SIMULATION OF MINE DRAINAGE FOR PRELIMINARY DEVELOPMENT OF OIL SHALE AND ASSOCIATED MINERALS, PICEANCE BASIN, NORTHWESTERN COLORADO

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CONTENTS

PLATE

FIGURES

TABLES

CONVERSION FACTORS

The inch-pound units used in this report may be converted to International System of Units (SI) by the following conversion factors:

Multiply inch-pound units	*By*	*To obtain SI units*
barrel	1.59×10^{-1}	cubic meter
cubic foot per second (ft^3/s)	2.832×10^{-1}	cubic meter per second
foot (ft)	3.048×10^{-1}	meter
foot per day (ft/d)	3.048×10^{-1}	meter per day
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
square mile (mi^2)	2.590	square kilometer
ton	907.2	kilogram

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ABSTRACT

The Piceance basin of northwestern Colorado contains large resources of oil shale, nahcolite, and dawsonite. Development of these minerals will require drainage of water from mines. A six-layer anisotropic hydrologic model of the basin was prepared to simulate mine drainage for mineral development. Streams and major tributaries were simulated as head-dependent nodes. Stream nodes were gaining or losing, but the rate of loss was constrained by the leakance of the streambed and stream stage. Springs also were simulated as head-dependent nodes that stop flowing if the aquifer head declines below the spring orifice.

The model was tested in steady state and used for predictive transient simulations. Results of steady-state simulation of the hydrologic system indicated reasonably accurate head distributions in bedrock aquifers, gains and losses in Yellow and Piceance Creeks, and low-flow characteristics of Roan and Parachute Creeks. Several 20-year transient simulations of selected pumping plans indicated that initially most pumped water will be derived from ground water in storage. Toward the end of a 20-year period, most water will be derived from reduced discharge to springs and streams; however, if pumping causes widespread conversion from confined to unconfined conditions, most water will be derived from ground water in storage. Pumping also will induce increased recharge from reaches of streams that normally lose water to the ground-water system.

INTRODUCTION

Oil shale, nahcolite, and dawsonite occur within the Piceance basin. The basin contains a complex hydrologic system that must be considered during mineral development. Most potential mine sites will have to be drained of water before mining can proceed. Complete mineral development and mine drainage will require hundreds of years, even with intense development. Mine-drainage water may be consumed, discharged into streams, or injected into aquifers of the Uinta and Green River Formations at sites distant from drained mines to store water for later withdrawal and use. Mine drainage and injection in the complex hydrologic system need to be appraised to determine the likely efficiency of mine-drainage plans and to estimate the effects on the hydrologic system.

Purpose and Scope

The purpose of this report is to predict the hydrologic effects in the Piceance basin of preliminary mine drainage, that is, the drainage of mine workings without areally extensive aquifer drainage that would greatly alter the hydrologic characteristics of the aquifers. This prediction was done using a model that integrates the major features of the hydrologic system.

General Hydrogeology of Study Area

The Piceance basin encompasses an area of 1,600 mi^2 in northwestern Colorado (fig. 1). This basin includes the drainage basins of Piceance and Yellow Creeks, and Roan and Parachute Creeks (fig. 2).

Normal annual precipitation includes rain and snow and ranges from 12 to 20 in. Part of the precipitation is drained by the principal streams into the Colorado River or its tributaries. Precipitation also recharges two major bedrock aquifers that extend over most of the Piceance basin.

Valley-fill alluvium of Quaternary age consisting of clay, sand, and gravel is present along the major streams and parts of their tributaries. Maximum thickness of the alluvium is about 200 ft. Recent exploratory drilling in the alluvium along the valleys of Piceance and Yellow Creeks indicates that clay is the dominant rock type in these valleys.

Stratigraphically below the alluvium are the Uinta and Green River Formations of Eocene age, as shown in figure 3. The Uinta Formation consists of fractured sandstone, marlstone, and siltstone; the Parachute Creek Member of the Green River Formation consists of fractured marlstone (Donnell, 1961). The Garden Gulch Member of the Green River Formation and its equivalents are relatively low-permeability marlstone, shale, and sandstone (Weeks and others, 1974).

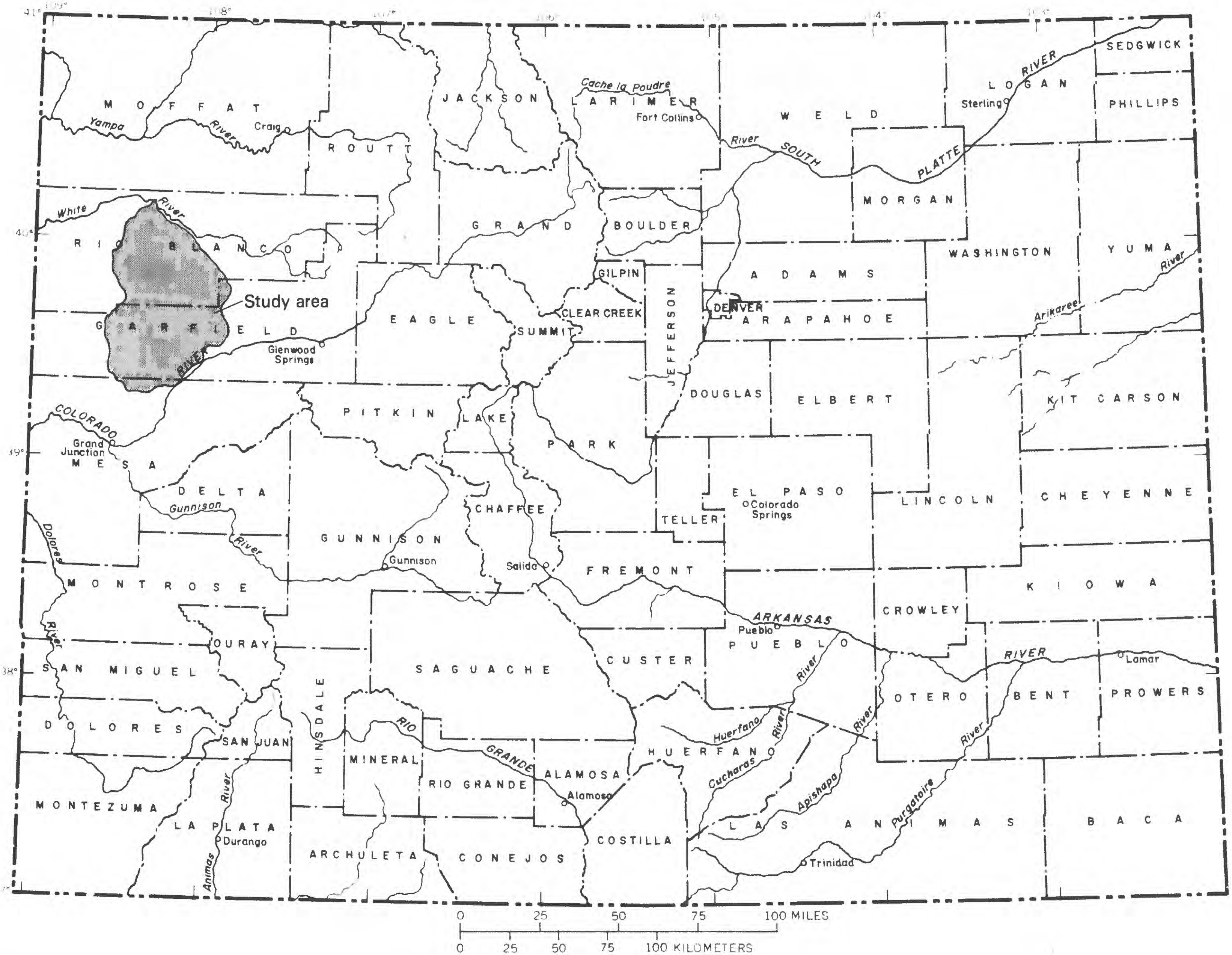
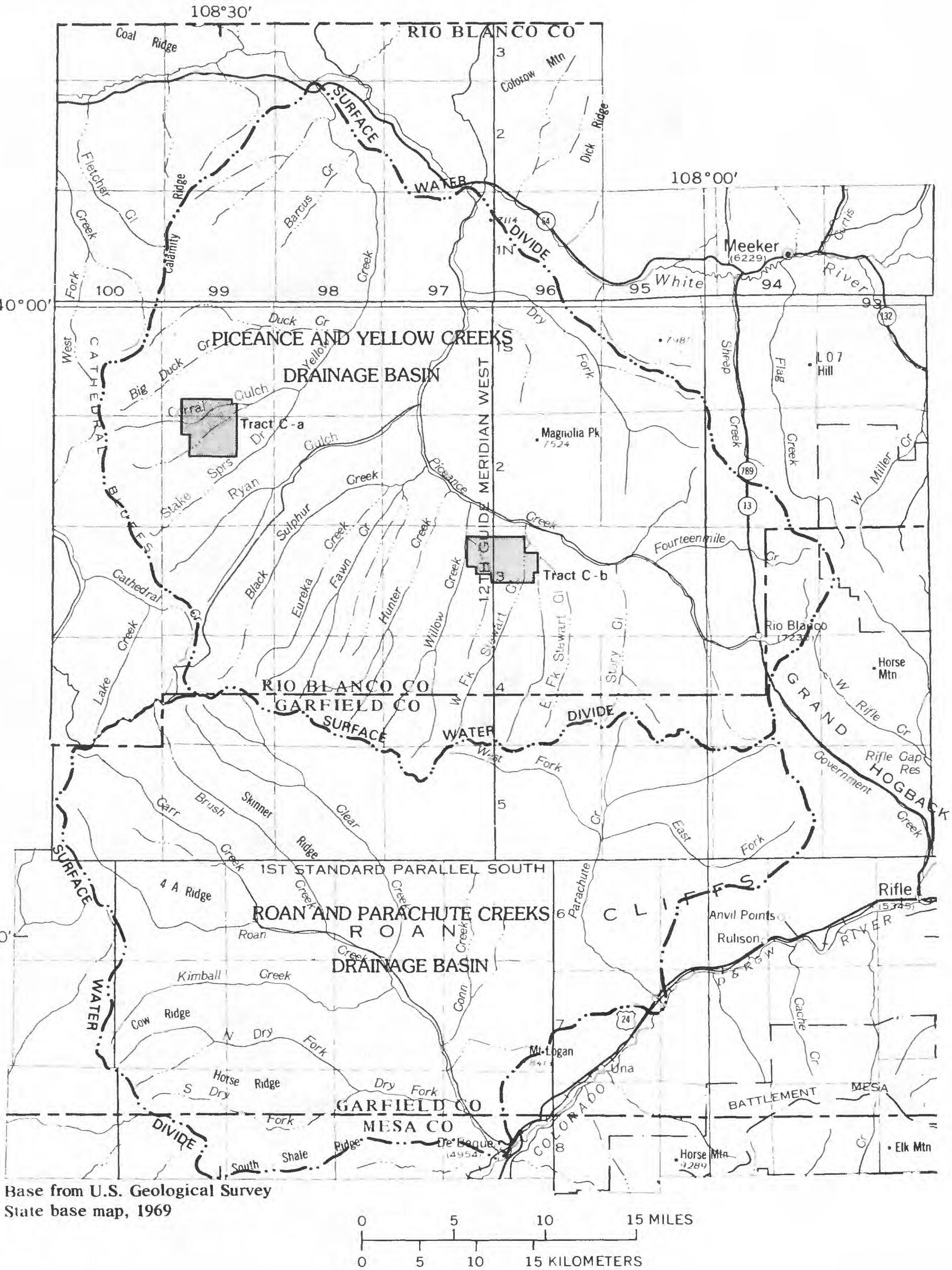


Figure 1.--Location of the study area.



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

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

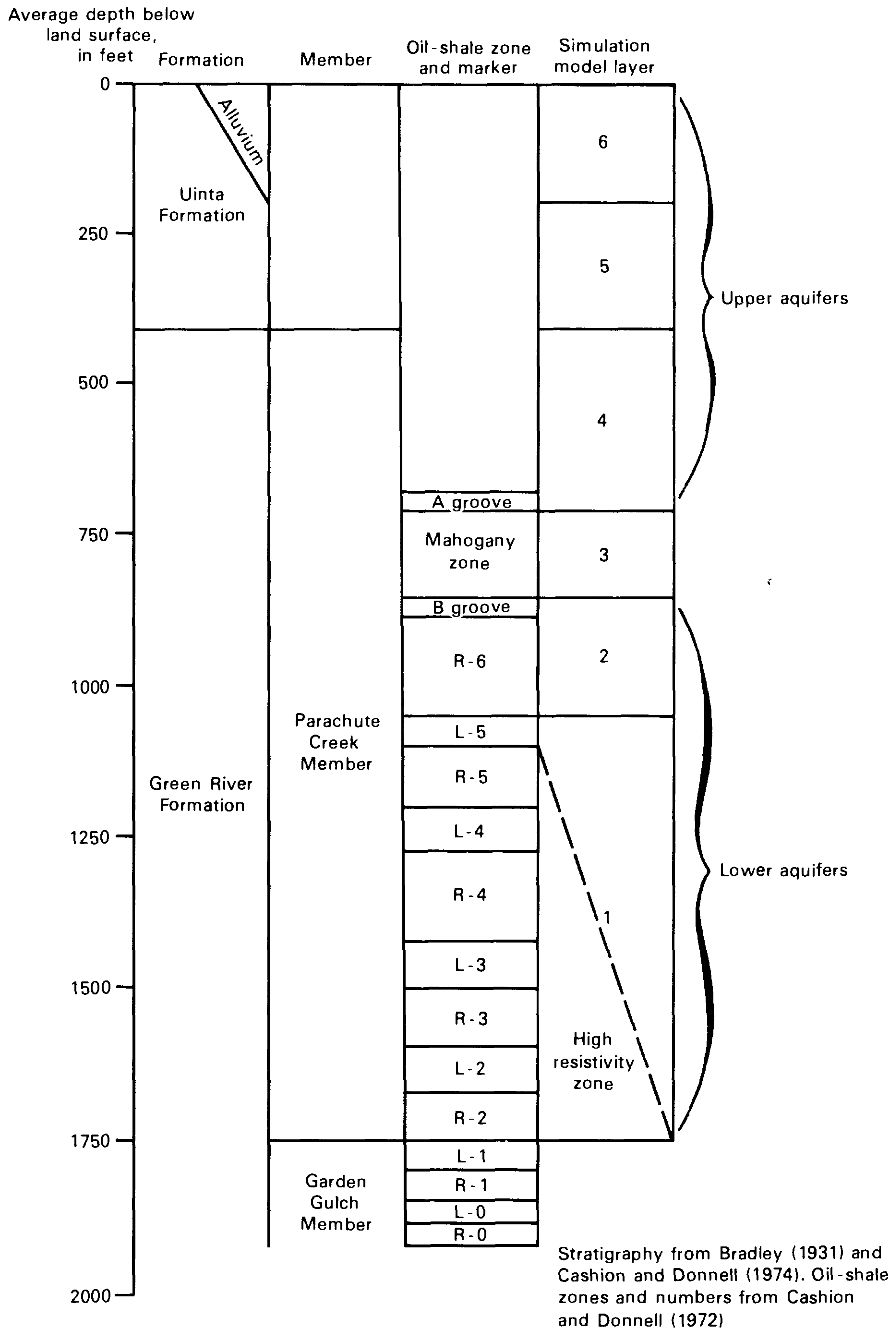


Figure 3.--Generalized correlation of stratigraphic, oil-shale, and simulation-model layers, Piceance basin.

The Uinta and Green River Formations in the Piceance basin contain the largest known deposit of shale oil--about 1.2×10^9 barrels. The oil-shale beds have been classified into numerous zones and markers (fig. 3). Zones designated with L- and R- prefixes are lean and rich zones (Cashion and Donnell, 1972). The Mahogany zone is a rich oil-shale layer. The A and B grooves are lean fractured oil-shale zones that bound the Mahogany zone. Resources of about 50×10^9 tons of the minerals, nahcolite and dawsonite, also occur in these formations in the northern part of the Piceance basin. Nahcolite is a source of soda ash which is used in the manufacture of glass and other industrial chemicals; it also is used to remove sulfur dioxide from industrial stack gases. Dawsonite is a source of aluminum. Development of oil shale, nahcolite, and dawsonite may occur together or separately, depending on mineral rights, mining techniques, and demand.

The complex hydrologic systems of the basin are portrayed schematically in figure 4. The valley-fill alluvium is an aquifer where it contains coarse material; in general the alluvium is more permeable in the valleys of Roan and Parachute Creeks than in the valleys of Piceance and Yellow Creeks and their tributaries. Two aquifer systems generally are recognized within the Uinta and Green River Formations. An upper aquifer extends from the top of the Mahogany zone in the Parachute Creek Member of the Green River Formation to the land surface; a lower aquifer extends from the top of the Garden Gulch Member of the Green River Formation to the base of the Mahogany zone.

The flow systems are different in the northern and southern parts of the basin. In the north, in Piceance and Yellow Creek drainage basins, natural recharge from precipitation mostly occurs in the high-altitude areas of the drainage basins. Recharged water circulates through bedrock aquifers and the Mahogany zone to discharge into the valley-fill alluvium or as springs in the valleys of Piceance and Yellow Creeks and their tributaries. In the south, in Roan and Parachute Creek drainage basins, natural recharge from precipitation also occurs in the high-altitude areas of the drainage basins. However, the recharge water moves downward through the bedrock aquifers and Mahogany zone to springs located on the walls of the steeply incised canyons.

The ground-water divide that separates Piceance and Yellow Creeks from Roan and Parachute Creeks differs from the surface-water divide (fig. 2). Preliminary potentiometric maps indicate that the ground-water divide is south of the surface-water divide. Therefore, water recharged in some parts of the drainage basins of Roan and Parachute Creeks probably moves to the north, where it discharges to the valleys of Piceance and Yellow Creeks.

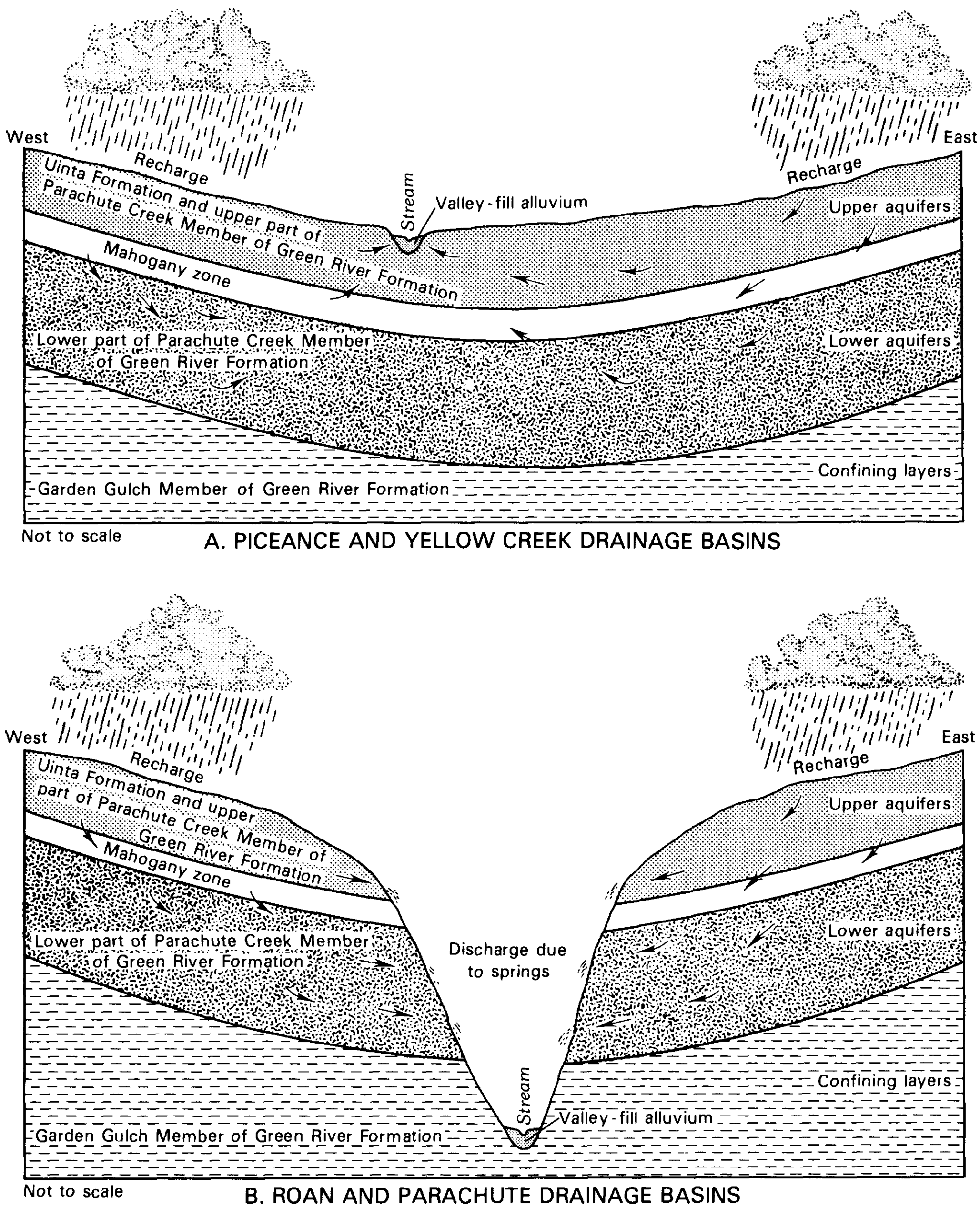


Figure 4.--Schematic diagrams of ground-water flow systems. A, Piceance and Yellow Creek drainage basins, B, Roan and Parachute Creek drainage basins.

MATHEMATICAL MODEL OF HYDROLOGIC SYSTEM

Various ground-water models of the Piceance basin have been prepared: Weeks and others (1974) designed a transient-state model of the northern part of the basin; Robson and Saulnier (1981) prepared a transient-state anisotropic solute-transport model of the same region; Taylor (1982) described an anisotropic steady-state model of the entire basin.

The model described by Taylor (1982) was modified in several ways: (1) The uppermost layer was divided into two layers, (2) additional tributaries to Piceance Creek were simulated, (3) all nodes representing streams and springs were converted from constant head to head dependent, and (4) a revised steady-state analysis was made. This modified model is the basis for the transient-state model described in this report.

Model Framework

The computer program for solving the ground-water-flow equations is described by Trescott (1975) and Trescott and Larson (1976). Torak (1982) modified the original program to include head-dependent sources and sinks. The finite-difference grid for the model described in this report consists of 6 vertical layers (fig. 3), each subdivided horizontally into 46 rows and 40 columns (pl. 1). Layers 1 and 2 represent the lower aquifers; layer 3 is the Mahogany zone; layers 4, 5, and 6 are the upper bedrock aquifers. Layer 6 also represents the valley-fill alluvium along Yellow Creek, Piceance Creek, and the major tributaries of Piceance Creek: Stewart Gulch, Willow Creek, Hunter Creek, Black Sulphur Creek, and Dry Fork. Lateral boundaries for the bedrock aquifers and the Mahogany zone are indicated by a line on plate 1 that represents the average limit of outcrop for all six layers. The model grid extends beyond the limit of the aquifers and confining layers in the basin, but nodes beyond this limit are inactive. The limits of major bedrock units and valley-fill alluvium were compiled by Donnell (1961).

Yellow Creek, Piceance Creek, and the major tributaries of Piceance Creek were simulated as head-dependent sources or sinks in layer 6. Simulated flow to stream nodes from the aquifers is proportional to the height of the potentiometric head above the stream level and the leakance of the streambed. If the potentiometric head is below the base of the streambed, flow from stream nodes to the aquifers is proportional to the constant distance between the stream level and the bottom of the streambed and the leakance of the streambed. The average depth of water for each stream node was estimated as 1 ft. Estimated leakance values for stream nodes ranged from 4.5×10^{-10} to 9.0×10^{-10} seconds^{-1}. The estimated leakance values for streams and tributaries were calculated by presuming that the streambed thickness is 10 ft for Piceance and Yellow Creeks and Dry Fork, and 5 ft for the relatively small tributaries to Piceance Creek that were simulated. Values of leakance also included estimates of streambed vertical hydraulic conductivity and the fraction of the nodal area occupied by the stream.

Springs in the southern part of the basin were simulated as head-dependent sinks at sites where the various layers are exposed along the steep canyons of the drainage basin of Roan and Parachute Creeks. The altitudes of spring orifices were specified at the midpoints of layers 1 and 2 and at the bases of layers 4 and 5 (see pl. 1). Spring orifices were simulated at the midpoints of layers 1 and 2 because talus deposits hide springs that discharge from these layers, and their stratigraphic position is uncertain. Orifices were simulated at the bases of layers 4 and 5 because springs have been observed at these horizons. Exceptions to the spring locations specified are the tributaries to the East Fork of Parachute Creek where springs are not simulated in layers 1 and 2 because the tributary streambeds are considerably above layers 1 and 2 and springs are unlikely. Simulated discharge from springs is proportional to the height of the potentiometric head above the spring orifice and the leakance value for the head-dependent node that represents the spring. Estimated leakance values for springs ranged from 1.3×10^{-11} to 4.8×10^{-11} seconds^{-1}. These values for leakance were calculated from the estimated maximum spring discharge of 1.0 ft^3/s, the average node area, and the presumption that spring discharge is steady when the aquifer head is 10 ft or more above the spring orifice.

The hydrologic characteristics of aquifers and confining layers are poorly known because of the paucity of aquifer tests in the Piceance basin. Therefore, measured hydrologic parameters were interpolated and extrapolated in simulation studies in attempts to obtain areally distributed characteristics that were feasible and reasonable. Distributed values of transmissivity were used in all layers in this model; these values ranged from 0.016 to 400 ft^2/d.

Estimated hydrologic characteristics of model layers are summarized in table 1. Hydraulic conductivity and transmissivity are anisotropic according to Robson and Saulnier (1981) and Taylor (1982). The ratio of horizontal hydraulic conductivity to vertical hydraulic conductivity appears to increase with depth. Lateral anisotropy of transmissivity was reported by Taylor (1982) for layer 4; the regional transmissivity along the trend N 15° W is probably two times greater than the regional transmissivity along the trend N 75° E. The anisotropic ratios of hydraulic conductivity and transmissivity probably result from a combination of fracture aperture, spacing, and continuity.

Storage coefficients for each layer (table 1) were estimated from aquifer tests and from the theoretical analysis of storage characteristics described by Jacob (1950). The storage coefficients represent artesian conditions in all layers, as indicated in field studies, including the valley-fill alluvium. Because of the paucity of data describing the distribution of the storage coefficient, uniform rather than distributed storage values were used in each layer.

Table 1.--*Summary of estimated hydrologic characteristics of model layers*

[T_{yy} is transmissivity along the trend N 15° W; T_{xx} is transmissivity along the trend N 75° E; K_{xx} is hydraulic conductivity along the trend N 75° E; K_{zz} is hydraulic conductivity in the vertical]

Layer	Average thickness (feet)	Ratio of K_{xx} to K_{zz}	Ratio of T_{yy} to T_{xx}	Storage coefficient
6	200	2.0	1	[1] 1.0×10^{-4}
5	200	2.0	1	1.0×10^{-4}
4	300	2.0	2	1.5×10^{-4}
3	160	3.3	1	3.0×10^{-5}
2	190	13.4	1	1.0×10^{-4}
1	700	15.0	1	3.0×10^{-4}

[1] Changed to 1.0×10^{-2} in later simulations.

Steady-State Analysis

Initially the model was utilized to make a steady-state analysis of the anisotropic flow system. By comparing the steady-state response of the model to known characteristics of the flow system, the model was adjusted to reduce the differences between simulated and observed streamflow, and between simulated and observed heads in the aquifers.

In the steady-state analysis, only natural recharge from precipitation and natural discharge to streams and springs were considered; underflow into or out of the basin was assumed to be negligible because the underlying and outlying beds have small permeabilities. Natural recharge from precipitation to aquifers is difficult to measure. However, in the steady-state system, recharge and discharge rates are equal. Therefore, streamflow analysis was made to estimate natural discharge from aquifers to streams using gain-and-loss studies along Piceance and Yellow Creeks and low-flow statistics for Roan and Parachute Creeks. Natural recharge was equated to estimated natural discharge. This resulted in considerable modification to the amount and distribution of natural recharge and discharge of the previous steady-state model described by Taylor (1982).

Measured and simulated base flow of Piceance and Yellow Creeks are similar, as shown in figures 5 and 6. Streamflow was calculated by accumulating simulated flow to or from appropriate head-dependent stream nodes in the downstream direction. The two curves for Piceance Creek are similar in shape, with positive and negative departures. The two curves for Yellow Creek have small departures over much of the creek. Near the head of the creek the simulation did not predict the flow of more than 2 ft^3/s that was measured; the model predicted a losing stream; that is, water flowed from the stream to the aquifers.

Gain-and-loss studies were incomplete for Roan and Parachute Creeks, so the discharge of springs in these drainage basins was compared to low-flow characteristics of the streams (table 2). Monthly mean flow for January and February (7-day, 2-year low flow and 14-day, 2-year low flow for December, January, and February), and minimum monthly flow for December, January, and February were tabulated for comparison with simulated springflow. Values of monthly mean flow were not used because those values may include surface runoff during warm periods. Low-flow values also were not used because the conditions under which these flows occurred were unknown. The minimum monthly flows probably represent the best estimates of discharge from springs to the creeks, and December values were selected arbitrarily to avoid effects of phreatophytes, irrigation, and runoff. However, the minimum-flow values were similar for December, January, and February for Roan Creek as well as Parachute Creek.

Table 2.--*Low-flow characteristics of major streams of Piceance basin*

[All discharge data are averages, in cubic feet per second]

Station number and name	Monthly mean flow		Low flow for December, January, and February with 2-year recurrence interval		Minimum monthly flow		
	January	February	7-day	14-day	December	January	February
09306222 Piceance Creek at White River, Colo.	24.6	27.6	17.79	19.12	13.90	11.40	16.30
09306255 Yellow Creek near White River, Colo.	1.15	3.72	.94	1.02	.15	.01	.22
09095000 Roan Creek near De Beque, Colo.	17.00	18.30	12.74	13.42	5.99	5.88	6.83
09093500 Parachute Creek at Parachute, Colo.	11.70	13.10	9.26	9.39	5.66	6.77	6.57

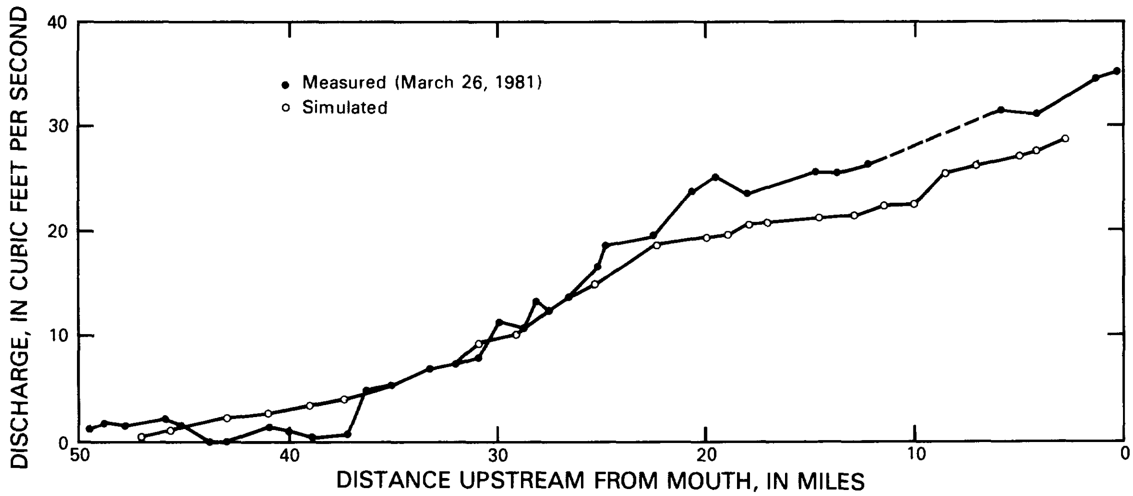


Figure 5.--Comparison of measured and simulated base flow of Piceance Creek.

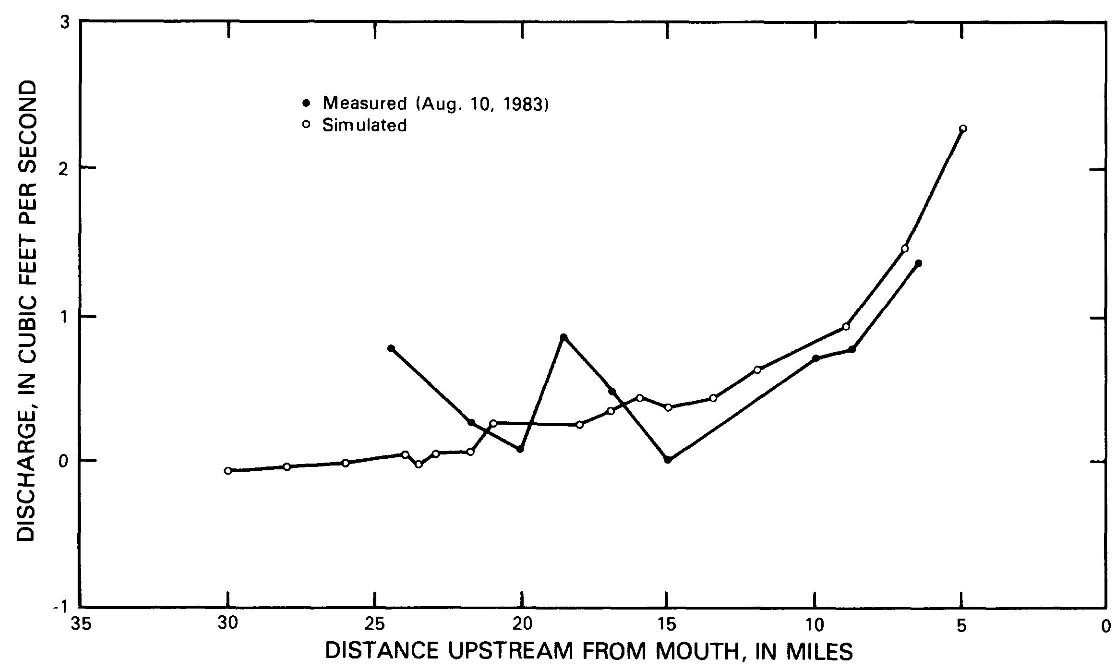


Figure 6.--Comparison of measured and simulated base flow of Yellow Creek.

The distribution and amount of recharge was adjusted to equal the measured and selected values of discharge that are described above. Recharge values ranged from 0 to 2.3 in/yr and were distributed approximately in patterns proportional to the land-surface altitude. The resulting ground-water budget, simulated by the steady-state model is shown below:

Natural recharge, in cubic feet per second:	
Precipitation	41.6
Losing streams	0.7
Total	42.3
Natural discharge, in cubic feet per second:	
Yellow and Piceance Creeks	30.7
Roan and Parachute Creeks (springs within drainage basins)	11.6
Total	42.3

The accuracy of the head distribution in various layers was appraised by calculating the difference between measured and simulated water levels in 56 wells completed in layers 1, 2, 4, and 5 and determining the mean-square error for these differences. The mean-square error for the steady-state calibrations for the present model was 17,579 ft^2, substantially lower than the error of 23,428 ft^2 for the earlier model (Taylor, 1982). Errors ranged from 5.39 to 320.47 ft and appear to be randomly located; however, many of the larger errors result from the limitations of the model grid to permit detailed solutions of head in regions where hydraulic gradients are large.

The steady-state model also indicated that many possible springs in the drainage basins of Roan and Parachute Creeks have no discharge because the local potentiometric head is below the simulated spring orifice. Numerous simulated spring sites at the base (layer 5) of the Uinta Formation, and several sites at the base of layer 4 and the midpoint of layer 2 in the Parachute Creek Member of the Green River Formation, are dry. However, injection of water or above-normal recharge may raise the potentiometric surface and cause springs to discharge at these sites.

Transient Analysis

Ground-water development in the Piceance basin has been local and temporary, and analyses of the transient response of the hydrologic system are few and incomplete. Therefore, the transient analyses described below have not been calibrated and should be regarded as estimates of the response of the hydrologic system to pumping.

A transient analysis was completed to evaluate the hydrologic effects of selected pumping and injection plans. The steady-state model was converted to a transient model by incorporating the values of the storage coefficients listed in table 1. Pumping and injection schemes were designed to avoid large drainage of any layer, because the model is not capable of converting from confined to unconfined conditions or adjusting transmissivity values during simulation periods. This conversion would require changing the storage coefficient to a specific-yield value when any layer begins to be drained, and reducing the transmissivity as the saturated thickness of any layer is reduced. The lower bedrock aquifers have large artesian heads over most of the basin so the simulated drawdowns of the potentiometric surface do not represent aquifer drainage.

Mining of oil shale and other minerals may begin in any part of the Parachute Creek Member of the Green River Formation or the Uinta Formation within the basin (fig. 3). Therefore, the location and timing of future mine-drainage activities cannot be forecast. Five hypothetical mine-drainage plans were designed to stress the hydrologic system in various layers and regions of the basin and to observe the response. Stress nodes are shown on plate 1. Simulated pumping using these plans locally would drain mining sites, because of the steep drawdown cones that are associated with aquifers of small transmissivity. This pumping would not result in areally extensive aquifer drainage. In plans 1 and 2, the upper and lower bedrock aquifers are pumped separately near Piceance and Yellow Creeks to simulate the effects of pumping on the aquifer and nearby streams. In plan 3, the lower bedrock aquifers are pumped near discharging springs in the drainage basins of Roan and Parachute Creeks. In plan 4, the water pumped from the lower aquifers in plan 3 was injected into the upper bedrock aquifers. Plans 3 and 4 test the effects of pumping and injections on the aquifers and springs. In plan 5, the upper and lower aquifers were pumped at 17 sites at which mining and mine drainage are likely, in order to observe the hydrologic response to basinwide development.

The effects of pumping on streamflow can be evaluated by comparing the sum of simulated reduced discharge to streams and simulated increased recharge from streams with the flow statistics of streams given in table 2. If the net reduction in streamflow exceeds the base flow at the mouth of the stream, direct surface runoff is being recharged through the streambed to the bedrock aquifers.

For plan 1, two hypothetical wells were located in layers 1 and 2 near Piceance Creek, in row 19, column 25 of the model grid. Each well was pumped at a rate of 1.0 ft^3/s for 20 years. Maximum nodal drawdown for each layer after 20 years is tabulated below:

Plan 1

Layer	Drawdown, in feet (row 19, column 25)
6	116.76
5	117.46
4	118.82
3	130.12
2	146.10
1	152.42

Maximum drawdown resulting from plan 1 occurs in layer 1 because layers 1 and 2 are pumped, and rocks below layer 1 are presumed impermeable. Drawdown decreases upward and outward with distance from the pumps. Instantaneous sources of water to the pumps for plan 1 are shown in figure 7. Initially, most water is derived from ground water in storage. However, this source decreases rapidly as discharge to Piceance and Yellow Creeks decreases. In addition, losing reaches of Yellow Creek and tributaries to Piceance Creek begin to recharge the bedrock aquifers at greater rates because of the lower aquifer heads induced by pumping. After 20 years of pumping, the sources of water are nearly stable, and the pumped water is derived mostly from the streams; the system is nearly at equilibrium because of the relatively high ratio of hydraulic conductivity to specific storage--the hydraulic diffusivity of the hydrologic system in this region.

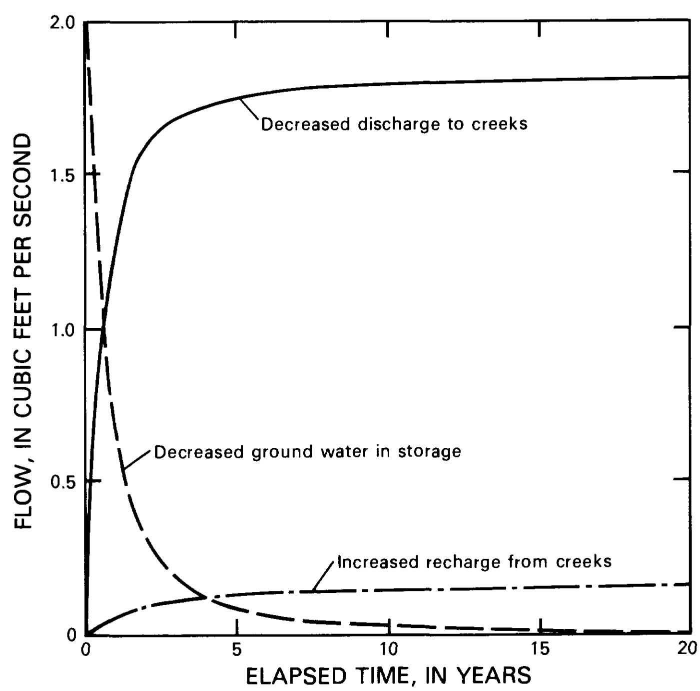


Figure 7.--Instantaneous sources of water for pumpage for plan 1.

In the simulation for plan 2, two hypothetical wells that each pumped 1.0 ft^3/s for 20 years were placed in layers 4 and 5 of row 19, column 25. Maximum nodal drawdown is shown below:

Plan 2

Layer	Drawdown, in feet (row 19, column 25)
6	161.79
5	163.06
4	160.20
3	147.35
2	130.89
1	105.39

The drawdown decreases downward and outward with increased distance from the pumps. Instantaneous sources of water for plan 2 are shown in figure 8, these sources are almost identical to those of plan 1.

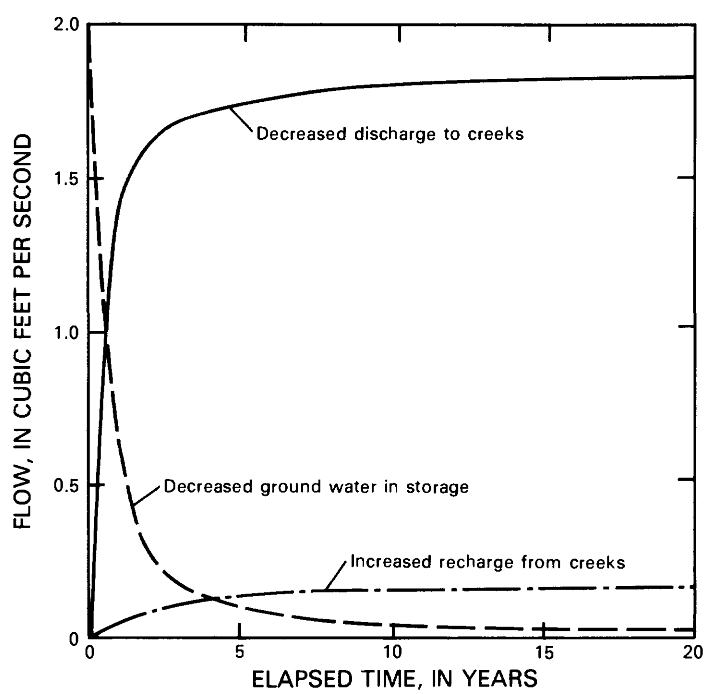


Figure 8.--Instantaneous sources of water for pumpage for plan 2.

In the simulation in plan 3, two hypothetical wells were located in layers 1 and 2 near several springs at row 40, column 23. Pumping rates were decreased to 0.25 ft^3/s for each well, because of the low transmissivity in this region compared to that of the region near Piceance Creek. Maximum nodal drawdown is shown below:

Plan 3

Layer	Drawdown, in feet (row 40, column 23)
6	88.14
5	88.20
4	88.28
3	314.95
2	544.13
1	537.44

Drawdown in layers 1 and 2 is much greater than that of layers 4, 5, and 6, because the vertical hydraulic conductivity of layer 3, the Mahogany zone, is relatively low in comparison to the hydraulic conductivity of the zone near the pumping site of plans 1 and 2. Instantaneous sources of water pumped for plan 3 are shown in figure 9. All water is derived from ground water in storage or from decreased discharge to springs; Piceance and Yellow Creeks are too distant to be affected by the pumping. The response curves on figure 9 show that an equilibrium state was not reached after 20 years of pumping; this is due to the low transmissivity of the aquifers in this region and associated low diffusivity.

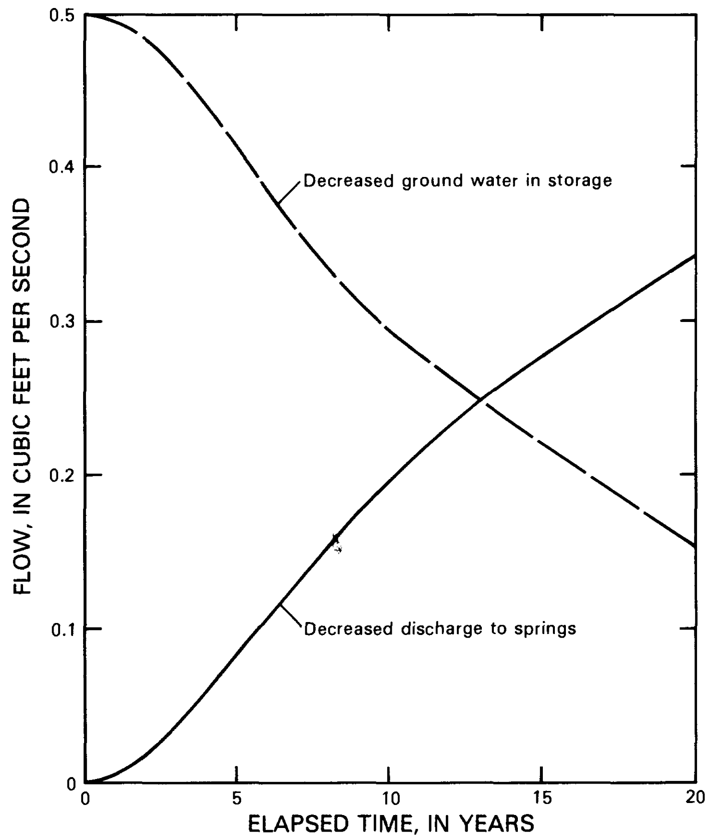


Figure 9.--Instantaneous sources of water for pumpage for plan 3.

In the simulation of plan 4, two wells were pumped in layers 1 and 2 in row 40, column 23, at 0.25 ft^3/s each, the same as for plan 3. However, another well was added in layer 4 of row 41, column 23; this well injected 0.5 ft^3/s for the entire 20-year pumping period. Therefore the net withdrawal rate was zero, although the pumping and injection centers did not coincide. Maximum drawdown and rise in water levels in, and directly above, the pumped nodes are listed below:

Plan 4

Layer	Change, in feet (row 40, column 23)
6	53.64 rise
5	53.61 rise
4	53.57 rise
3	205.83 drawdown
2	467.54 drawdown
1	462.29 drawdown

Compared to plan 3, the injection well in plan 4 has reduced drawdown in the lower aquifers and converted drawdown in the upper aquifers to rises above original levels. Again, the low vertical hydraulic conductivity of the Mahogany zone has permitted very different head changes in the upper and lower aquifers. Instantaneous changes resulting from plan 4 are shown in figure 10. Increased discharge to springs and decreased ground water in storage are almost equal, and they are the only changes. Plan 4 is closer to an equilibrium state after 20 years than plan 3 because the pumping and injection stresses tend to stabilize each other.

Plan 5 was designed to simulate preliminary drainage at 17 sites that represent major patented or fee land, unpatented claims, or Federal oil-shale leases Ca and Cb shown in figure 2 (The Pace Company Consultants and Engineers, Inc., 1977). Thirty-four wells were simulated, two at each site. Wells were located in layers 1 and 4. Discharge rates ranged from 0.1 to 0.5 ft^3/s; total discharge was 8.9 ft^3/s. Instantaneous sources of water to the pumps for plan 5 are shown in figure 11. Relative amounts of water from the various sources are similar to those amounts of other pumping plans. Initially, most water is derived from ground water in storage; after 20 years, most water is derived from decreased discharge to springs and creeks.

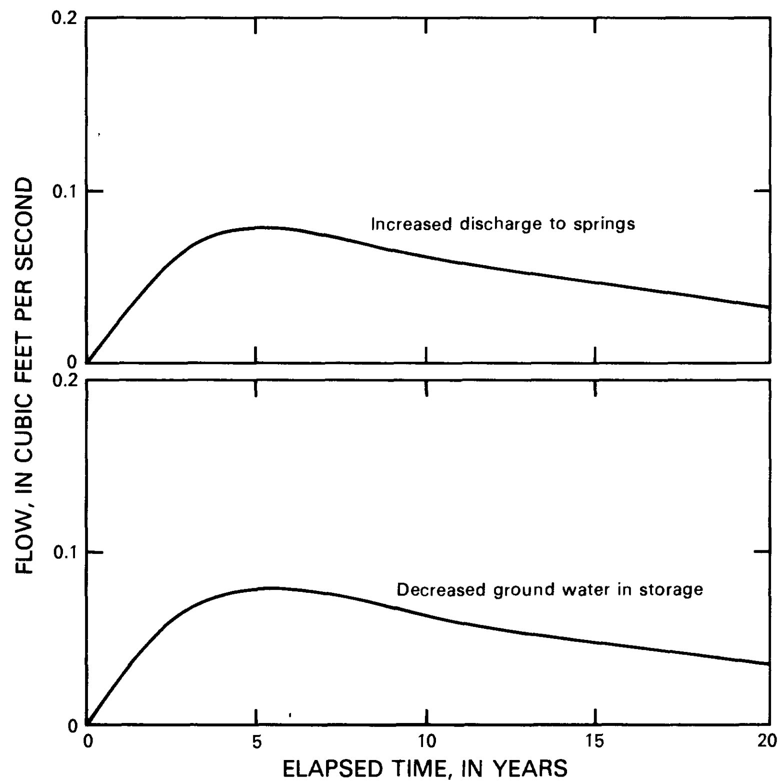


Figure 10.--Instantaneous changes resulting from pumping and injection for plan 4.

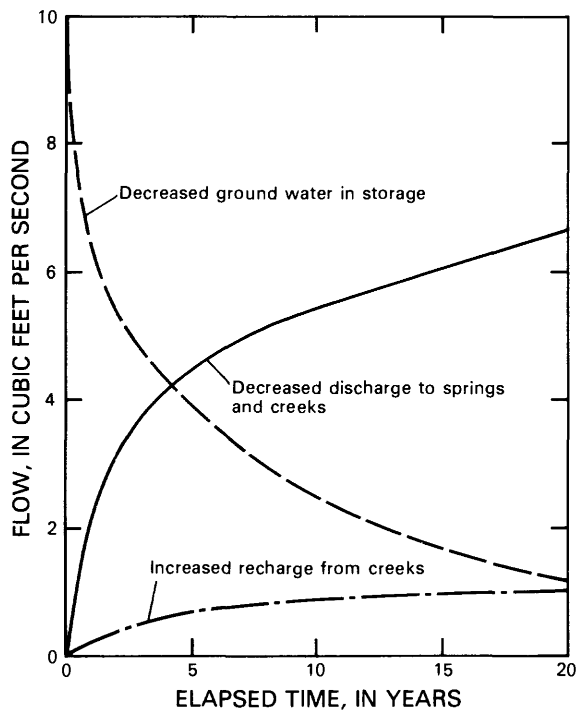


Figure 11.--Instantaneous sources of water for pumpage for plan 5.

The pumpage of plan 5 was simulated again after making adjustments to the storage characteristics of layer 6. These adjustments were designed to simulate a drainage-induced conversion from confined to unconfined conditions, and the associated change from a storage coefficient value to a specific yield value. First, the storage value for valley-fill alluvium along Piceance and Yellow Creeks and their tributaries was increased from 1.0×10^{-4} (table 1) to 1.0×10^{-2} and the 20-year pumpage was simulated again. Results of the simulation are plotted in figure 12. Sources of water appear similar to those shown in figure 11 for the original simulation, but a detailed analysis shows that during the 20-year simulations slightly more pumped water was derived from water in storage and slightly less was derived from streams and springs. Second, storage values for all nodes in layer 6 were increased from 1.0×10^{-4} to 1.0×10^{-2} and the simulation was repeated. Results of this simulation are plotted in figure 13. Compared to the result shown in figure 11, more pumped water was derived from ground water in storage and less water was derived from streams and springs. The greater storage throughout layer 6 has allowed more water to be derived from layer 6, especially above the pumping centers.

CONCLUSIONS

The new simulation model for Piceance basin discussed in this report appears to simulate the hydrologic system of the study area reasonably accurately in steady state. However, aquifer testing in the basin is inadequate, so the hydrologic system is not well understood. An analysis of the effects of preliminary mine drainage indicated that the effects of pumping on the hydrologic system are similar, regardless of whether the upper or lower aquifers are pumped. Initially, most pumped water will be derived from ground water in storage; after 20 years, most water will be derived from decreased discharge to streams or springs. Pumping also will induce greater recharge from losing reaches of streams. Effects of pumping stresses approach an equilibrium state more rapidly in the northern part of the basin than in the southern part; relatively large permeabilities in the north result in a rapid response to pumping, compared to the response in the southern part of the basin. If mine drainage induces a conversion from confined to unconfined conditions in layer 6 and other layers, more pumped water will be derived from ground water in storage and less water will be derived from streams and springs.

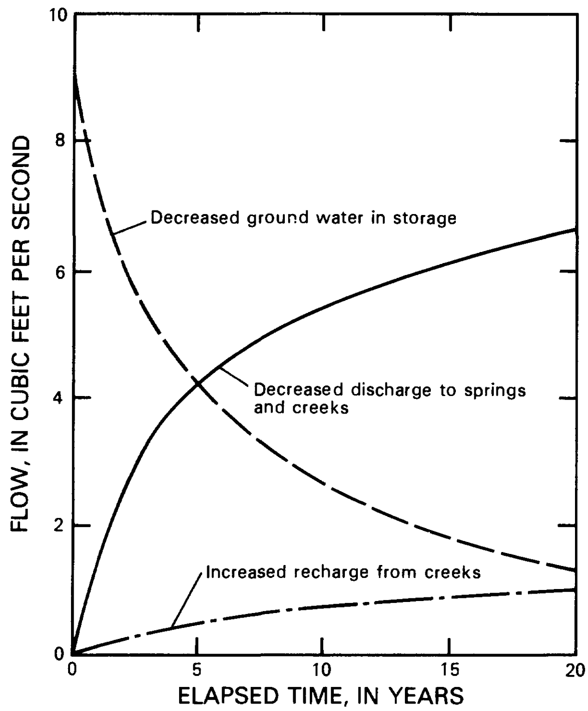


Figure 12.--Instantaneous sources of water for plan 5 with increased storage in the valley-fill alluvium of layer 6.

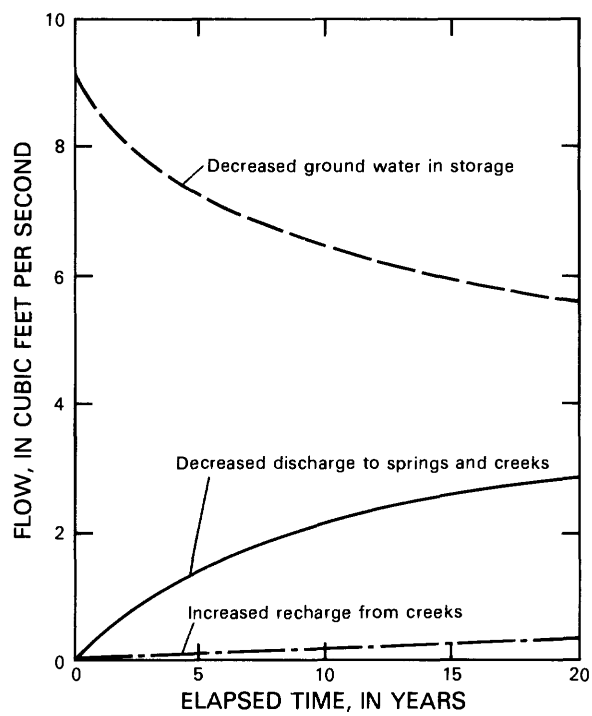


Figure 13.--Instantaneous sources of water for plan 5 with increased storage in layer 6.

The described model needs to be improved to simulate more extensive mine drainage. These improvements include:

1. Use of a model routine to convert from confined to unconfined conditions. This can be accomplished by use of a different model or by adapting the model described in this report.
2. Incorporation of a model routine to adjust transmissivity values during layer drainage.
3. More accurate determination of aquifer characteristics for use in model parameters. A statistical analysis of model parameters and regions that cause sensitive response in potentiometric head, stream depletion, and natural discharge would be helpful.

REFERENCES CITED

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

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

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

Donnell, J.R., 1961, Tertiary geology and oil-shale resources of the Piceance Creek basin between the Colorado and White Rivers, northwestern Colorado: U.S. Geological Survey Bulletin 1082-L, p. 835-891.

Jacob, C.E., 1950, Flow of ground water, chapter 5, *in* Rouse, Hunter, Engineering hydraulics: New York, John Wiley, p. 321-386.

Robson, S.G., and Saulnier, G.J., Jr., 1981, Hydrogeochemistry and simulated solute transport, Piceance basin, northwestern Colorado: U.S. Geological Survey Professional Paper 1196, 65 p.

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

The Pace Company Consultants and Engineers, Inc., 1977, Oil shale mineral rights ownership, Piceance - Uinta basins, Colorado - Utah: Denver, scale 1:192,000.

Torak, L.J., 1982, Modifications and corrections to the finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Water-Resources Investigations 82-4025, 30 p.

Trescott, P.C., 1975, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 75-438, 106 p.

Trescott, P.C., and Larson, S.P., 1976, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 76-591, 21 p.

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

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