is not a function of time. Mathematically, the time derivative of the hydraulic head in equation 3 is equal to zero. Consequently, the term involving the storage coefficient is zero, and the solution of equation 3 does not depend on the storage coefficient. The steady-state solution depends only on the transmissivity of the aquifers, the leakance of the confining layer, the source function, and boundary conditions. Furthermore, because the solution is independent of time, it is also independent of the initial conditions. Thus, the model will reproduce the steady-state potentiometric map if the transmissivity of the aquifers, leakance of the confining layer, boundary conditions, and water budget have been adequately described.

STEADY-STATE SOLUTION

The steady-state conditions existing in the Piceance basin were simulated, using the transmissivity distributions shown in figures 43 and 44. As previously discussed, a uniform leakance value of 1.35×10^{-5} day^{-1} was used for the confining layer. Recharge to the upper aquifer was limited to the area of the model above an altitude of 7,000 feet (2,134 m). A total recharge rate of 33.4 ft^3/s (0.94 m^3/s) was applied and distributed over the recharge area, as shown in figure 45. The resulting steady-state solutions for the upper and lower aquifers are shown in figures 46 and 47, respectively. For the contour interval shown, the potentiometric maps for the two aquifers are nearly the same. However, differences ranging up to 70 feet (21 m), but generally less than 50 feet (15 m), exist between the computed heads in the two aquifers. this result compares favorably with the head differences measured in the field and discussed in relation to figure 22.

Figures 46 and 47 also show the altitudes of water levels in wells which are open only to the respective aquifer. Although the data are sparse, the computed potentiometric maps compare fairly well with the field data.

Accurate potentiometric maps of the upper and lower aquifers cannot be constructed from the field data. Coffin, Welder, and Glanzman (1971) published a potentiometric map for the Piceance Creek basin. They relied heavily on spring and stream altitudes to fill in the areas where observation well data were lacking. Most of the observation wells in the basin are open to both aquifers, and heads measured in the wells are not necessarily representative of either aquifer. The springs are generally upper aquifer phenomena, many of which may be perched and not representative of the head in the upper aquifer. Consequently, the potentiometric map given by Coffin, Welder, and Glanzman (1971) does not accurately represent the steady-state head distribution in either aquifer, nor does it represent a map of the composite heads in wells which are open to both aquifers. Rather, it represents the first attempt to show the configuration of the potentiometric surface and the general direction of ground-water flow in the Piceance basin. It should be noted that the concept of the hydrologic system in the basin put forth by Coffin, Welder, and Glanzman (1971), as shown earlier in figure 2, has proven to be correct. The present investigation has refined and quantified the hydrologic description presented by Coffin, Welder, and Glanzman (1971).

A potentiometric map based on the water levels in wells that are open to both aquifers was shown in figure 22. The data used to construct figure 22 can be used to calibrate the ground-water digital model. Under steady-state conditions, the hydraulic head, h, in a well that is open to both aquifers is given by Sokol (1963) as:

$$h = \frac{T_1 h_1 + T_2 h_2}{T_1 + T_2}, \qquad (5)$$

where T_1 and h_1 are the transmissivity and head in the upper aquifer, and T_2 and h_2 are the transmissivity and head in the lower aquifer. Using equation 5, a potentiometric map of composite heads can be calculated from the digital model solution for the upper and lower aquifers shown in figures 46 and 47. The composite head map can then be compared with the observation well data used to construct figure 22.

The resulting composite-head map is compared with field data in figure 48. The data points shown in figure 48 are those used to construct the potentiometric map shown in figure 22. The shape of the computed solution compares well with the potentiometric map shown in figure 22. This indicates that the conceptual model (fig. 40) adequately describes the geohydrologic system. Water flows from the margins toward the north-central part of the basin, where it is discharged principally to Piceance and Yellow Creek valleys. The computed composite-head map fits the field data shown in figure 48 very well. In general, the computed heads are within 50 feet (15 m) of the observed water levels, which is about the accuracy to be expected considering that the variation in head is over 1,200 feet (365 m), that the head gradient averages about 50 feet per mile (9.5 m/km), and that the modeled area is about 900 square miles (2,330 km^2). Only 6 water levels out of the 47 shown in figures 46, 47, and 48 differ from the computed heads by more than 100 feet (30 m) and only 1 water level differs by more than 200 feet (60 m).

Together, figures 46, 47, and 48 present the calibration of the ground-water digital model. Field data are particularly lacking east of Piceance Creek. Water levels from two wells are the only data available from the area; however, the computed heads match these two data points extremely well (figs. 46, 47).

EXPLANATION

6456● WELL – Number shows water level in upper aquifer, March 1974. Underline denotes September 1973

—*6400*— POTENTIOMETRIC CONTOUR – Shows computed hydraulic head in upper aquifer. Interval is 200 feet (61 metres). Datum is mean sea level

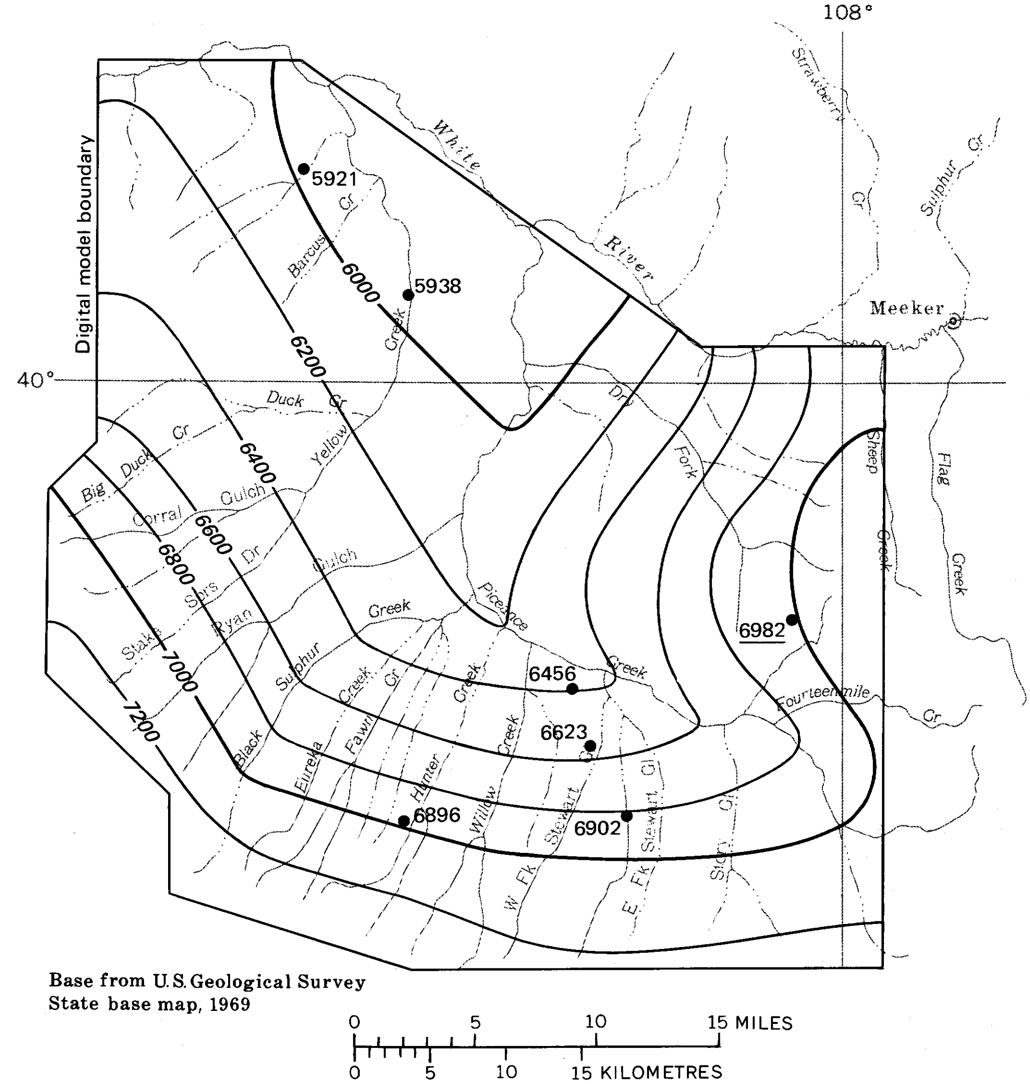


FIGURE 46. — Potentiometric map of the upper aquifer computed by the digital model.

GROUND-WATER BUDGET

Under steady-state conditions the ground-water discharge rate is equal to the recharge rate. The recharge rate used to simulate the steady-state conditions in the Piceance basin was 33.4 ft^3/s or 24,100 acre-feet per year (29.7 hm^3/year). Annual recharge is 8,200 acre-feet (10.1 hm^3) in the Yellow Creek drainage area and 15,900 acre-feet (19.6 hm^3) in the Piceance Creek drainage area. The digital model computes ground-water discharge to the constant-head boundaries shown in figure 41. The model estimates that 4,300 acre-feet (5.3 hm^3) are discharged in Yellow Creek drainage area and 19,800 acre-feet (24.4 hm^3) are discharged in Piceance Creek drainage area annually. Thus, 18 percent of the total recharge is discharged in Yellow Creek drainage area, and 82 percent is discharged in Piceance Creek drainage area. As discussed in relation to figure 22, Piceance Creek valley is the main ground-water discharge area in the basin, which can be seen from the potentiometric maps (figs. 46, 47) and from the ground-water discharge computed by the model. The above discharge estimates include both ground-water discharge to streams and evapotranspiration because the digital model does not distinguish between the two.

EXPLANATION

5930● WELL – Number shows water level in lower aquifer, March 1974. Underline denotes September 1973

—6800— POTENTIOMETRIC CONTOUR – Shows computed hydraulic head in lower aquifer. Interval is 200 feet (61 metres). Datum is mean sea level

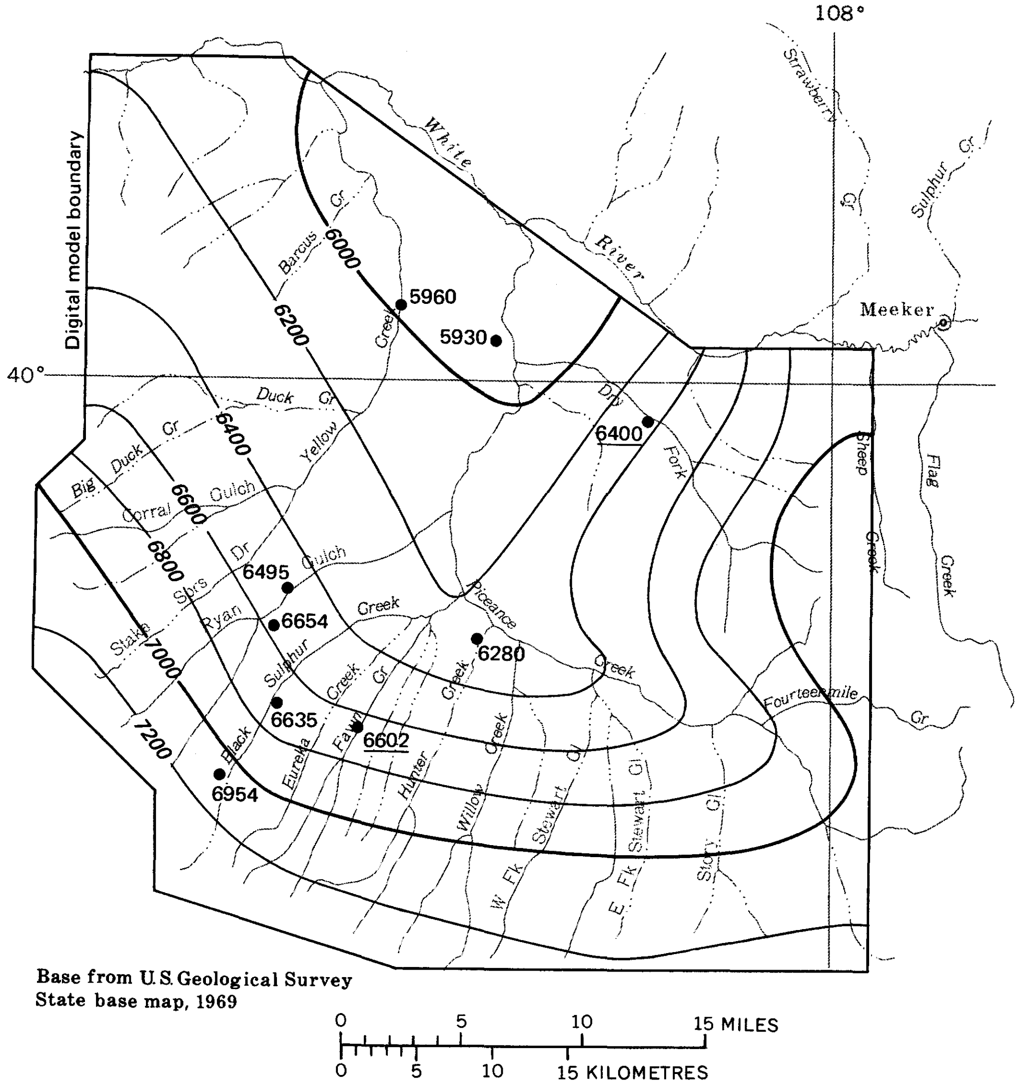


FIGURE 47. — Potentiometric map of the lower aquifer computed by the digital model.

DISCUSSION

The recharge rate required by the model to simulate steady-state conditions was 33.4 ft^3/s (0.94 m^3/s) which is within 10 percent of the water-budget estimate of 36 ft^3/s (1.0 m^3/s). This estimate was based on the assumption that 80 percent of the average annual discharge from the basin was ground-water discharge. As discussed in relation to table 13, the watershed model estimates that about 80 percent of the average annual discharge is from ground water. Furthermore, nearly all the recharge in Piceance Creek drainage occurs in the area above the gage below Ryan Gulch. The ground-water model estimates that recharge to this area is 0.61 inch (15.5 mm) and, as shown in table 12, the watershed model estimates that recharge is 0.66 inch (16.8 mm). Thus, the two models are in very good agreement.

The agreement between the models, the water budgets, and the computed and measured potentiometric levels indicates that the ground-water model satisfactorily simulates the existing steady-state conditions in the Piceance basin. However, the model calibration and reliability would be improved if potentiometric maps of each aquifer could be constructed from field data. This would require water-level data from

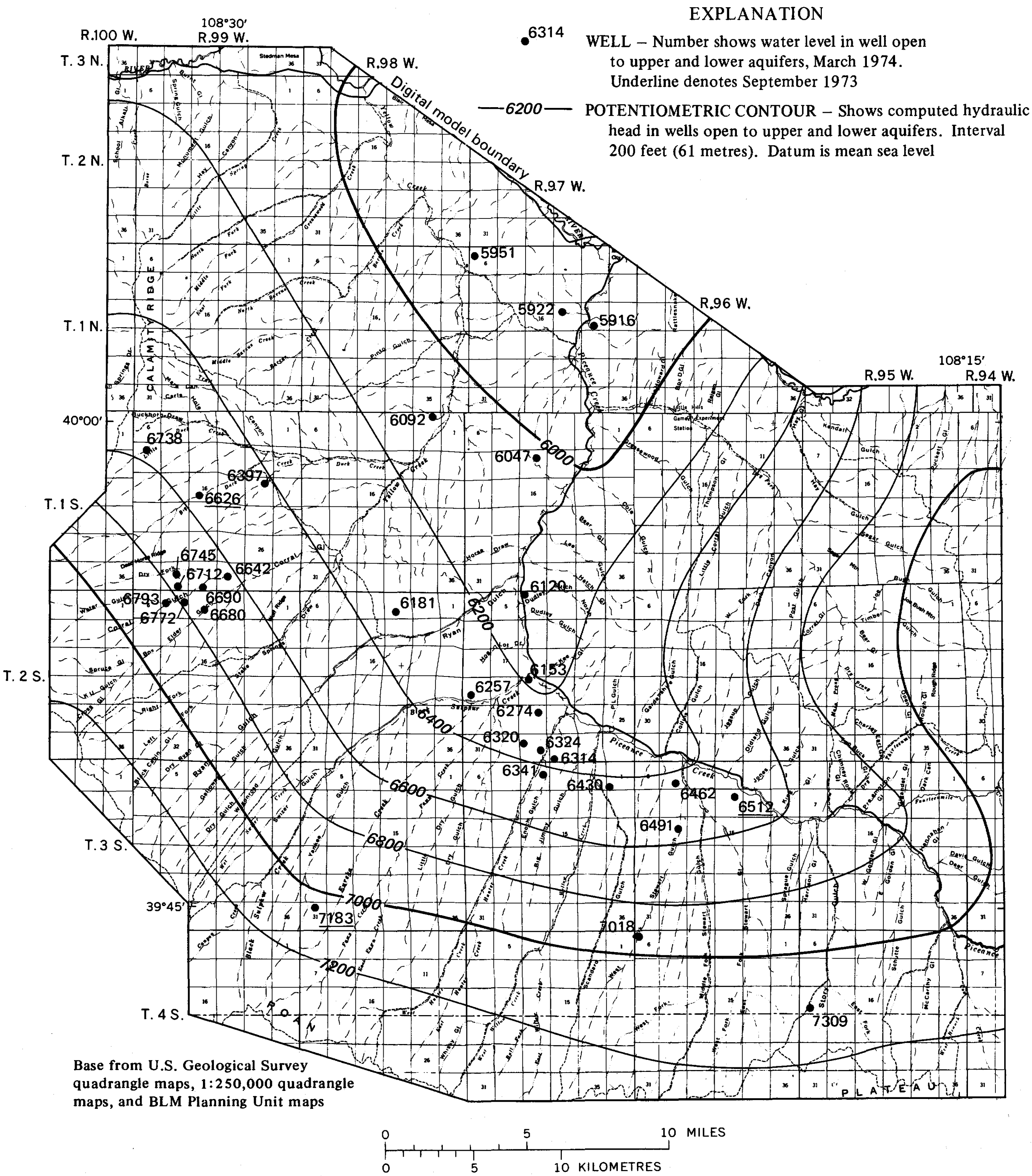


FIGURE 48. — Potentiometric map of composite heads computed by the digital model.

wells completed in either the upper or lower aquifer. About 50 observations of head in each aquifer, uniformly distributed over the basin, would be needed to accurately map the potentiometric surface in each aquifer. Furthermore, as previously discussed, the steady-state solution does not depend on the value of the storage coefficients of the aquifers. Consequently, the accuracy of the storage coefficients used in the digital model have not been tested and cannot be adequately tested in the absence of measured regional changes in the potentiometric surface of each aquifer. Thus, the only measure of reliability for simulated transient problems is the accuracy and adequacy of the field data from which the storage coefficients were determined. As shown in table 5, the storage coefficients are few. The model reliability would be further improved if additional data on the storage properties of the aquifers were available.

The proposed prototype oil-shale development may provide some of the needed data to improve the calibration of the digital model. Hydrologic monitoring programs conducted by the lessees will provide additional aquifer-test data from the vicinity of the development tracts. Mine dewatering during development will provide the stress and measured transient response of the hydrologic system needed to verify the model for unsteady-flow conditions. In the meantime, simulated steady-state response of the model should be fairly reliable, and transient response is uncertain.

SIMULATED EFFECTS OF DEWATERING ON THE HYDROLOGIC SYSTEM

Dewatering operations associated with prototype oil-shale development will cause significant changes in the hydrologic system in the Piceance basin. The digital model of ground-water flow, described in the previous section, was used to simulate the effects of dewatering operations. The Preliminary Development Plans for Colorado tracts C–a and C–b were described in the introduction to this report. The development plans do not present detailed mine-dewatering plans, and hypothetical dewatering schemes were used to simulate the effects of mine dewatering on the hydrologic system. When development plans are known in detail, the proposed dewatering schemes can be simulated.

HYPOTHETICAL DEWATERING SCHEME

The hypothetical mines in tracts C–a and C–b are 4 square miles (10.4 km^2) in area as shown in figure 49. Both mines are assumed to be in the Mahogany zone, which is the richest oil-shale interval in the Green River Formation. Mining of the Mahogany zone will remove the confining layer which separates the upper and lower aquifers (fig. 18), and it is assumed that complete hydraulic connection between the aquifers occurs at both mines. This implies that the confining layer is removed and does not impede the flow of water into the mines. Under these conditions, the upper aquifer is completely dewatered in the area of the mines to the mine floor, and the flow rate into the mines does not depend on the type of mine (underground or open pit).

The hypothetical dewatering plan is illustrated in figure 50. It is assumed that the potentiometric surface of each aquifer is instantaneously drawn down to a specified altitude and maintained at that level throughout the life of the mine, which is assumed to be 30 years. At both mines the potentiometric surface of the upper aquifer is drawn down to the top of the Mahogany zone (the base of the upper aquifer), and the potentiometric surface of the lower aquifer is drawn down to the bottom of the Mahogany zone (the top of the lower aquifer), as shown in figure 50. Under these conditions, water will flow into the mines from each aquifer at a rate that decreases as the hydraulic head in each aquifer adjacent to the mine decreases with time. In the vicinity of the mines the upper aquifer will become unconfined. The development of a seepage face at the mine-aquifer interface is ignored. However, the storage coefficient of the upper aquifer is increased from 10^{-3} to 10^{-1} wherever the hydraulic head declines by more than 100 feet (30 m).

At the mine in tract C–a the altitude of the top of the Mahogany zone averages about 6,500 feet (1,980 m), and the bottom of the Mahogany zone is about 6,300 feet (1,920 m) above mean sea level. At the mine in tract C–b the top of the Mahogany zone is about 5,600 feet (1,710 m) in altitude, and the bottom of the Mahogany zone is about 5,400 feet (1,650 m) above mean sea level. These altitudes are assumed to be the dewatering levels in the respective aquifers at each of the mines.

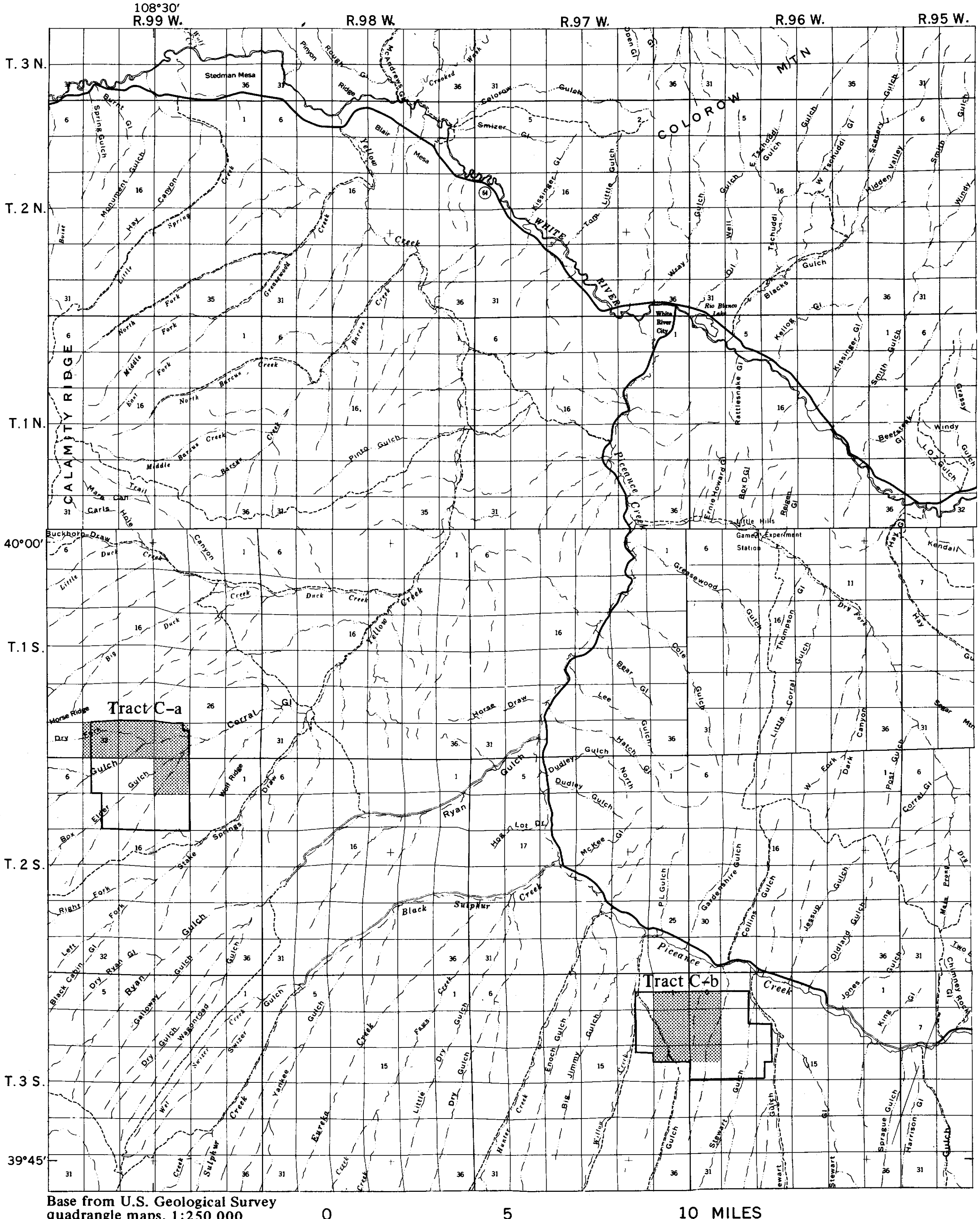
SIMULATION RESULTS

The hypothetical mine-dewatering schemes were simulated, using the digital model of ground-water hydraulics. Dewatering operations in tracts C–a and C–b were simulated simultaneously so that the combined effects on the ground-water system could be estimated. Figures 51 and 52 show the discharge from each mine computed by the model.

MINE DISCHARGE

In figure 51, the total discharge from the mine in tract C–a ranges from about 9 ft^3/s (0.25 m^3/s) at the end of 1 year to 7 ft^3/s (0.20 m^3/s) at the end of 30 years. Most of the discharge is supplied by the lower aquifer. Discharge from the upper aquifer is small because the thickness and transmissivity of the upper aquifer are small near tract C–a. The preliminary development plan for tract C–a estimated the water demand for oil-shale processing and disposal at 16 ft^3/s (0.45 m^3/s). Only half of the estimated demand can be supplied by the hypothetical mine-dewatering scheme. However, additional water could be obtained from the lower aquifer by increasing the drawdown at the mine.

Figure 52 presents a completely different situation at tract C–b. The total discharge from the mine ranges from 28 ft^3/s (0.80 m^3/s) at the end of 1 year to 20 ft^3/s (0.57 m^3/s) at 30 years. About two-thirds of the discharge is supplied by the upper aquifer. The discharge required to dewater the hypothetical mine exceeds the 14 ft^3/s



Base from U.S. Geological Survey quadrangle maps, 1:250,000 quadrangle maps, and BLM Planning Unit maps

FIGURE 49. — Locations of hypothetical mines shown by patterned areas in prototype oil-shale lease tracts C-a and C-b.

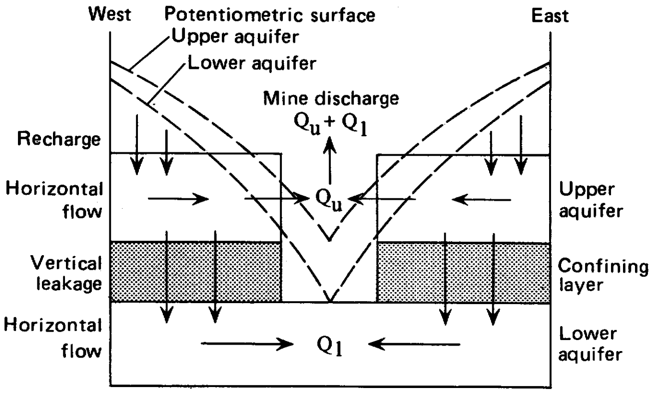


FIGURE 50. — Mine-dewatering scheme used in the digital model of the aquifer system

(0.40 m³/s) water demand estimated in the Preliminary Development Plan. Consequently, the hypothetical mine in tract C–b will have to dispose of the excess water produced during dewatering operations. Several methods for disposal of the excess water have been proposed, such as evaporation, reinjection into aquifers, and discharge to streams following any required upgrading of the water quality. The digital-model solution indicates that another alternative exists; namely, the excess water produced at tract C–b could be used to increase the supply at tract C–a.

The water discharged from the mines is supplied by water from storage in the aquifers and recharge to the ground-water system. The recharge captured by the mines would have been discharged to the valleys as evapotranspiration and streamflow; thus, ground-water discharge to the valleys is reduced. The components of the total discharge from both mines are shown in figure 53. After 30 years the mine discharge is still mostly supplied by water from storage. Ground-water discharge to streams and evapotranspiration has been reduced by 8 ft³/s (0.23 m³/s) and 19 ft³/s (0.54 m³/s) is supplied by water from storage. If mine dewatering continued indefinitely, a steady-state condition would eventually be reached. At that time the discharge from storage would be zero, and the mine discharge would be totally supplied by a reduction in discharge to streams and evapotranspiration. The digital-model solution at steady state resulted in a total discharge from both mines of 18 ft³/s (0.41 m³/s), which is achieved after several centuries of mine dewatering. However, this time period is considerably longer than the life of the mines.

WATER QUALITY

The quality of the water discharged by the mines can be qualitatively estimated. Potentiometric maps of the upper and lower aquifers are shown in figures 54 and 55, respectively. The maps show the hydraulic head in the aquifers computed by the digital model after 30 years of mine dewatering. Water flows along lines that are perpendicular to the lines of constant hydraulic head in

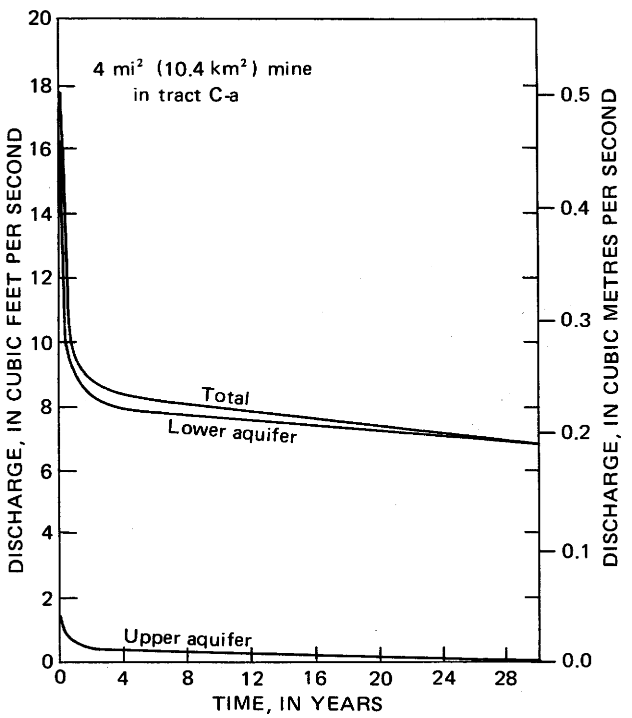


FIGURE 51. — Discharge from a hypothetical mine in tract C–a.

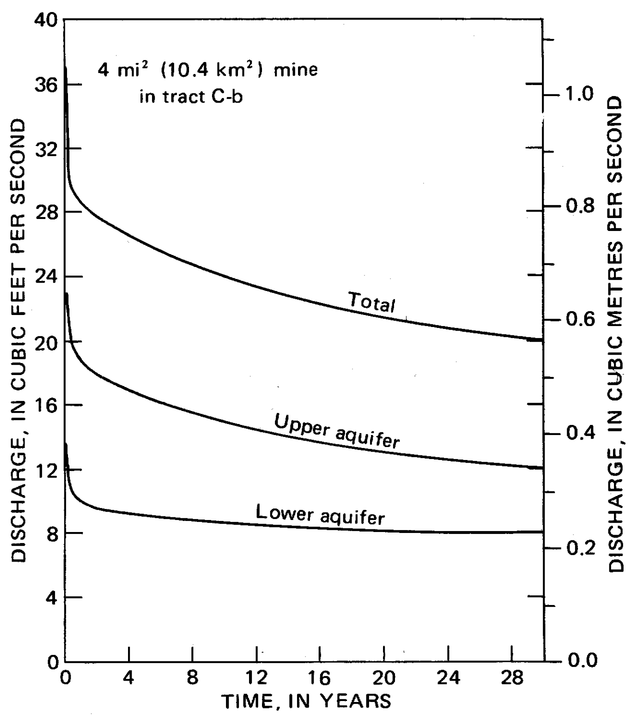


FIGURE 52. — Discharge from a hypothetical mine in tract C–b.

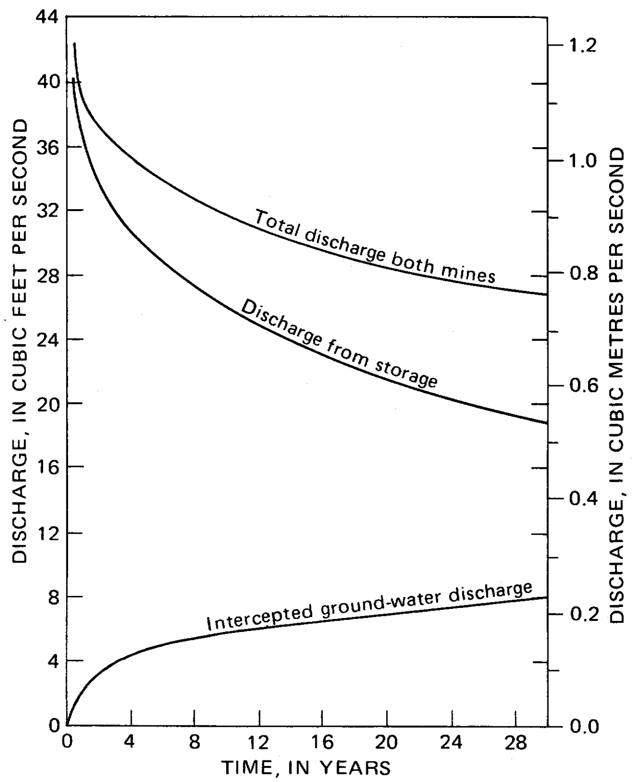


FIGURE 53. — Components of the total discharge from both hypothetical mines.

the direction of decreasing head. The dashed lines in figures 54 and 55 outline the areas within which all recharge to the aquifers contributes to mine discharge. Only flow lines originating within the area bounded by the dashed lines contribute to the discharge from the mines. Consequently, the quality of the water discharged from the mines depends only on the quality of the water in the areas shown by the dashed lines in figures 54 and 55. The concentration of dissolved solids in the upper and lower aquifers was shown in figures 28 and 30, respectively. The concentration of dissolved solids in the upper aquifer (fig. 28) in the area tributary to tract C–a is less than 1,500 mg/l and that for tract C–b is less than 1,000 mg/l. The concentration of dissolved solids in the lower aquifer (fig. 30) is less than 5,000 mg/l in the area of the aquifer that is tributary to each mine. Assuming that changes in the flow direction and velocity caused by mine dewatering do not alter the water chemistry, the concentration of dissolved solids in the water discharged from the mines should not exceed 5,000 mg/l for the hypothetical dewatering scheme and flow model considered here.

The occurrence of sodium bicarbonate brines at the base of the Parachute Creek Member of the Green River Formation in tracts C–a and C–b was discussed previously. The chemical analyses of the brines were presented in tables 8 and 9. The zone containing the brine is assumed to underlie the lower aquifer and to have no significant permeability in the digital model. Consequently, there would be no significant effect of the saline zone on the quality of the mine discharge. However, additional data on the extent and permeability of the zone are needed to substantiate the above assumptions.

EFFECTS ON WATER RESOURCES

Dewatering the hypothetical mines reduces ground-water discharge to the stream valleys. The ground-water discharge intercepted by the mines is shown in figure 53. At the end of 30 years of dewatering, ground-water discharge is reduced by 8 ft^3/s (0.23 m^3/s). Nearly the entire reduction in discharge occurs in the Piceance Creek drainage area. There is very little reduction in discharge in the Yellow Creek drainage area. Ground-water discharge consists of both evapotranspiration and streamflow. The digital model does not estimate which component of the discharge is reduced. However, where the streams are not deeply incised in the alluvium, the evapotranspiration demand will probably be met, so long as there is baseflow to the streams. Thus, during the growing season, baseflow to streams will probably be depleted before evapotranspiration losses are reduced.

The effect of mine dewatering on Piceance Creek is apparent in figure 54. In the area of the upper aquifer which is tributary to the mine at tract C–b (shown by the dashed lines in fig. 54), there is a 10-mile (16-km) reach in which there is no discharge to Piceance Creek. The hydraulic head in the upper aquifer has been drawn down below the valley bottom so that no discharge can take place. In fact, water that is discharged to Piceance Creek upstream from this area will probably flow into the area, infiltrate into the upper aquifer, and flow to the mine. Consequently, there will be little, if any, flow in this 10-mile (16-km) reach of Piceance Creek except during periods of surface runoff from snowmelt or rainfall. The upstream end of the reach has been observed to be dry in the past. However, this has been the result of irrigation diversions and evapotranspiration losses from irrigated land. As was shown in figure 14, the quality of the water in the upper reaches of Piceance Creek is considerably better than that in the lower reaches. Consequently, reducing the ground-water discharge to Piceance Creek in the vicinity of tract C–b will reduce streamflow in the downstream reach. The decrease in streamflow will reduce the effects of dilution and increase the concentration of dissolved solids in the water. However, irrigation as well as ground-water discharge causes the dissolved-solids concentration of Piceance Creek to increase in the downstream direction. A reduction in the irrigated acreage could offset some of the

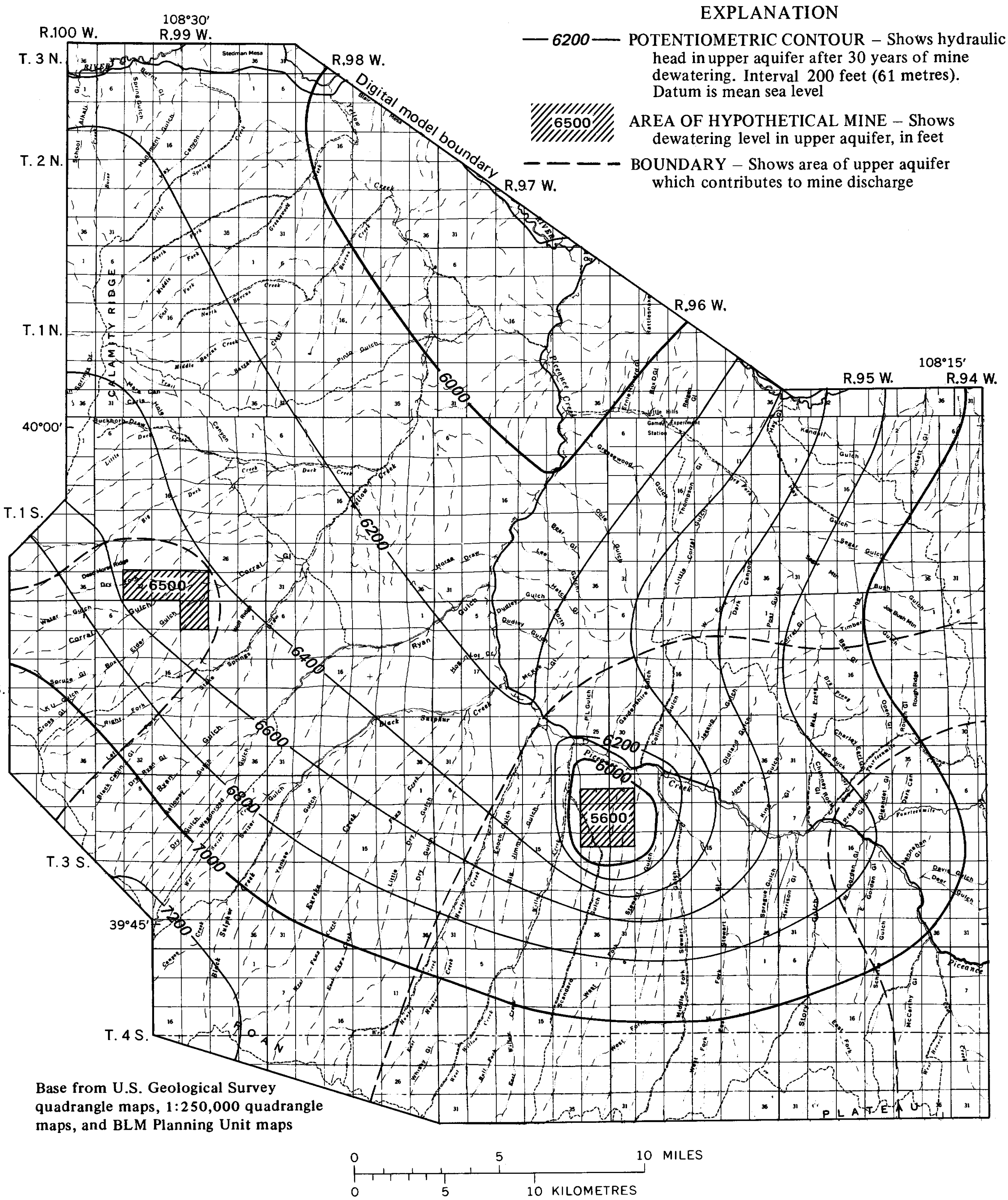


FIGURE 54. — Potentiometric map of the upper aquifer after 30 years of mine dewatering, computed by the digital model.

effects of reduced ground-water discharge on the water quality of Piceance Creek.

The change in hydraulic head (drawdown) in the upper aquifer after 30 years of mine dewatering is shown in figure 56. The drawdown is computed by the digital model as the difference between the initial, steady-state potentiometric surface (fig. 46) and the potentiometric surface after 30 years of dewatering (fig. 54). At the end

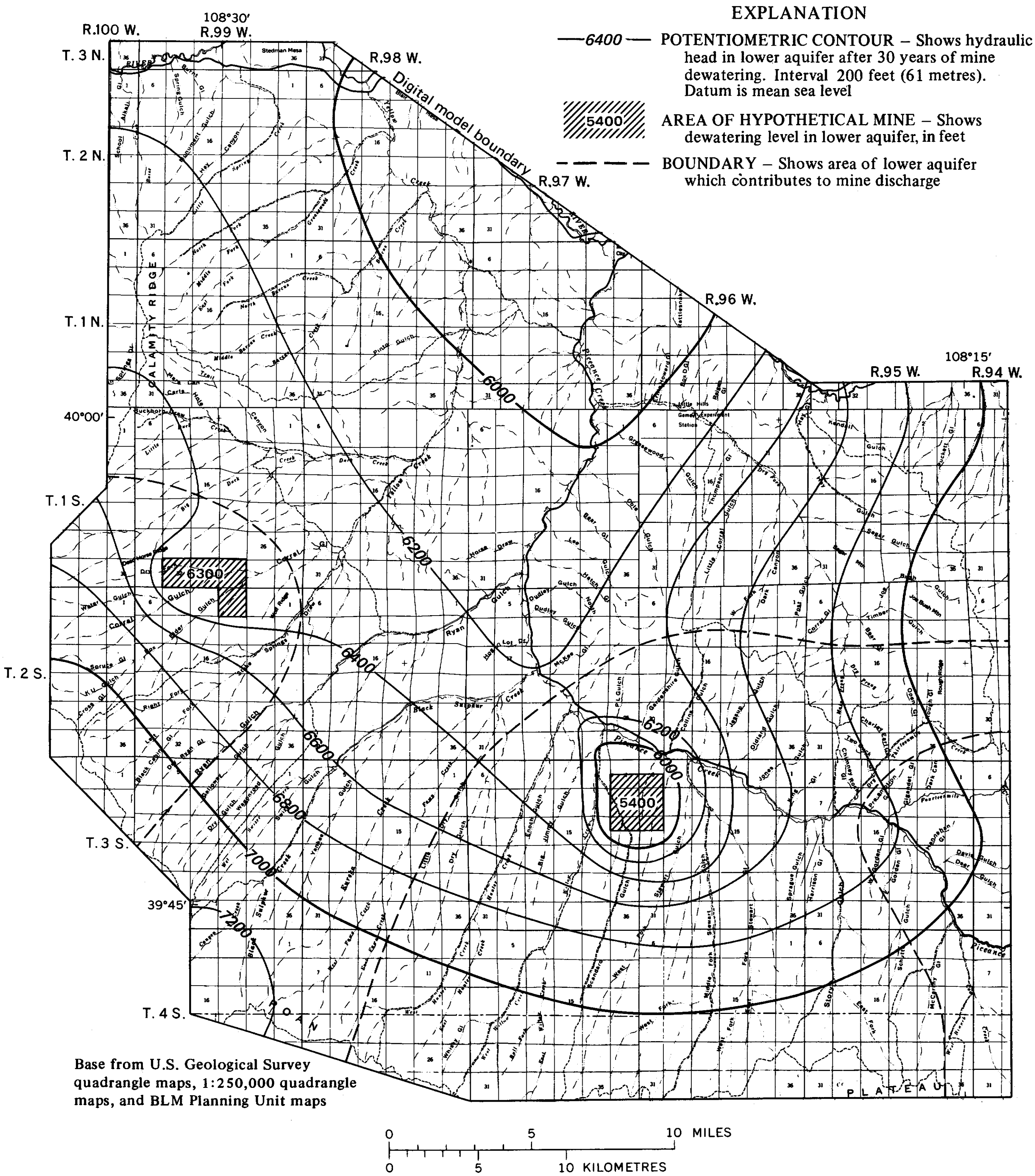


FIGURE 55. — Potentiometric map of the lower aquifer after 30 years of mine dewatering, computed by the digital model.

of 30 years the hydraulic head in the upper aquifer has been affected by mine dewatering in about 75 percent of the modeled area. A steep hydraulic gradient and well-developed cone of depression have formed around the mine in tract C–b where the maximum drawdown is 1,200 feet (365 m). At the mine in tract C–a, there is only

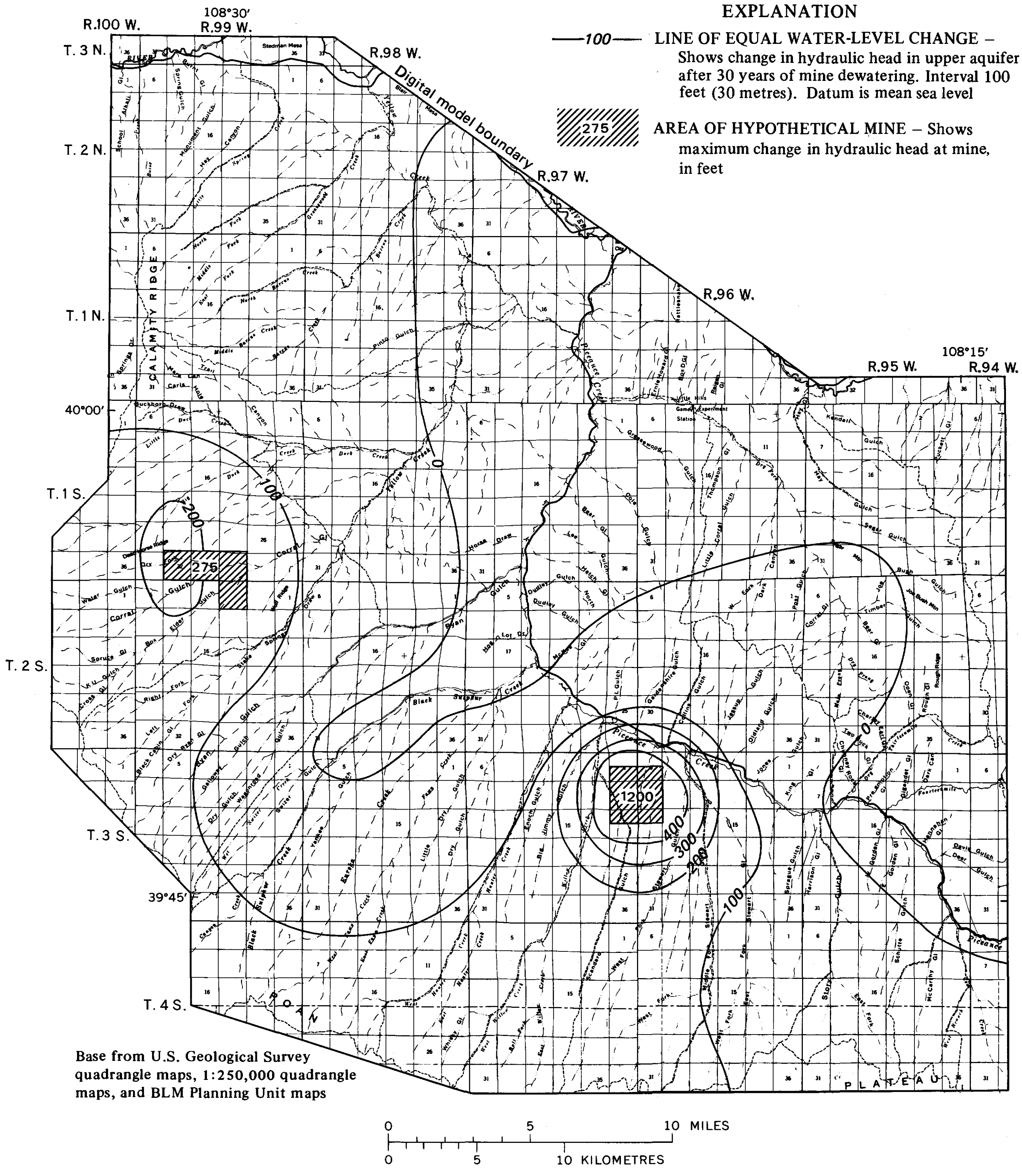


FIGURE 56. — Drawdown in the upper aquifer after 30 years of mine dewatering, computed by the digital model.

275 feet (84 m) of drawdown and the hydraulic gradient is relatively flat. This explains the difference in the components of the mine discharge received from the upper aquifer in figures 51 and 52. The larger hydraulic gradient (and larger transmissivity) at tract C–b generates much more discharge from the upper aquifer

than at tract C–a. The position of the zero drawdown line in figure 56 indicates that there is no interference between the mines. That is, during the 30 years simulated, neither mine affects the discharge from the other. This conclusion was tested by simulating the dewatering operation at each mine separately. It was found that there was no significant effect on the hydraulic head in either aquifer at the location of the other mine after 30 years of dewatering.

The volume of water removed from the aquifers was computed by the model to be about 500,000 acre-feet (620 hm³) during the 30 years of simulated dewatering. This is 2 to 20 percent of the estimated 2.5 to 25 million acre-feet (3,100 to 31,000 hm³) of water in storage.

The effects of mine dewatering on the discharge from springs in the Uinta Formation can only be indirectly determined. Many springs occur in the valleys of Piceance Creek, Yellow Creek, and their tributaries. Several springs along Piceance Creek are used for irrigation. Adequate data are not available to determine which springs are hydraulically connected to the upper aquifer and which are the result of discharge from perched water-bearing zones. The springs that result from perched water bodies will not be affected by dewatering. However, those that are the result of ground-water discharge from the upper aquifer may be significantly affected. The drawdown map shown in figure 56 shows the area within which ground-water discharge from the upper aquifer will be reduced. Wherever the drawdown is greater than zero, there will be a reduction in discharge from the upper aquifer. If the drawdown lowers the hydraulic head in the upper aquifer to an altitude below a discharge point, discharge will cease at that point. As pointed out previously, the digital-model solution indicates that there will be only a slight reduction in ground-water discharge in Yellow Creek drainage. The springs that will be most significantly affected are those along the 10-mile (16-km) reach of Piceance Creek where ground-water discharge is reduced to zero after 30 years of dewatering (fig. 54). Springs that are hydraulically connected to the upper aquifer in this reach will cease to flow.

DISCUSSION

The above analysis is based on a hypothetical dewatering scheme (instantaneous drawdown) that cannot and need not be achieved at a real mine. The water levels in the aquifers will actually be drawn down over a period of a few years while access to the mining interval is being prepared. Consequently, the response of the hydrologic system during the first few years of dewatering may be much different from that simulated. The water demand at each tract will vary during development. Initially, the demand will be small until the retorting plant is in operation, and excess water may be produced at both tracts during the initial phase of development. However, after 30 years of dewatering, the response of the digital model is virtually the same for any dewatering scheme that is accomplished within the first few years of operation, so long as all other assumptions (depth, area, location) remain the same. Additionally, as steady-state conditions are approached, the simulation results become less dependent on the storage properties of the aquifers and more reliable. For these reasons, most of the preceding analysis was limited to the effects on the hydrologic system after 30 years of dewatering. Within the limitations of the data available on the aquifer system and the calibration of the model, the simulated effects of mine dewatering on the hydrologic system are the best estimates that can be made until additional information becomes available during development of the prototype oil-shale lease tracts.

SUMMARY AND CONCLUSIONS

The Piceance Creek basin has received much attention since 1971 when the Department of the Interior announced plans for a prototype leasing program to develop the oil-shale resource in the Green River Formation. In 1972 the U.S. Geological Survey, in cooperation with the Colorado Department of Natural Resources, began a 2-year investigation designed to assess the potential impact of development on the water resources of Piceance Creek basin. The purpose of the investigation was to collect baseline hydrologic data, describe the hydrologic system, and predict the effects of development on the hydrologic system. Leases on Colorado tracts C–a and C–b in the Piceance basin were awarded to industry in 1974 and preparations for development have already begun.

To meet the objectives of the investigation, basic data were collected on the surface- and ground-water systems in the basin. Data on surface-water quantity and quality were collected at more than 50 sites in the study area. Geophysical and hydrologic data were collected or compiled from over 100 wells in the basin. These data were used to describe the hydrologic system and develop digital models of the surface- and ground-water systems. The models provided the analytic tools needed to predict the effects of oil-shale development on the hydrologic system.

The surface-water and ground-water systems in the Piceance basin (Piceance Creek and Yellow Creek drainage basin) are intimately related. The annual volume of runoff from the basin is estimated to be 15,650 acre-feet (19.2 hm³). Ground-water discharge accounts for about 80 percent of the annual volume of runoff. Ground-water discharge dominates the water chemistry of the streams except during spring runoff from snowmelt.

The runoff from Piceance Creek is greatly affected by irrigation. The mean annual volume of runoff to the White River is estimated to be 14,520 acre-feet (17.9 hm^3). Streamflow depletions resulting from irrigation are estimated to be 4,740 acre-feet (5.8 hm^3). Thus, in the absence of irrigation, the annual runoff from Piceance Creek drainage would be about 19,260 acre-feet (23.7 hm^3).

The runoff from Yellow Creek is slightly affected by irrigation. For the single year of record, the volume of runoff to the White River was measured to be 1,130 acre-feet (1.4 hm^3). Streamflow depletions are estimated to be 60 acre-feet (0.07 hm^3). In the absence of irrigation, runoff from Yellow Creek would be about 1,190 acre-feet (1.5 hm^3), and the total runoff from the Piceance basin would be 20,450 acre-feet (25.2 hm^3).

Low flows and peak flows in Piceance Creek are also influenced by irrigation diversions. The period of lowest flow normally occurs during the spring and summer, when irrigation diversions are greatest. Peak flows from snowmelt and thunderstorms also occur during this period. The largest peak flow measured on Piceance Creek at White River is 407 ft^3/s (11.5 m^3/s) for the 5 years of record. A regionalized flood-frequency analysis using the index-flood method was made for Piceance and Yellow Creeks. The flood-frequency estimates exclude the effects of irrigation. The analysis estimated the mean annual flood in Piceance Creek at White River to be 800 ft^3/s (22.7 m^3/s) or about twice the highest flow observed.

The peak flow on Yellow Creek for the single year of record was 468 ft^3/s (13.3 m^3/s). The mean annual flood was estimated by the index-flood method to be 390 ft^3/s (11.0 m^3/s).

The quality of surface water in the Piceance basin is affected by irrigation practices and ground-water discharge. The chemical composition of the water varies from a mixed bicarbonate type in the upper reaches of the streams to sodium bicarbonate in the lower reaches. The concentration of dissolved solids varies from less than 500 to more than 5,000 mg/l in Piceance Creek and from about 700 to 3,000 mg/l in Yellow Creek drainage. Surface water is generally not potable but is acceptable for livestock watering. Surface water is widely used for irrigation, although the salinity hazard and sodium hazard are high.

The water quality decreases in the downstream direction due to ground-water discharge and, to some extent, irrigation return flows, and evapotranspiration. This is particularly evident in the reach of Piceance Creek below Ryan Gulch during periods of low flow. Ground water from the Green River Formation moves upward, through the Uinta Formation, and is discharged to the valley alluvium. The dissolved-solids concentration of springs found in this reach is as high as 22,000 mg/l.

The ground-water system in the Piceance basin consists of two principal aquifers that are separated by the Mahogany zone in the Parachute Creek Member of the Green River Formation. The Mahogany zone is less permeable than the aquifers it separates. Recharge to the aquifers mainly occurs from snowmelt above 7,000 feet (2,130 m) in altitude along the basin margins. The recharge infiltrates to the upper aquifer and flows toward the north-central part of the basin. In the recharge area, the hydraulic head in the upper aquifer is higher than that in the lower aquifer, and water moves down through the Mahogany zone to the lower aquifer. In the north-central part of the basin and in the major stream valleys, the heads in the aquifers are reversed, and water moves upward from the lower aquifer through the Mahogany zone. Water from the aquifers is eventually discharged as evapotranspriation and baseflow in the streams. Estimates of the volume of water stored in the aquifers range from 2.5 to 25 million acre-feet (3,100 to 31,000 hm^3). The annual volume of ground-water recharge and discharge is estimated to be 26,100 acre-feet (32.2 hm^3).

At the time of deposition, part of the lower aquifer contained soluble minerals by as much as 20 percent by volume. Percolating water is actively leaching these minerals and the lower aquifer is frequently referred to as the leached zone. The Mahogany zone impedes the movement of water between the aquifers and large chemical differences have developed. Water in the upper aquifer generally has less than 2,000 mg/l dissolved solids, except where discharge from the lower aquifer affects the water quality of the upper aquifer. The concentration of dissolved solids in the lower aquifer exceeds 30,000 mg/l in the northern part of the basin.

A digital watershed model used available descriptive, climatic, and hydrologic data to define the hydrologic characteristics of the basin. To account for temporal and spatial variations in these characteristics, the basin was partitioned into 22 subunits considered homogeneous with respect to their hydrologic response. Application of the model was limited to the drainage area above the gage on Piceance Creek below Ryan Gulch because of the limited data available.

The model was calibrated, using 9 years of available discharge data. Calibration entailed the comparison of simulated daily discharges with measured winter and spring discharges and the comparison of simualted and estimated annual "natural" basin discharges. The complexity of the fitting procedure was necessitated by the effects of irrigation diversions on measured discharges. The model calibration was considered good, given current data constraints.

The model was used to predict the effects of precipitation modification on the hydrologic system. Precipitation modification could result from either the introduction of pollutants into the atmosphere as the result of oil-shale development or intentional attempts to augment natural precipitation over the basin. Consideration of precipitation changes was given only to winter storms because of the limited areal coverage of summer thunderstorms and the large evapotranspiration demands during the summer. A 10-percent decrease and a 0-, 10-, and 20-percent increase in natural precipitation were examined. These changes were simulated by imposing a constant percentage change on all winter storms over the 9 years of record.

Precipitation modification may have a significant effect on the basin hydrologic system. For the area simulated, the predicted changes in average annual ground-water recharge were directly proportional to the precipitation modification simulated. Each 10-percent change in natural precipitation produced about a 40-percent change in ground-water recharge, which is equivalent to about 0.25 inch (63 mm) or about 6,500 acre-feet (8.0 hm^3). The predicted changes in average annual stream discharge were a function of the magnitude and sign of the precipitation change. A 10-percent decrease in precipitation produced a 30-percent decrease in stream discharge, whereas a 10- and 20-percent increase in precipitation produced a 40- and 85-percent increase in discharge. Changes in stream discharge were distributed throughout the year because ground-water discharge remained the major source of annual discharge for all precipitation modifications simulated.

A digital model of the ground-water flow system was developed, based on the description of the aquifer system. Aquifer test and geophysical data collected and compiled during the study were used to evaluate the hydraulic characteristics of the system. A water budget was developed to estimate the ground-water recharge rate. The ground-water system was assumed to be in a steady-state condition. The digital model was calibrated by comparing the computed steady-state potentiometric surface with water-level measurements collected from wells in the basin. The annual volume of ground-water recharge used in the model to obtain the steady-state solution was found to be within 10 percent of that estimated by the water budget.

The digital model of the aquifer system was used to predict the effects of mine dewatering on the hydrologic system. Proposed mines in the prototype lease tracts C–a and C–b will remove the Mahogany zone which separates the aquifers, and large pumping rates may be required to dewater the mines. The digital model was used to simulate dewatering operations at the two mines. The hydraulic head in the upper aquifer was assumed to be drawn down to the top of the Mahogany zone and the head in the lower aquifer was assumed to be drawn down to the bottom of the Mahogany zone at each mine. Each of the hypothetical mines is 4 square miles (10.4 km^2) in area and located in the lease tracts. Dewatering of the mines was assumed to occur simultaneously for a period of 30 years.

The results of the model study indicate that, after the first few years of dewatering, discharge from the hypothetical mine in tract C–a will be about 7 ft^3/s (0.20 m^3/s). This is only about half of the estimated water demand for processing and disposal of the oil shale. After 30 years, discharge from the hypothetical mine in tract C–b will be 20 ft^3/s (0.57 m^3/s), which is larger than the estimated water demand. The excess water produced at tract C–b could be used to offset the deficiency at tract C–a. Analysis of the potentiometric surfaces of the aquifers, computed by the model after 30 years of dewatering, indicate that the concentration of dissolved solids of the discharge from both mines might not exceed 5,000 mg/l. After 30 years of dewatering the discharge from both mines is 27 ft^3/s (0.76 m^3/s) and is supplied by intercepted ground-water discharge and water from storage in the aquifers. About 500,000 acre-feet (620 hm^3) of water is removed from storage during the 30 years of simulated dewatering.

Hypothetical dewatering operations will only slightly affect ground-water discharge in the Yellow Creek drainage area. However, after 30 years of dewatering, ground-water discharge in the Piceance Creek drainage area will be reduced by 8 ft^3/s (0.23 m^3/s). The reduction in discharge will reduce both evapotranspiration and streamflow. The study indicates that ground-water discharge will cease in a 10-mile (16-km) reach of Piceance Creek near tract C–b during the 30 years of dewatering. The decrease in ground-water discharge in this reach could cause an increase in the concentration of dissolved solids in the downstream reach of Piceance Creek.

Dewatering operations will decrease the hydraulic head in the aquifers in about 75 percent of the modeled area during the life of the mines. Ground-water discharge from springs that are hydraulically connected to the upper aquifer will be reduced where significant drawdown occurs. The discharge from springs resulting from perched ground-water zones will not be affected.

The potential impact of oil-shale development on the hydrology of the Piceance basin was investigated by using digital watershed and ground-water models. The models are based on data currently available but which, in several cases, are severely lacking. However, the models were shown to reasonably simulate existing hydrologic conditions in the basin and, therefore, the simulated precipitation modifications and mine-dewatering operations are reasonable estimates of the potential effects of development on the hydrologic system. It is evident from the study that the developing oil-shale industry will have significant effects on the hydrology of the Piceance basin.

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