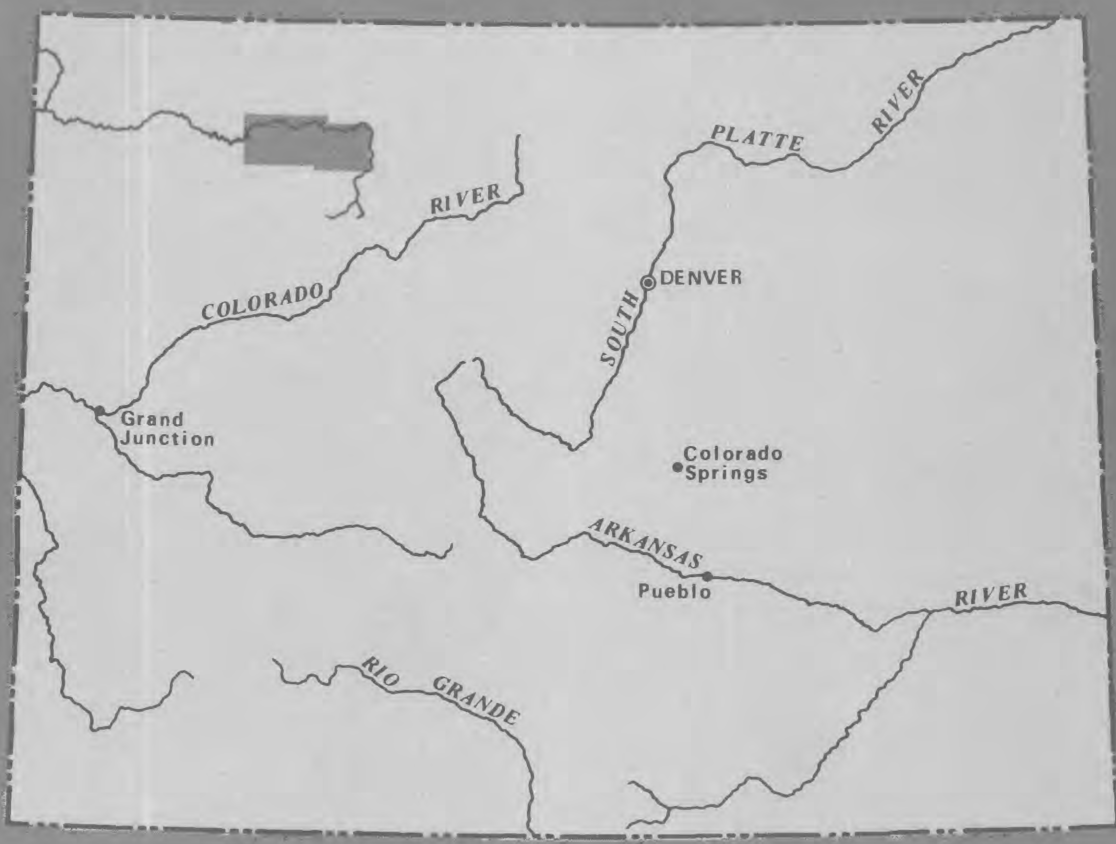
DIGITAL-TRANSPORT MODEL STUDY OF THE POTENTIAL EFFECTS OF COAL-RESOURCE DEVELOPMENT ON THE GROUND-WATER SYSTEM IN THE YAMPA RIVER BASIN, MOFFAT AND ROUTT COUNTIES, COLORADO

U.S. GEOLOGICAL SURVEY



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James W. Warner and Robert H. Dale

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Large increases in coal mining currently (1979) taking place in the Yampa River basin are expected to continue during the 1980's and may adversely impact both the ground-water and surface-water quality in the basin. One potential source of adverse impact is the dissolution of soluble minerals contained in overburden material disturbed during the mining. This potential impact was investigated using digital ground-water transport-modeling techniques.

Results of the simulations indicate that dissolved-solids concentrations in ground water would increase by about 200 milligrams per liter within a 0.5- to 1.0-mile (0.8- to 1.6-kilometer) radius of the mine sites. Development of the plumes of degraded ground water would be relatively slow bacause much of the degraded water would be intercepted by nearby streams within a few miles of the mine sites. This degraded ground-water discharge would cause dissolved-solids concentrations in streamflow to increase by several hundred milligrams per liter during low-flow periods but should not cause any observable change in water quality of the Yampa River because of its comparatively greater flow. The techniques used in this study may be applied in varying degrees to other areas of surface-mined coal in the Rocky Mountain region.

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Dallas L. Peck, Director

For additional information write to:

Colorado District Chief
U.S. Geological Survey, Mail Stop 415
Box 25046, Denver Federal Center
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CONTENTS

ILLUSTRATIONS

CONTENTS

CONTENTS

METRIC CONVERSION TABLE

Inch-pound units used in this report may be converted to metric SI (International System) units by the following conversion factors:

Multiply inch-pound units	*By*	*To obtain metric units*
cubic foot per second (ft^3/s)	0.02382	cubic meter per second (m^3/s)
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per mile (ft/mi)	0.18943	meter per kilometer (m/km)
foot per year (ft/y)	0.3048	meter per year (m/y)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
gallon per minute (gal/min)	6.308×10^{-5}	cubic meter per second (m^2/s)
inch (in.)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
ton (short)	0.9072	metric ton (t)
ton per year (ton/yr)	0.9072	metric ton per year (t/yr)

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ABSTRACT

Large increases in coal mining currently (1979) taking place in the Yampa River basin in Colorado are expected to continue during the 1980's and may adversely impact both the ground-water and surface-water quality in the basin. One potential source of adverse impact is the dissolution of soluble minerals contained in overburden material disturbed during mining. Ground-water degradation is anticipated from deep infiltration of water percolating through the waste-spoil piles at the mines. Digital-transport modeling techniques were used to evaluate the potential effects of this anticipated ground-water degradation.

Most coal is strip mined from the Mesaverde Group of Late Cretaceous age, a thick sequence of interbedded sandstones, shales, and coals. Digital models were constructed of the Mesaverde Group in the Twentymile Park and the Williams Fork Mountains areas. The Mesaverde Group was modeled as a single-aquifer system and steady-state flow conditions were assumed. The calibration procedure consisted of a comparison of measured and model-calculated potentiometric-surface altitudes. In addition, measurements of ground-water discharge at springs and gain-loss measurements of discharge to streams were compared with ground-water discharges calculated by the model.

The models were used to predict the potential impacts on ground-water quality in the vicinity of each major coal-strip mine in the model areas. In the models, the effects of spoil-pile leachate containing 2,000, 5,000, and 10,000 milligrams per liter of dissolved solids were simulated. The models simulated conservative (nonreactive) mass transport.

Results of the simulations indicate that dissolved-solids concentrations in ground water would increase by about 200 milligrams per liter within a 0.5- to 1.0-mile (0.8- to 1.6-kilometer) radius of the mine sites. Development of the plumes of degraded ground water would be slow because much of the degraded water would be intercepted by nearby streams within a few miles of the mine sites. This degraded ground-water discharge would cause dissolved-solids concentrations in streamflow to increase by several hundred milligrams per liter during low-flow periods but should not cause any observable change in water quality of the Yampa River because of its comparatively greater flow. The techniques used in this study may be applied in varying degrees to other areas of surface-mined coal in the Rocky Mountain region.

INTRODUCTION

The Yampa River basin is an area of about 8,080 mi^2 (20,900 km^2) located in northwestern Colorado and south-central Wyoming along the western slope of the Rocky Mountains (fig. 1). The basin contains abundant coal and other energy resources and limited water resources (Steele and others, 1979). The coal resources in the basin are planned for rapid development during the 1980's, with emphasis on easily strippable coal deposits. Coal production in the basin is expected to increase from an annual production of less than 2 million tons (1.8 million t) in the early 1970's to an estimated 20 million tons (18 million t) by the late 1980's. Production in 1978 was about 9.4 million tons (8.9 million t).

The U.S. Geological Survey has conducted a 3-year multidisciplinary river-basin assessment of the Yampa River basin (Steele and others, 1976a; 1976b). The objectives of the assessment were: (1) to evaluate the impact on the basin's water resources due to the development of regional water and energy resources (primarily coal), and (2) to apply and document assessment methods that might be readily transferable to similar regions of the United States. As part of this river-basin assessment, the potential effects of coal-resource development on the ground-water resources of the basin were investigated and the results are summarized in this report.

Most coal will be mined by surface-stripping techniques from the Mesaverde Group of Late Cretaceous age, a thick sequence of interbedded sandstones, shales, and coals. The sandstone layers and the coal beds act as the major aquifers for ground-water movement within the Mesaverde aquifer system. Mining will be concentrated in the Williams Fork Mountains area and in the Twentymile Park area in Colorado (fig. 1).

Digital models were constructed of the Twentymile Park and the Williams Fork Mountains areas (fig. 1) to simulate the effects of coal development on ground-water movement and chemical quality of ground and surface water in these major coal-mining areas. Two models were required in order to have a small enough nodal-grid interval to enable a detailed simulation of the aquifer. The results of these models are based on data collected over a 3-year period from 1976 to 1979.

The models used in this study were written and programed by L. F. Konikow and J. D. Bredehoeft of the U.S. Geological Survey and documented in Book 7, Chapter C2, Techniques of Water-Resources Investigations of the United States Geological Survey (Konikow and Bredehoeft, 1978). These models were modified by the authors to fit conditions in the Yampa River basin. The models simulate conservative (nonreactive) mass transport and are based on an iterative alternating-direction-implicit mathematical solution of the ground-water flow equation as described by Pinder and Bredehoeft (1968), coupled with a method of characteristics solution of the solute-transport equation described by Reddel and Sunada (1970) and by Bredehoeft and Pinder (1973). These mathematical procedures require each modeled area to be divided into rectangular segments or nodes of equal dimensions called the model grid. At each node the average geohydrologic and chemical characteristics of the aquifer within the area of the node are specified. Boundary conditions must be specified at each node along the edge of the model grid. These boundary conditions may represent either a constant-head boundary or a constant-flux boundary. These boundary conditions also may be specified at nodes in the interior of the model. For example, a constant-head node may be specified at a physical location containing a spring to allow the model to more closely approximate actual physical conditions.

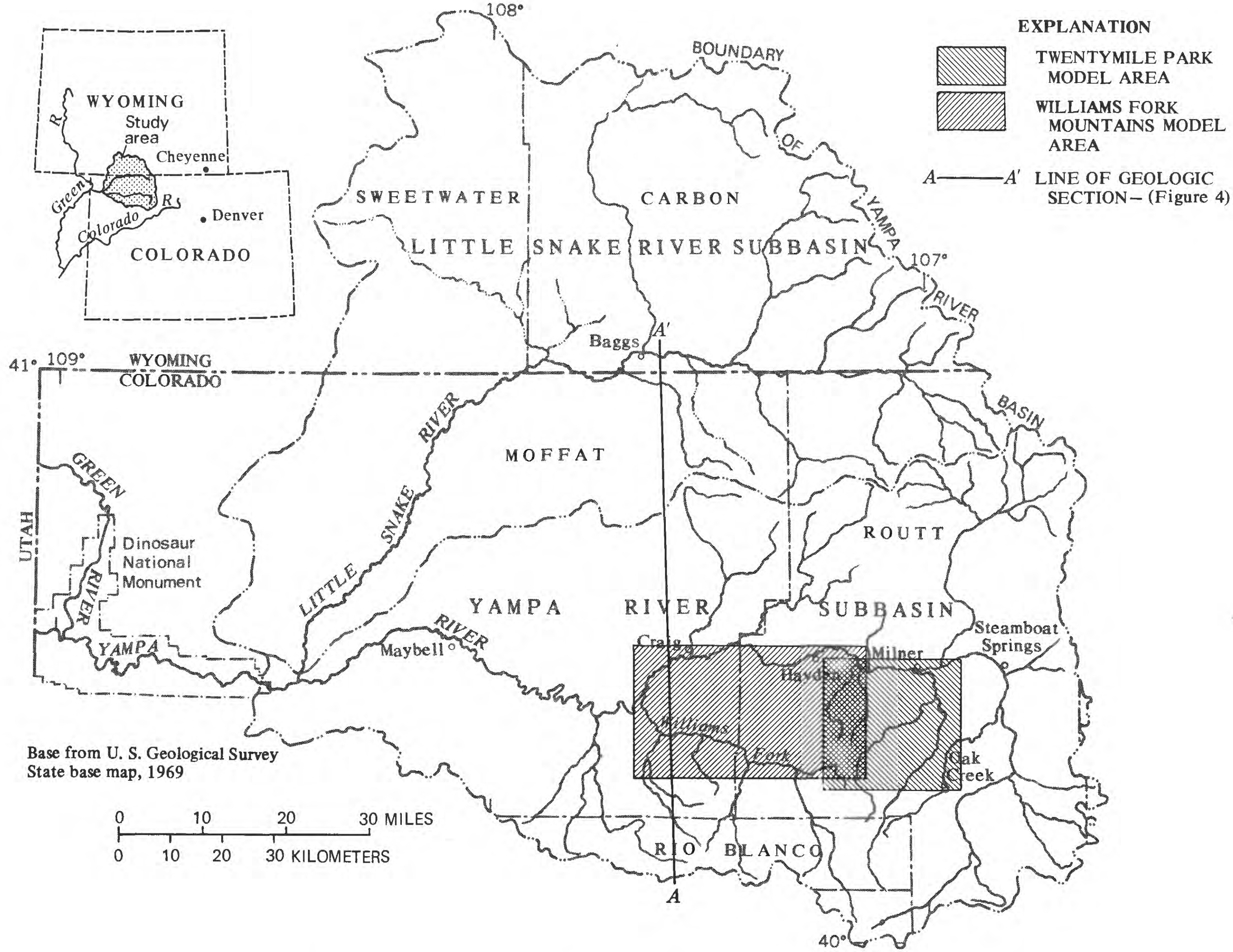


Figure 1.-- Yampa River basin and location of model areas.

GEOHYDROLOGY

Geohydrologic Units and Occurrence of Ground Water

Water occurs in all the sedimentary rocks underlying the Yampa River basin. Rocks exposed in the model areas (figs. 2 and 3) range in age from Late Cretaceous to Holocene. Only that geology necessary for the understanding of the models is presented in this report. For a more complete discussion of the geology of the Yampa River basin, the reader is referred to Steele and others (1979).

The Mancos Shale is a thick (approximately 5,000 ft or 1,500 m), homogenous, dark-gray marine shale of Late Cretaceous age and is the oldest geologic unit exposed in the model areas. The Mancos Shale contains sandstone and limestone beds, but the extensive shales in the upper part of the formation can be considered as relatively impermeable barriers to the subsurface movement of water. For the purposes of modeling, the Mancos Shale was considered as an impermeable, confining layer underlying the Mesaverde Group.

The Mesaverde Group overlies the Mancos Shale and consists of interbedded sandstones, marine shales, and coal beds of Late Cretaceous age. In the model areas, the Mesaverde Group is divided into two units, a lower unit--the Iles Formation--and an upper unit--the Williams Fork Formation. The Iles Formation is approximately 1,500 ft (450 m) thick and capped by the Trout Creek Sandstone Member in most of the area. The Williams Fork Formation is approximately 1,000 to 2,000 ft (300 to 600 m) thick and contains the Twentymile Sandstone Member, which is approximately in the middle of the Williams Fork Formation. Water-table conditions occur in the outcrop areas of the Mesaverde Group. Elsewhere, water in the Williams Fork and Iles Formations is confined by the underlying Mancos Shale and by the overlying Lewis Shale.

The Lewis Shale, consisting primarily of a 1,500- to 2,000-ft (450- to 600-m) thick sequence of homogenous marine shales of Late Cretaceous age, overlies the Mesaverde Group. In many areas, such as along the north face of the Williams Fork Mountains, confinement by the Lewis Shale causes some wells perforated in the Mesaverde Group to flow. For the purposes of modeling, the Lewis Shale was considered as an impermeable confining layer overlying the Mesaverde Group.

The Browns Park Formation of Miocene age is found in the Twentymile Park model area overlying small areas of the Mesaverde Group and the Mancos Shale. The Browns Park Formation, consisting of sandstone and conglomerate, is probably the best aquifer in the Yampa River basin and yields water with a dissolved-solids concentration generally less than 500 mg/L (milligrams per liter).

River-channel deposits in the model areas generally are less than 30 ft (9 m) thick and are found most extensively along the Yampa River, Williams Fork, and Trout Creek (figs. 2 and 3). Water in the river-channel deposits is hydraulically connected to the streams and to the bedrock aquifers. In most instances, water in the bedrock aquifers discharges to these river-channel deposits instead of directly into the streams.

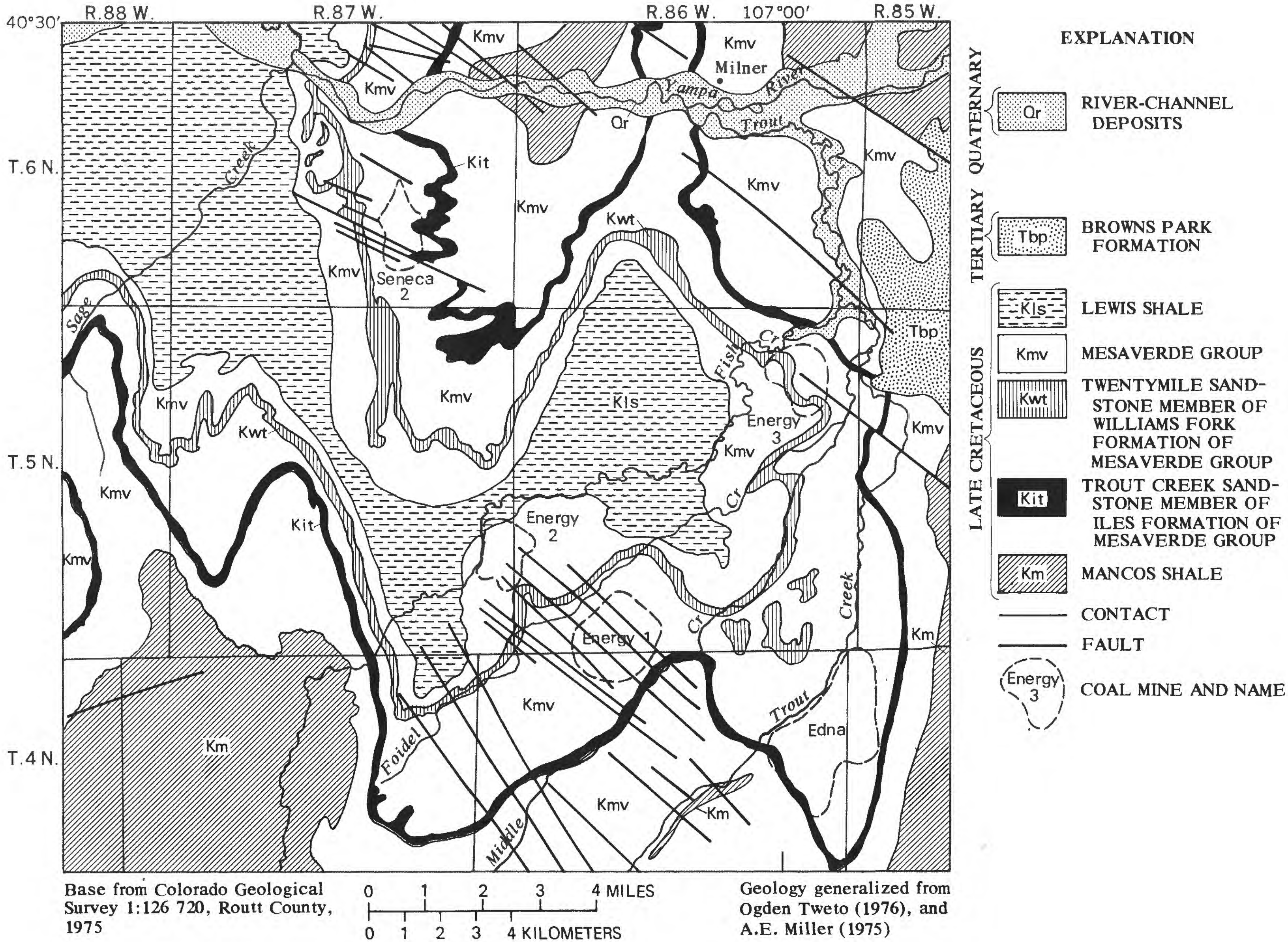


Figure 2.--Geohydrologic map of Twentymile Park model area.

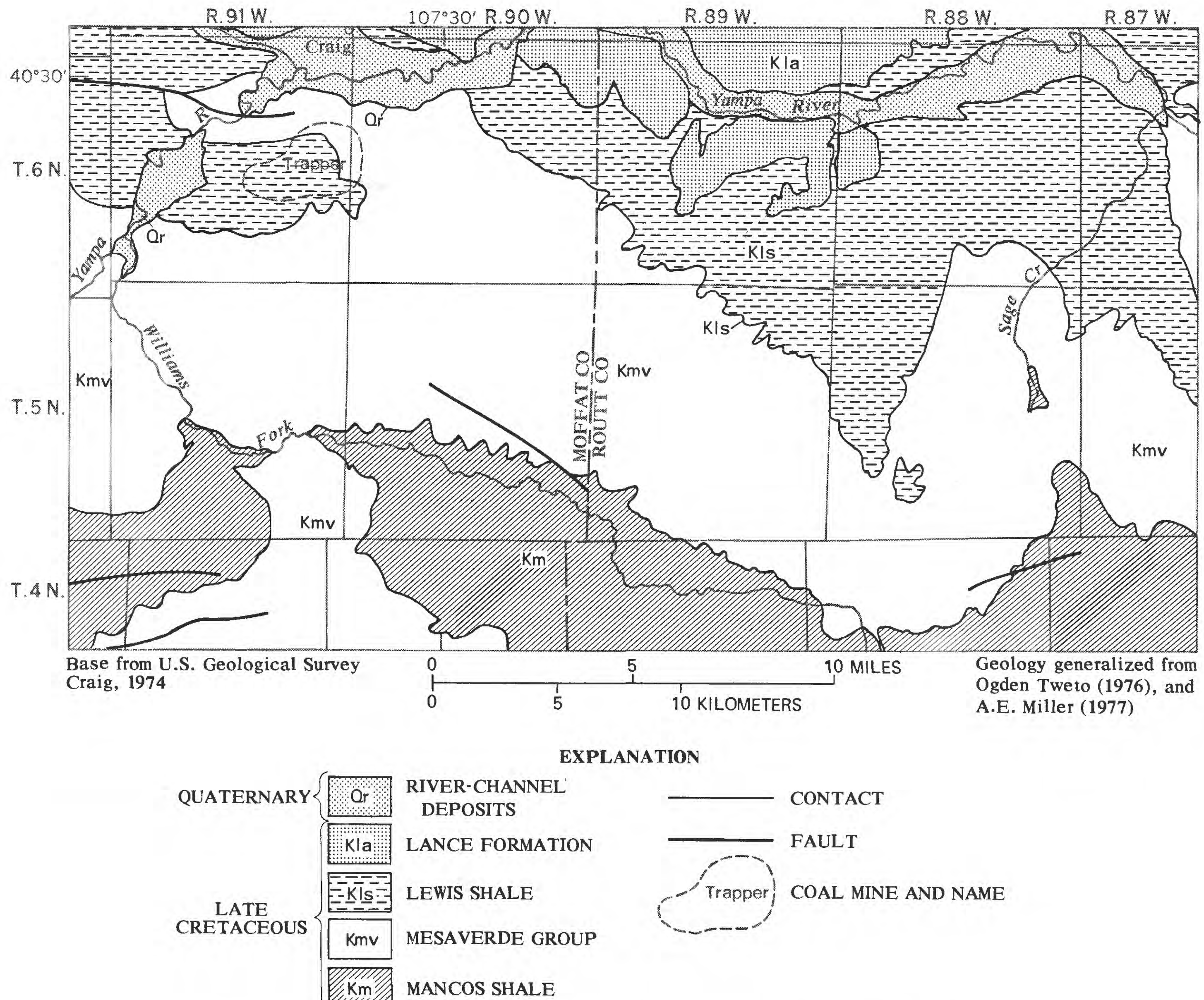


Figure 3.-- Geohydrologic map of Williams Fork Mountains model area.

Recharge, Discharge, and Direction of Ground-Water Movement

The direction of ground-water movement is greatly affected by the local geologic structure in the model areas, which are situated on the southern part of a regional structural depression called the Sand Wash basin (Steele and others, 1979). The bedrock strata in the Williams Fork Mountains dip generally to the north toward the center of this regional structural depression (fig. 4). The Twentymile Park area is located in the southeastern corner of the regional structural depression, and, as a result, the bedrock strata dip both to the north and west in this area.

The Williams Fork Mountains and the Twentymile Park areas are major recharge areas for the Mesaverde Group. In general, water movement in the Mesaverde Group in the model areas follows the dip of the bedrock strata (fig. 5). Much of the ground water moves only a short distance from the local recharge areas before being discharged, either at springs or into streams draining the area. The remaining water moves down dip beneath the Yampa River and into the Sand Wash structural basin. Discontinuous shale layers cause local potentiometric-head differences in wells obtaining water from the Mesaverde. These discontinuous shale layers do not appear to be extensive but cause an increase in potentiometric head with depth in the Mesaverde.

The Mesaverde aquifer system was modeled as a single-aquifer system. Prior to the construction of the two models described in this report, a preliminary model was constructed of only the Trout Creek Sandstone aquifer within the Mesaverde (Warner and Brogden, 1976). Results obtained using this preliminary model were compared with the observed regional flow patterns of other sandstone aquifers contained in the Mesaverde. The conclusion was that flow patterns in these multiple sandstone aquifers are similar and may be grouped together for simulation purposes. The results of this model study represent the regional movement of ground water in the Mesaverde aquifer system. Locally the movement of ground water in some aquifers may be contrary to the regional flow of ground water.

TWENTYMILE PARK MODEL

Model-Input Data

The Twentymile Park model (fig. 6) was constructed to simulate hydrologic conditions in the Williams Fork Formation and the Trout Creek Sandstone. The model encompasses an area of about 218 mi^2 (565 km^2). The majority of the coal mining in the Yampa River basin occurs in the Twentymile Park area.

Grid Interval

The model contained a total of 676 nodes with 357 active nodes (fig. 6). The model was constructed with a grid interval of 3,000 by 3,000 ft (900 by 900 m). This grid interval enabled aquifer conditions to be simulated in the rather large model area, but resolution in the model was not as great as it would have been had a smaller grid interval been used. A smaller grid interval was not practical due to the excessive number of nodes required.

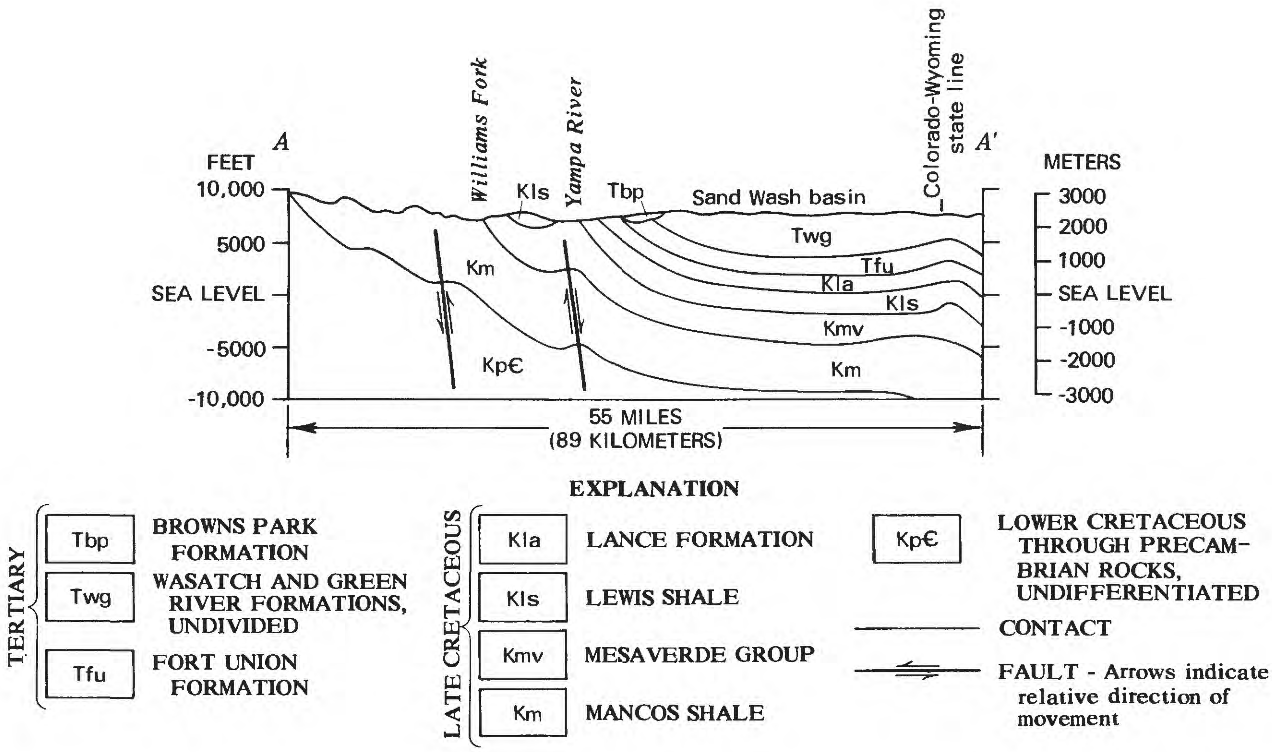


Figure 4.--Generalized geologic section through the Williams Fork Mountains model area.

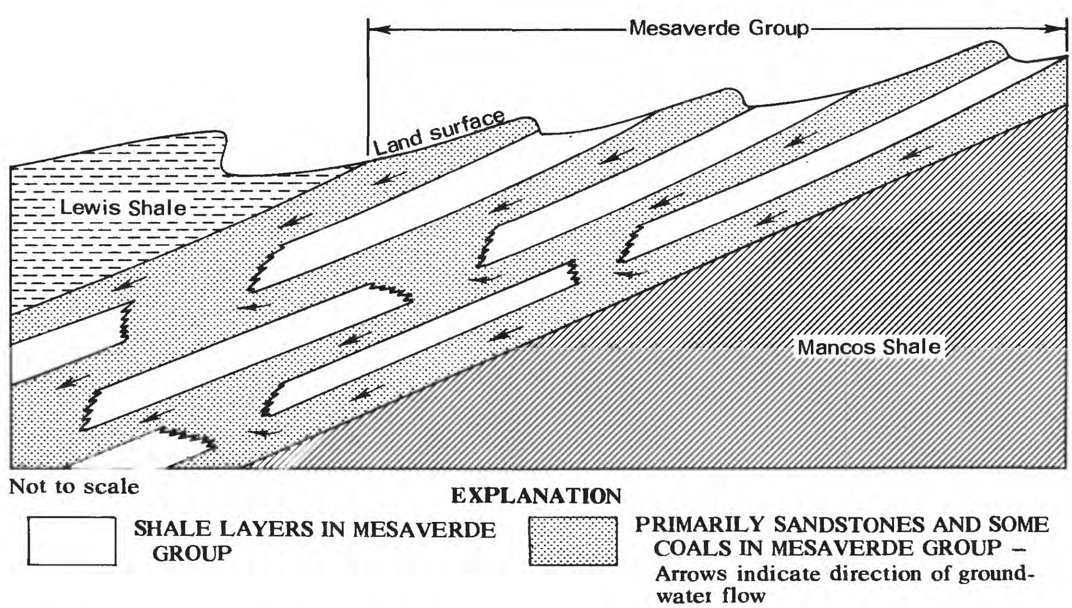


Figure 5.--Diagram of ground-water flow system in the Mesaverde Group within the model areas.

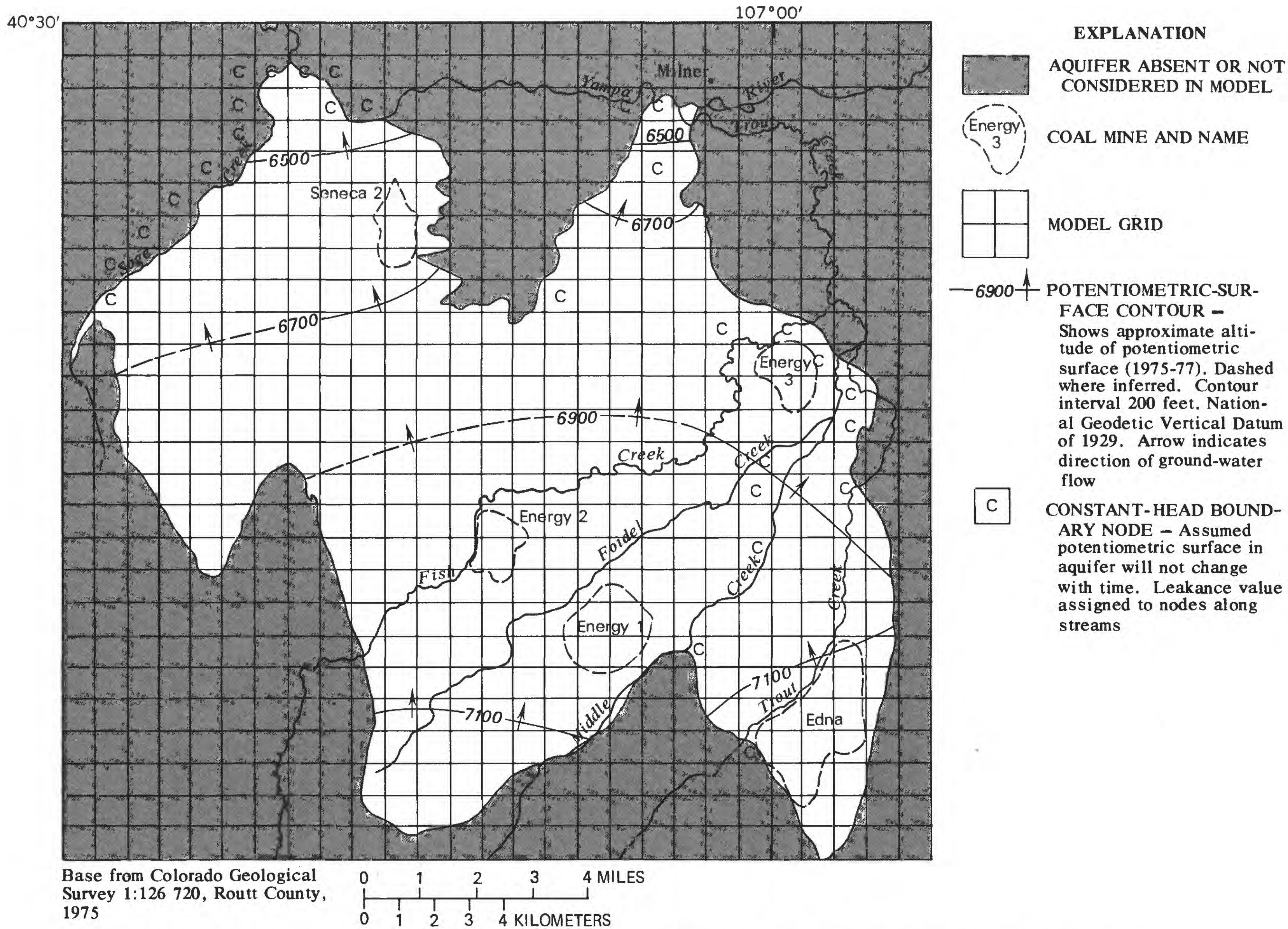


Figure 6.--Model grid, location of constant-head boundary nodes and potentiometric-surface contours for 1975-77, Twentymile Park model area.

Boundary Conditions

Boundary conditions in the model were either constant flux or constant head. The constant-flux condition most commonly used was a no-flow boundary condition. No-flow boundaries were simulated between the Mesaverde Group and the Mancos Shale by using a transmissivity equal to zero at the boundary nodes. A no-flow boundary also was simulated between the Trout Creek Sandstone Member and the underlying shale layers in the Mesaverde Group. Elsewhere, a constant-head boundary was simulated where the model boundary intersected adjacent parts of the Mesaverde Group or where the potentiometric surface in the aquifer remained fairly constant. In the constant-head boundary nodes shown in figure 6, the potentiometric surface in the aquifer was assumed not to change with time, although the rate of flow across the model boundary was allowed to vary. A constant-head boundary was simulated at the intersection of the sandstone aquifers in the Mesaverde Group with the Yampa River, Trout Creek, Middle Creek, Foidel Creek, and Fish Creek. A constant-head boundary also was simulated near Sage Creek along the common boundary between the Twentymile Park model and the Williams Fork Mountains model.

In one model simulation, the constant-head boundary condition was replaced by a constant-flux boundary condition along the intersection between the two models. In this simulation, hypothetical large-scale development of ground water in the Mesaverde Group resulted in drawdown of the potentiometric surface along the boundary; hence the constant-head boundary specification was no longer valid. When the constant-flux boundary was used, the rate of flow across the model boundary was held constant, and the potentiometric surface in the Mesaverde Group was allowed to vary.

Potentiometric Surface

Minimal ground-water pumpage occurs in the vicinity of the Twentymile Park model area, and steady-state conditions were assumed in the Mesaverde aquifer. The potentiometric-surface contours for 1975-77 in the model area are shown in figure 6. In the model area, the direction of water movement follows the general dip of the aquifer; generally, flow is northward and westward. Locally, the direction of some ground-water movement is to the east. All ground water occurring in the model area is derived from infiltration of snowmelt or rainfall within the model area. No ground-water underflow into the model area was assumed. However, some small upward movement of water into the aquifer may occur from underlying geologic formations. Ground water is discharged out of the model area by streams and springs and also as underflow to the northwest. The ground-water gradient within the model area is about 64 ft/mi (130 m/km), with a total decrease in potentiometric altitude of about 870 ft (265 m) occurring across the model area.

Recent evidence (1981) indicates the local movement of ground water in some individual aquifers is contrary to the regional movement of ground water. The local movement of ground water may follow local geologic structure of the individual aquifer, whereas overall the regional movement of ground water follows the regional geologic structure of the Mesaverde aquifer system. An example of this occurs north of Fish Creek in T. 5 N., R. 86 W. The regional ground-water flow is north towards the Yampa River and east towards Fish and Trout Creeks. However the local movement of ground water in the Wadge coal seam is southward and eastward off of the north rim of Twentymile Park and towards Fish Creek. The Wadge coal seam does not extend to the Yampa River but outcrops north of Fish Creek about a mile and a half south of the Yampa River. A similar example is near Seneca No. 2 mine, where local ground-water flow is southwest, south, and southeast off the nose of the Tow Creek anticline, whereas the regional ground-water flow is primarily north towards the Yampa River and northwest as underflow out of the model area and down dip into the Sand Wash Basin.

Recharge Rate

Ground-water recharge from infiltration of rainfall and snowmelt was estimated at 1 in. (25 mm) per year. Potential evapotranspiration exceeds average annual precipitation in the basin and thus limits recharge. The recharge rate of 1 in. (25 mm) per year was determined in model studies of the Piceance Creek basin (Weeks and others, 1974). The Piceance Creek basin, located immediately south of the Yampa River basin, has a climate, topography, and vegetation similar to those of the model area; the use of this recharge rate of 1 in. (25 mm) per year appears to yield reasonably good results in this model study, when applied uniformly over the outcrop area of the Mesaverde Group. Total recharge from infiltration of precipitation to the Mesaverde Group within the model area was estimated at 6.0 ft^3/s (0.17 m^3/s).

Saturated Thickness and Transmissivity

Other geohydrologic data needed for model input include the saturated thickness and transmissivity of the aquifer. The saturated thickness of the Mesaverde ranges from zero, at the contact with the Mancos Shale, to a maximum of 500 ft (150 m), where it is overlain by the Lewis Shale (fig. 7). Only the sandstone layers and the coal beds in the Mesaverde are included in the saturated thickness. The transmissivity of the aquifer was calculated as the product of the hydraulic conductivity and the saturated thickness. The hydraulic conductivity was determined in the model calibration to be 1 ft/d (0.3 m/d). This value of hydraulic conductivity was considered to be uniform in the model area. Calculated values of transmissivity of the aquifer ranged from 0 to 500 ft^2/d (0 to 46 m^2/d). The values of transmissivity correspond to the saturated thickness shown in figure 7, with a constant hydraulic conductivity of 1 ft/d (0.3 m/d).

Dissolved-Solids Concentrations

Initial constituent concentration values for the ground water are also required for model input. One of the most important potential sources of water-quality degradation caused by coal mining results from the dissolution of soluble minerals when disturbed overburden materials are contacted by water. A recent study by McWhorter and others (1975) found a general increase in all major ionic constituents in water that comes in contact with the waste-spoil piles at coal mines--either as runoff or as percolation.

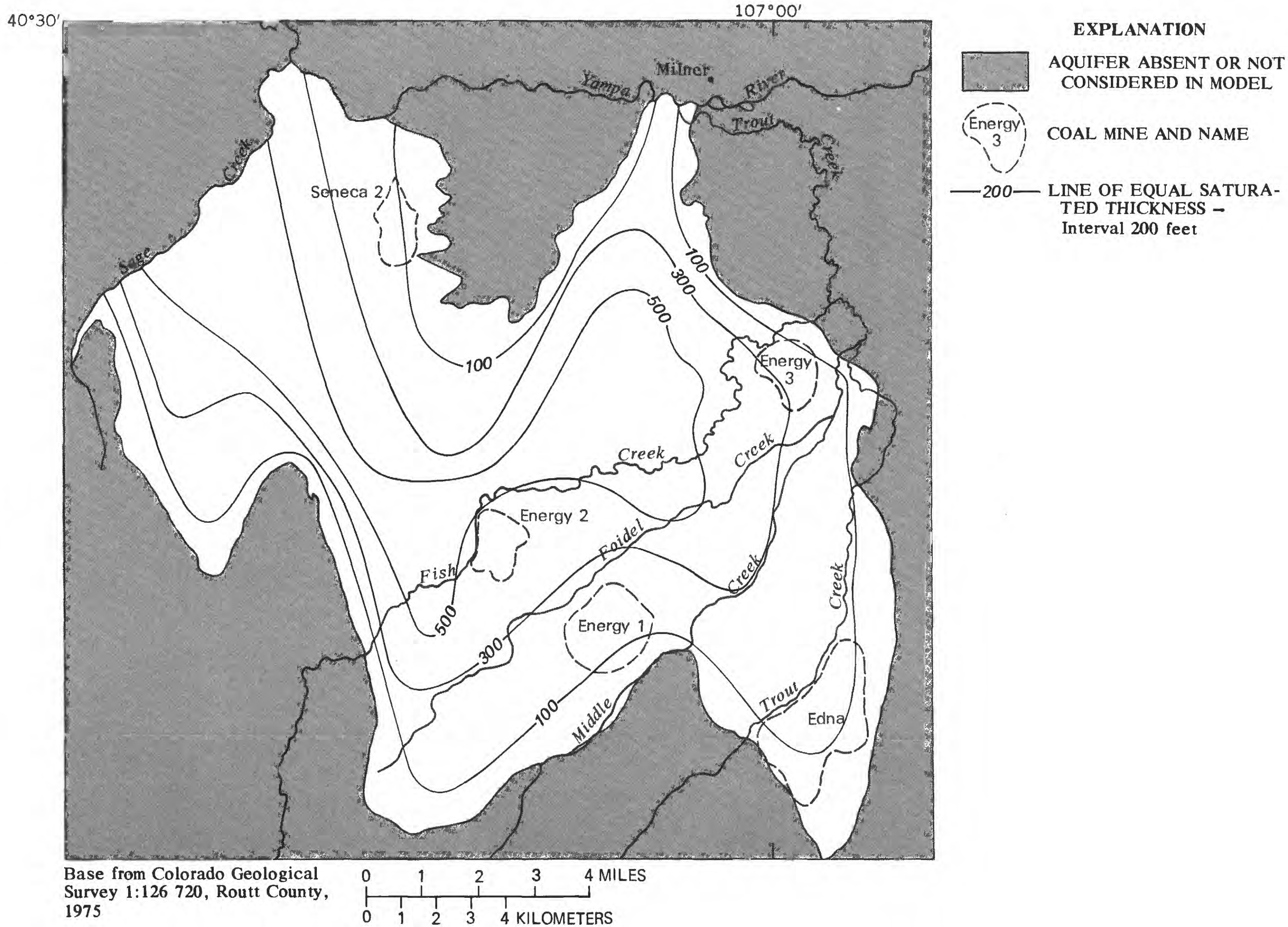


Figure 7.--Saturated thickness of the Mesaverde aquifer, Twentymile Park model area.

Dissolved-solids concentration was selected for modeling, as it is probably the best indicator of the overall effects of coal mining on the ground water. The initial concentration was assigned a value of zero in the model; thus, concentrations values due to mining calculated in the simulations represent increases in dissolved-solids concentration above premining values rather than absolute concentration values.

Model Calibration

Calibration procedures for transport models normally involve comparison of the measured potentiometric-surface altitudes with model-calculated potentiometric-surface altitudes and comparison of measured constituent concentrations with model-calculated concentrations of the constituent. The degree of agreement between the two comparisons is indicative of the capability of the transport model to simulate potentiometric-surface altitudes and constituent concentrations.

The calibration procedure used in this study involved a comparison of the measured and the model-calculated potentiometric-surface altitudes. In addition, measurements of ground-water discharge at springs and gain-loss measurements of ground-water discharge to streams along selected reaches were compared with ground-water discharges calculated by the model. No comparison was made of measured dissolved-solids concentrations with model-calculated dissolved-solids concentrations. This calibration check on the transport part of the model was not performed because of lack of data.

Comparison of the potentiometric-surface altitude in the aquifer measured in 1975-77 (fig. 6) with the potentiometric-surface altitude calculated by the model (fig. 8) indicates a fairly good agreement. The aquifer was modeled as a single-aquifer system rather than the multiple-aquifer system that actually exists. Thus, the potentiometric surface shown represents the average potentiometric-surface altitude of the ground water in the aquifer. The greatest discrepancy between the measured and model-calculated potentiometric-surface altitudes occurred where the Mesaverde is overlain by the Lewis Shale. In this area few data were available to construct the potentiometric-surface contours shown in figure 6. Considering this lack of data, the differences between the measured and model-calculated potentiometric-surface altitudes in this area are considered to be acceptable.

Ground water discharges to streams draining the area and at springs and seeps. As a calibration check, the model-calculated ground-water discharges were compared with measured values. A group of springs occurs in the northeastern part of the model area. The estimated combined flow of these springs was about 0.5 ft^3/s (0.014 m^3/s). This compares to a model-calculated ground-water discharge of 0.55 ft^3/s (0.014 m^3/s) by springs (fig. 9). A gain-loss measurement of streamflow was conducted along a reach of Trout Creek located in the east-central part of the model area where the stream flows over the Trout Creek Sandstone Member of the Williams Fork Formation of the Mesaverde Group. The gain-loss measurements indicated a gain in streamflow of 0.9 ft^3/s (0.025 m^3/s) from ground-water discharge. This compares with a model-calculated ground-water discharge of 0.72 ft^3/s (0.020 m^3/s) to Trout Creek in this reach (fig. 9).

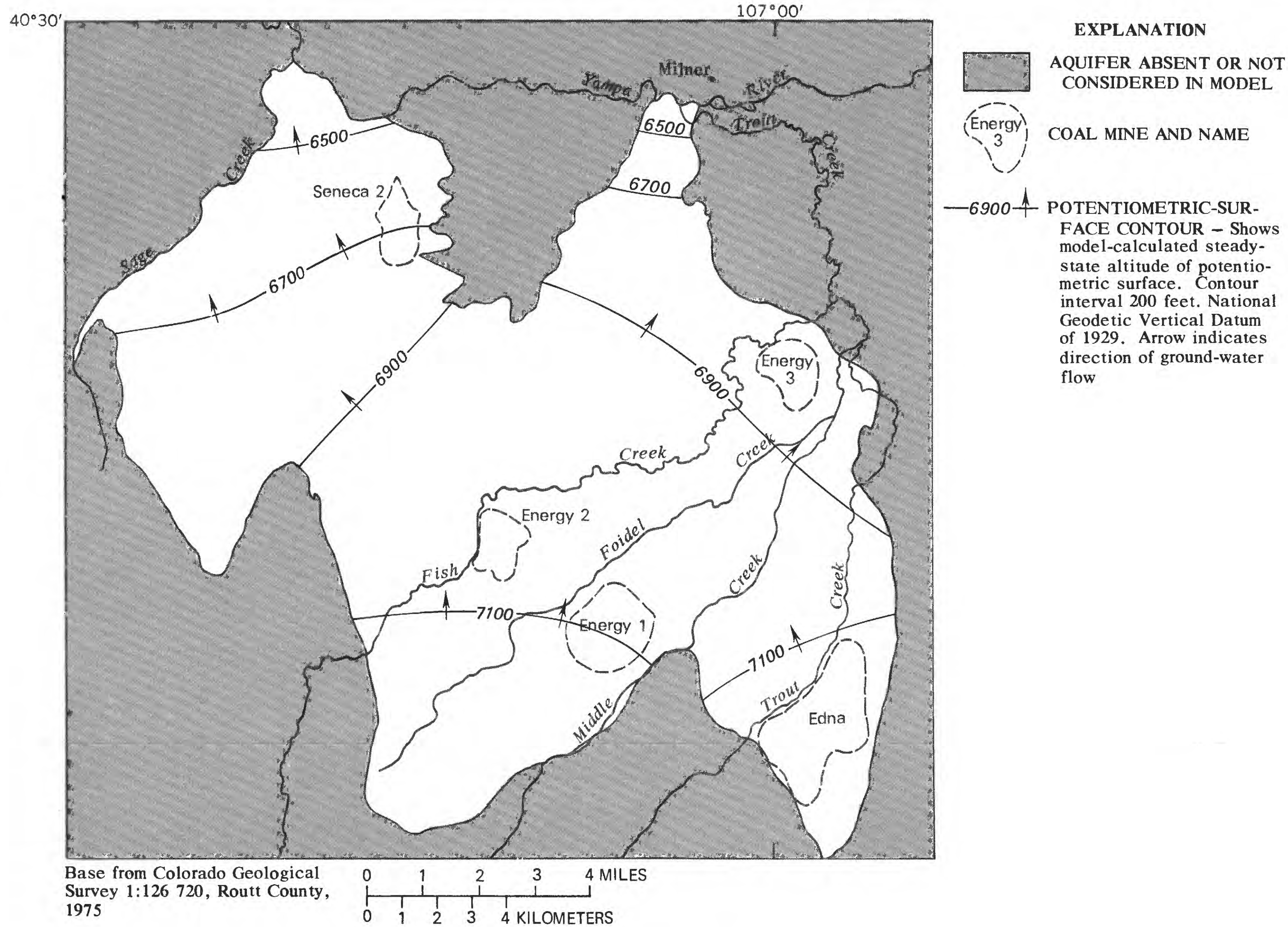


Figure 8.--Model-calculated potentiometric-surface contours, Twentymile Park model.

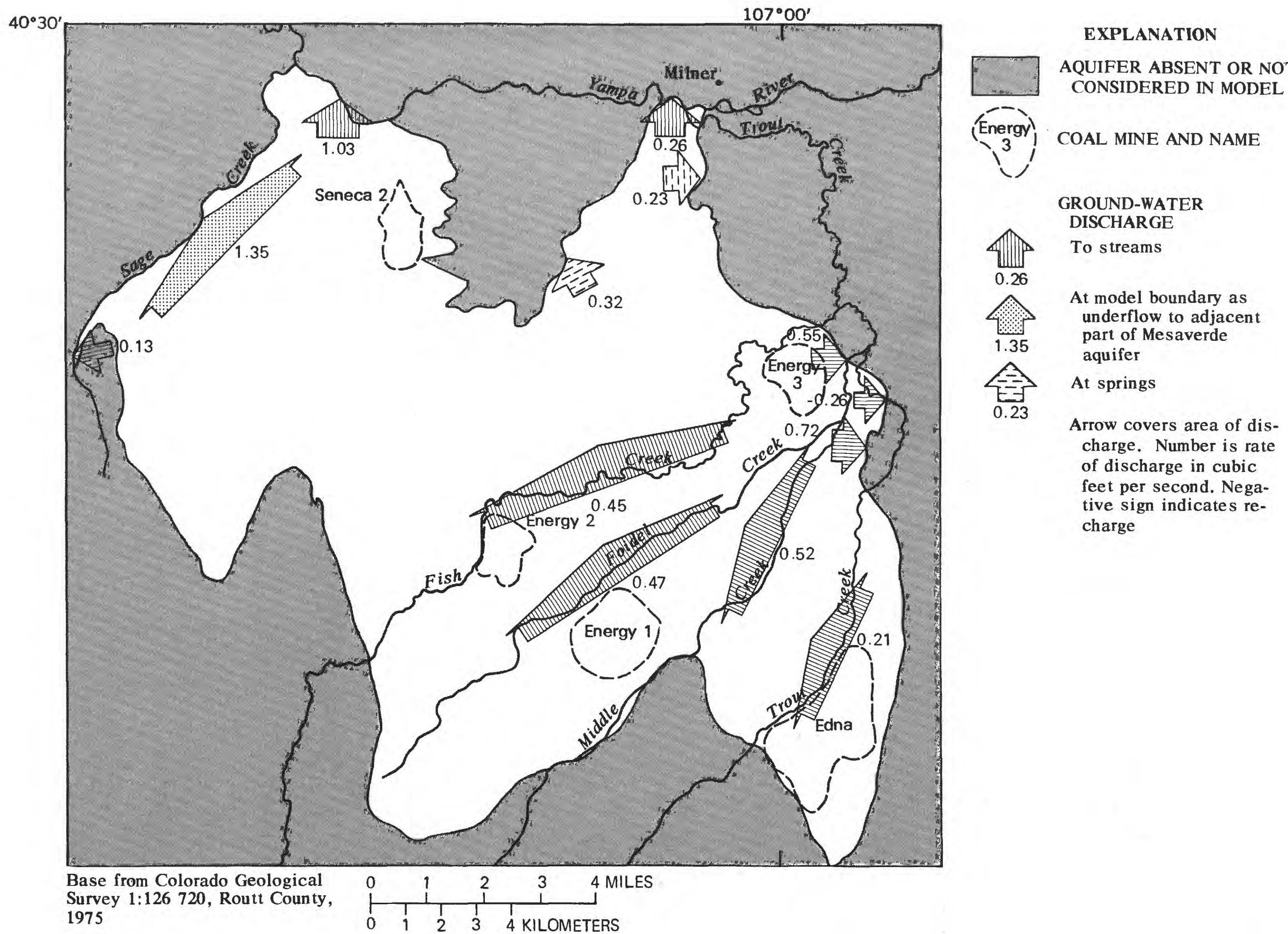


Figure 9.--Mean rates of model-calculated ground-water discharge, Twentymile Park model.

The calibrated model also was used to calculate ground-water underflow at other points in the model area. Calculated ground-water underflow out of the northwestern part of the model area along the common boundary between the two models is about 1.35 ft^3/s (0.038 m^3/s) (fig. 9). This underflow probably continues down dip into the Sand Wash structural basin. Ground-water discharge in the model area also occurs directly into the Yampa River where the river flows over the Twentymile Sandstone Member of the Williams Fork Formation and the Trout Creek Sandstone Member of the Iles Formation of the Mesaverde Group. This direct ground-water discharge was calculated by the model to be about 1.29 ft^3/s (0.037 m^3/s) (fig. 9). Because of the much greater comparative flows in the Yampa River, gain-loss measurements of streamflow could not be used to check this model calculation.

Model calculations indicate that water may discharge through confining shale layers in the Mesaverde into the four tributary streams (Fish, Foidel, Middle, and Trout Creeks) located in the southeastern part of the model area (fig. 9). A vertical hydraulic conductivity of 0.01 of the horizontal hydraulic conductivity was assigned to the aquifer along the entire length of each of these streams. The confining shale layers were estimated to be about 100 ft (30 m) thick. The resulting model calculations indicate diffuse ground-water discharge of between 0.21 and 0.52 ft^3/s (0.0059 and 0.015 m^3/s) occurs to these streams within the model area. These values of ground-water discharge were too small to be checked by onsite measurements.

The calibrated model was used to calculate the average interstitial ground-water velocities in the model area (fig. 10). The porosity of the aquifer was estimated to be 0.01 and was assumed to be constant throughout the model area. In general, ground-water velocities are small, ranging from about 200 to 1,000 ft/yr (60 to 300 m/yr). Near the Edna and the three Energy Mines, the ground-water velocity ranges from about 300 to 600 ft/yr (90 to 180 m/yr). Near the Seneca Mine the ground-water velocity ranges from about 600 to 900 ft/yr (180 to 270 m/yr).

Model Simulations

Through simulations of projected conditions, the model was used to predict the potential effects of coal-resource development on the regional ground-water system. The accuracy of the model predictions depends on the accuracy of the model calibration and the degree to which model assumptions and data used in the model simulations represent actual future conditions. The assumption was made that geohydrologic conditions upon which the model was calibrated would not differ significantly in the future.

Very little disruption of the sandstone aquifers is expected as the result of coal mining, and therefore the direction and rate of ground-water movement should not be altered significantly. The recharge rate of 1 in. (25 mm) per year for natural undisturbed conditions was also used in those areas disturbed by the coal mining. The assumption was made that disruption of the earthen material overlying the coal would have no long-term effect of either increasing or decreasing the infiltration rate of precipitation. The ground-water system in the model area was assumed to be in steady-state flow conditions. In most model simulations, the steady-state flow condition was assumed to extend indefinitely into the future;

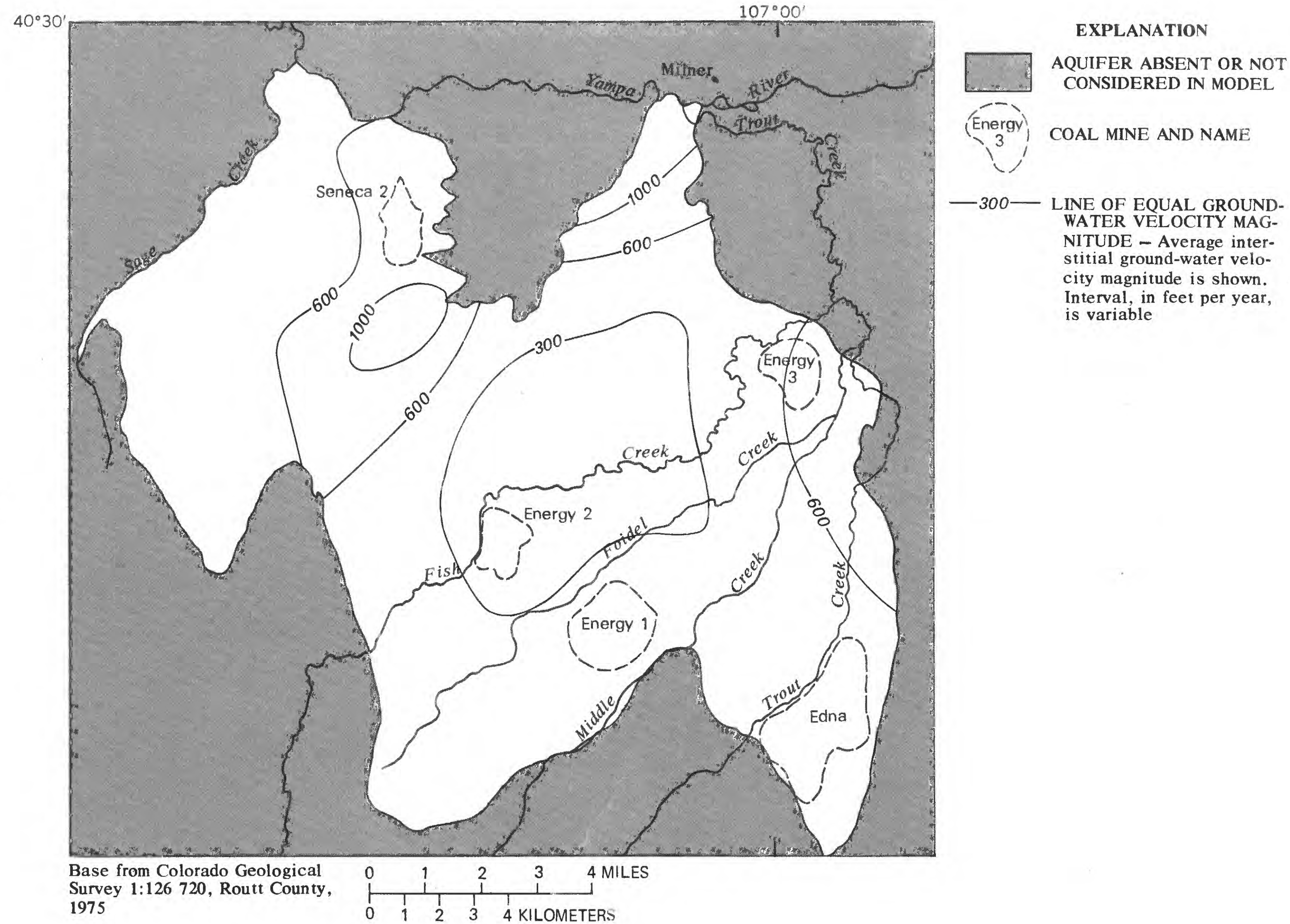


Figure 10.--Model-calculated ground-water velocities, Twentymile Park model.

[illegible] any minor changes that might occur in the [illegible] would not significantly alter the saturated thickness [illegible] the aquifer or the location of the aquifer boundaries.

Deep infiltration of water through waste-spoil piles at [illegible] [illegible]ation of ground-water quality. A recent study by [illegible] [illegible] found that the solution of soluble minerals when the [illegible] overburden [illegible]ls are contacted by water results in a general increase in [illegible] [illegible]ituents in the water. Data are generally lacking on the magnitude of the increase. McWhorter and others (1975), in their study used saturated [illegible] to estimate leachate concentrations that could be expected from water con[illegible] the waste-spoil piles. For the two mines they studied, dissolved-solid [illegible]ations of leachate from waste-spoil piles was 2,200 mg/L and 7,300 mg/L [illegible] suggests that this type of data may be very site specific, but their work i[s] [illegible] useful in determining the order of magnitude values. Quoting from McWhorter and others (1975, p. 60) as to the reliability of the data, "It is important to establish 'order of magnitude' values for average salt pickup rates and total salt pickup so that the problem of salt production from strip mine spoils can be more accurately judged in relation to national priorities and future research needs. The authors regard the numerical quantities reported in this section as indicator of magnitude and attach a limited significance to the actual numbers."

The Montana Bureau of Mines and Geology has studied leachate concentration [illegible] a coal-strip mine near Decker, Mont. VanVoast and Hedges (1975, p. 19) [illegible]ort, "Although these analyses are preliminary and their validity is not certai[n] [illegible] Decker mine spoils waters would have dissolved-solids concentration somewhat greater than 5,000 mg/L."

In this study, leachate concentrations of 2,000, 5,000, and 10,000 mg/L were simulated. In order to simplify presentation and discussion, only the results for the 5,000-mg/L source concentration were reported for most simulations. This does not indicate that the 5,000-mg/L value is a better estimate than the 2,000- or 10,000-mg/L values. It was beyond the scope of this study to collect data to further refine the source concentrations used in the model simulations. The authors place only "limited significance" on the numbers generated from this modeling study. The consequence of the differing levels of assumed source concentrations may or may not be significant, depending upon permissible impact level determined by applicable Federal, State, and local regulations.

The model was used to simulate the probable degradation effects on ground-water quality from the deep infiltration of water percolating through waste-spoil piles. Discharge of the degraded ground water to streams would, in some instances, cause a degradation of stream quality. The major impact of this degraded ground-water discharge on stream quality would occur at low flow when ground-water discharge would represent a major part of the streamflow. Surface runoff to local streams from the waste-spoil piles also would occur. This runoff would have significant detrimental effects on water quality in some of the streams in the basin but was not considered in this study.

In the model simulations, complete mixing of water degraded by contact with waste-spoil piles with ground water already present in the aquifer was assumed. Thus, the model-simulated concentrations represent an average concentration for the column of water in a given node. Actually, complete mixing would not occur, resulting in zones in the aquifer having water with dissolved-solids concentrations greater or less than the average concentrations simulated by the model.

In the past, most of the coal mining in the Yampa River basin has been concentrated in the Twentymile Park area. Coal mining in the area began about 1908, but it wasn't until 1972 that annual production exceeded 2 million tons (1.8 million t), and not until 1975 did coal production begin to increase significantly (Steele and others, 1979, fig. 8). Production in 1978 for the Twentymile Park area was about 6.1 million tons (5.5 million t), which is about triple the 1972 level and about double the 1974 level. Estimates are that production will again triple by the late 1980's. Prior to the mid-1940's, most of the coal mines were underground mines, but by the early 1960's, most of the coal was mined by surface-stripping techniques. Almost no data exist to evaluate the ground-water impacts of the earlier mining, but the impact was probably small and certainly much less than that caused by present-day mining activity. Presently five major strip mines exist within the Twentymile Park area. The effects on the ground-water quality were simulated for each mine separately and for the combination of all mines. The model simulations presented below represent the effect of coal mining on the regional ground-water system in the Yampa River basin. They do not represent a detailed picture of the effects; neither do they replace the need for site-specific studies or models on the effects of individual mines on the local ground water in individual aquifer units.

Model Simulation T1--Edna Mine

The results of model simulation T1 predict how ground-water quality would be affected by deep infiltration of water percolating through waste-spoil piles at the Edna Mine (fig. 2). The Edna Mine, the oldest strip mine in the Yampa River basin, is located in the southeastern part of the model area near Trout Creek. Mining at this site started in 1946. Mining is from the middle coal group, which includes coals between the Trout Creek and the Twentymile Sandstone Members. Cumulative mine production of coal through 1977 totaled 14.4 million tons (13.1 million t) (Steele and others, 1979, table 3) and production in 1978 was 0.96 million tons (0.87 million t) (Colorado Division of Mines, 1979).

All preceding model and data assumptions used in the calibration procedure apply to this model simulation. For simulation T1, the dissolved-solids concentration of ground water percolating through waste-spoil piles at the Edna Mine was assumed to increase by 5,000 mg/L, resulting in an additional dissolved-solids loading of about 1,200 tons/yr (1,090 t/yr) to the ground-water system.

The predicted effects from infiltration of this degraded water on the ground-water quality after 20 years are shown in figure 11. The dissolved-solids concentration of the ground water would increase by more than 3,000 mg/L at the mine site and a plume of degraded ground water would extend northwestward about 3 mi (5 km) to Middle Creek, occupying an area of about 16 mi^2 (41 km^2). Degraded ground water having an increase in dissolved-solids concentration of more than

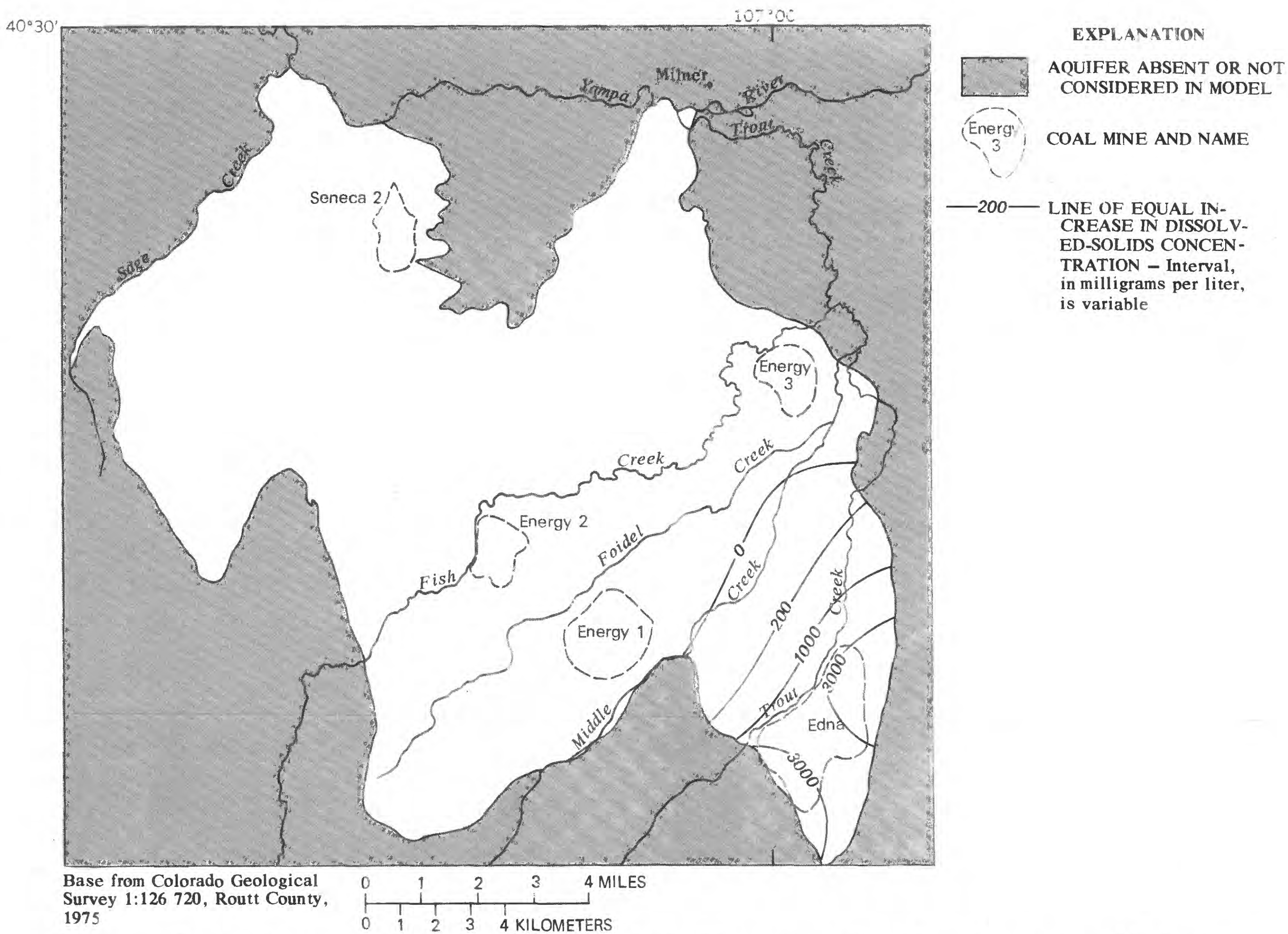


Figure 11.--Predicted increase after 20 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles at the Edna Mine--Model simulation T1.

1,000 mg/L would be discharged to Trout Creek. The rate of this degraded discharge would be about 0.5 ft^3/s (0.014 m^3/s) and would result in an increase in dissolved solids concentration of about 50 mg/L at low flow in Trout Creek. This degraded ground-water discharge load to Trout Creek (about 5,500 tons or 5,000 t) represents about 23 percent of the total load of dissolved solids leached from the Edna Mine waste-spoil piles during the 20-year period. The remainder (about 18,500 tons or 16,800 t) would be stored within the aquifer and an insignificant amount would be discharged to Middle Creek.

After 60 years, the plume of degraded ground water would extend about 5 mi (8 km) from the mine site to the northwest past Foidel Creek, occupying an area of about 25 mi^2 (65 km^2) (fig. 12). The rate of degraded ground-water discharge to Trout Creek would increase to about 0.65 ft^3/s (0.018 m^3/s) and have an increase in dissolved-solids concentration of more than 2,000 mg/L. This degraded discharge would result in an increase in dissolved-solids concentration of about 100 mg/L at low flow in Trout Creek. Degraded ground water then also would discharge to Middle Creek at a rate of about 0.5 ft^3/s (0.014 m^3/s), which would represent almost the entire low flow in this reach of Middle Creek. This degraded ground-water discharge would have an increase in dissolved-solids concentration of more than 500 mg/L, resulting in an increase in dissolved-solids concentration of about 470 mg/L at low flow in Middle Creek. The combined degraded ground-water discharge load (about 48,000 tons or 43,500 t) to Trout and Middle Creeks would represent about two-thirds of the total dissolved-solids loading leached from the Edna Mine waste-spoil piles during the 60-year period. The remaining load (about 24,000 tons or 21,800 t) would be stored within the aquifer, and a very small amount would be discharged to Foidel Creek. The increase in the dissolved-solids concentration of the ground water at the mine site still would exceed 3,000 mg/L.

After 200 years, the plume of degraded ground water would extend as far as Fish Creek, about 6 mi (10 km) from the mine site to the northwest, occupying an area of about 28 mi^2 (73 km^2) (fig. 13). The concentration and rate of degraded ground-water discharge to Trout and Middle Creeks would remain nearly the same as shown after 60 years. Degraded ground water then also would discharge to Foidel Creek, resulting in an increase in dissolved-solids concentrations at low flow of about 100 mg/L. The combined degraded ground-water discharge load (about 213,600 tons or 194,000 t) to these three streams would represent about 89 percent of the total dissolved-solids loading leached from the mine waste-spoil piles during the 200-year period. The remainder (about 26,400 tons or 24,000 t) would be stored within the aquifer. The increase in the dissolved-solids concentration of the ground water at the mine site still would be more than 3,000 mg/L.

In summary, model simulations indicate that ground water degraded from contact with the waste-spoil piles at the Edna Mine would move only a few miles before being intercepted by either Trout, Middle, or Foidel Creeks. Increases in dissolved-solids concentrations of about 100 mg/L in Trout Creek, about 470 mg/L in Middle Creek, and about 100 mg/L in Foidel Creek at low flows would result within 20 to 60 years. The ground-water quality at the mine site would degrade rapidly, with dissolved-solids increases of more than 3,000 mg/L observed within 20 years and fairly constant concentrations remaining after that time.

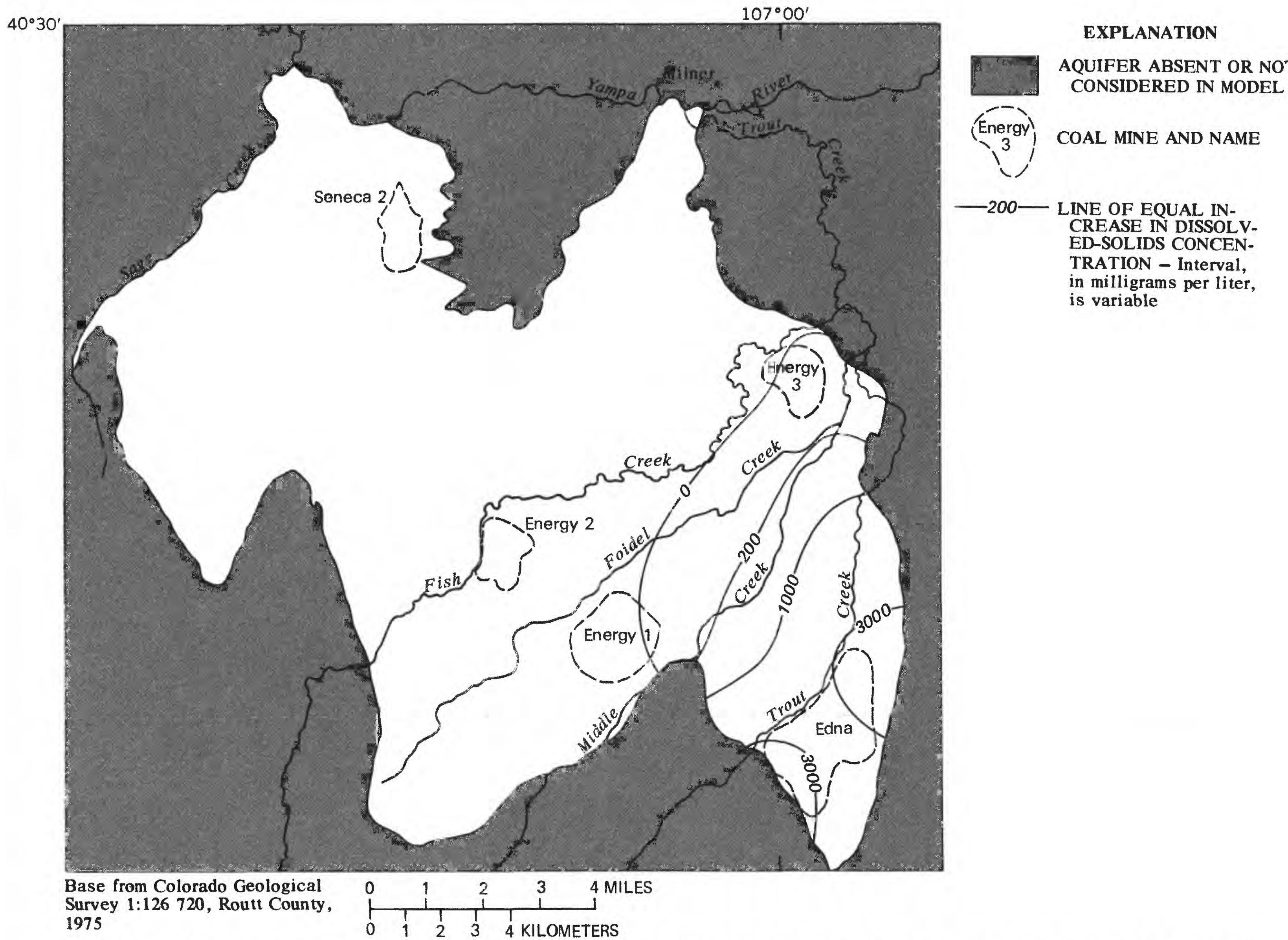
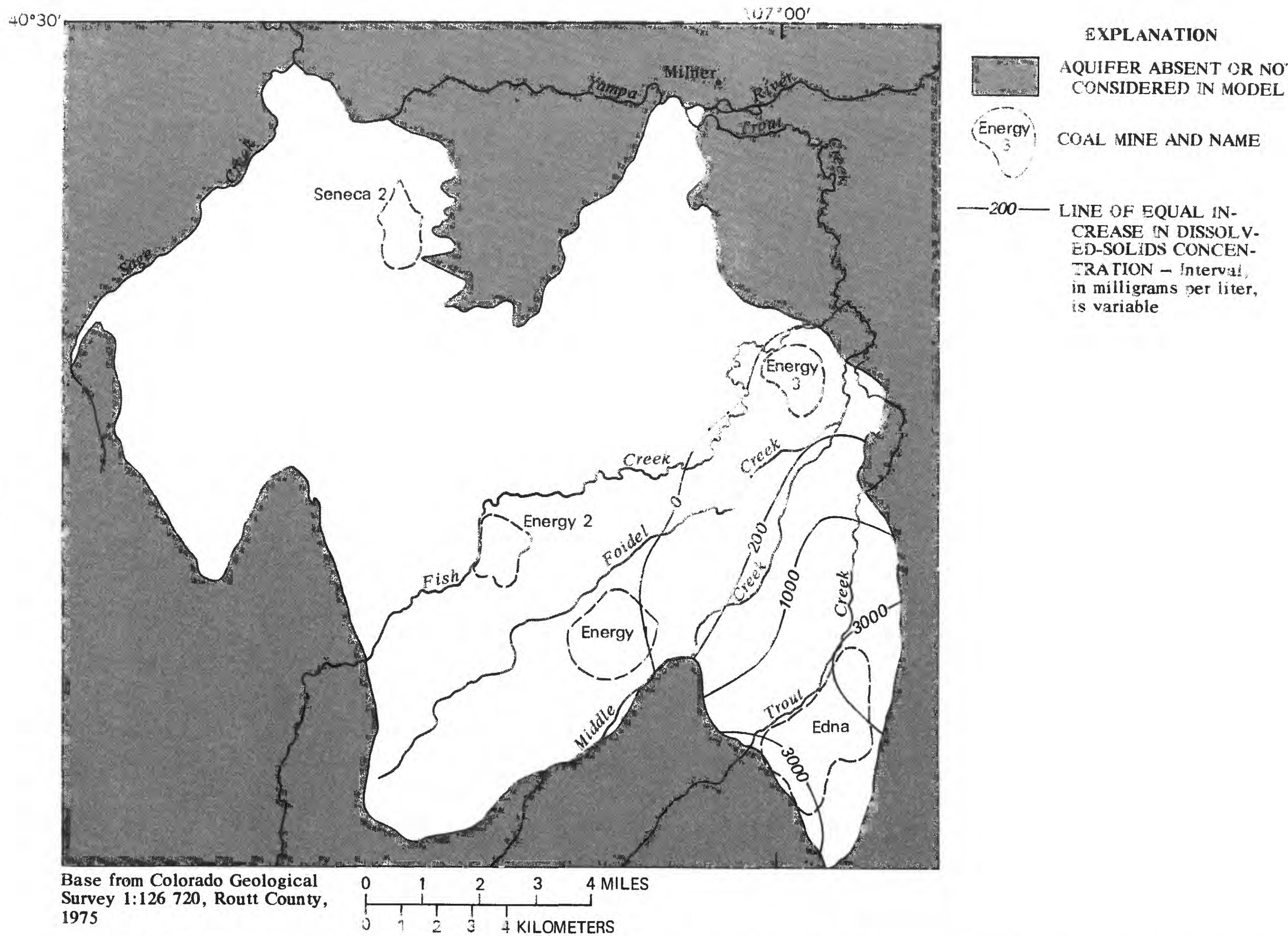


Figure 12.--Predicted increase after 60 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles at the Edna Mine--Model simulation T1.



Base from Colorado Geological Survey 1:126 720, Routt County, 1975

Figure 13.--Predicted increase after 200 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles at the Edna Mine--Model simulation T1.

Model Simulation T2--Energy No. 1 Mine

The results of model simulation T2 predict how ground-water quality would be affected by deep infiltration of water percolating through the waste-spoil piles at the Energy No. 1 Mine (fig. 2). The Energy No. 1 Mine is located between Middle and Foidel Creeks in the south-central part of the model area. Mining at this site began in 1962. Mining is from the middle coal group. Cumulative production of coal through 1977 totaled 12.3 million tons (11.1 million t) (Steele and others, 1979, table 3) and production in 1978 was about 2.91 million tons (2.63 million t) (Colorado Division of Mines, 1979).

All the preceding model and data assumptions used in the calibration procedure apply to this model simulation. For simulation T2, the dissolved-solids concentration of ground water contacting the waste-spoil piles at the Energy No. 1 Mine was assumed to increase by 5,000 mg/L, resulting in an additional dissolved-solids loading of about 700 tons/yr (635 t/yr) to the ground-water system.

After 20 years, the degraded ground water leached from the Energy No. 1 Mine waste-spoil piles would form a somewhat elliptical plume about 16 mi^2 (41 km^2) in an area around the mine site (fig. 14). This plume would extend about 3 mi (5 km) to the east, northeast, and northwest and about 1.5 mi (2.4 km) to the west and southwest. Degraded ground water having an increase in dissolved-solids concentration of about 200 mg/L would be discharged into both Middle and Foidel Creeks. The rate of this degraded discharge would be about 0.15 ft^3/s (0.004 m^3/s) to Middle Creek and about 0.17 ft^3/s (0.005 m^3/s) to Foidel Creek, resulting in an increase of 85 mg/L and 70 mg/L, respectively, in dissolved-solids concentration at low flow in the two streams. This degraded ground-water discharge load (about 3,300 tons or 3,000 t) to Middle and Foidel Creeks would represent about 24 percent of the total dissolved-solids loading leached from the Energy No. 1 Mine waste-spoil piles during the 20-year period. An estimated 10,700 tons (9,700 t) still would be in storage within the aquifer. An increase in the dissolved-solids concentration in the ground water of about 3,000 mg/L would occur in the vicinity of the mine site.

After 60 years, the plume of degraded ground water would continue to enlarge, occupying an area of about 30 mi^2 (78 km^2) and also would become more elliptical in shape than before, extending about 6 mi (10 km) to the northeast (fig. 15). The increase in dissolved-solids concentration of the degraded ground water discharged to Middle and Foidel Creeks then would be more than 1,000 mg/L. The rate of this degraded discharge then would be about 0.5 ft^3/s (0.014 m^3/s) to Middle Creek and about 0.35 ft^3/s (0.010 m^3/s) to Foidel Creek, which would result in an increase in dissolved-solids concentration of 260 mg/L and 400 mg/L, respectively, at low flows in the two streams. Also, degraded ground water then would discharge into Fish Creek, but because the amount of this discharge would be small, and because the dissolved-solids concentration increase of this discharge also would be small, there should be no observable effect on the water quality of this stream. The degraded ground-water discharge load (about 24,000 tons or 21,800 t) to these streams would represent about 57 percent of the total dissolved-solids loading leached from the Energy No. 1 Mine waste-spoil piles during the 60-year period. An estimated 13,000 tons (11,800 t) still would be in storage within the aquifer. The increase in the dissolved-solids concentration of the ground water at the mine site would remain fairly constant at a concentration increase of about 3,000 mg/L.

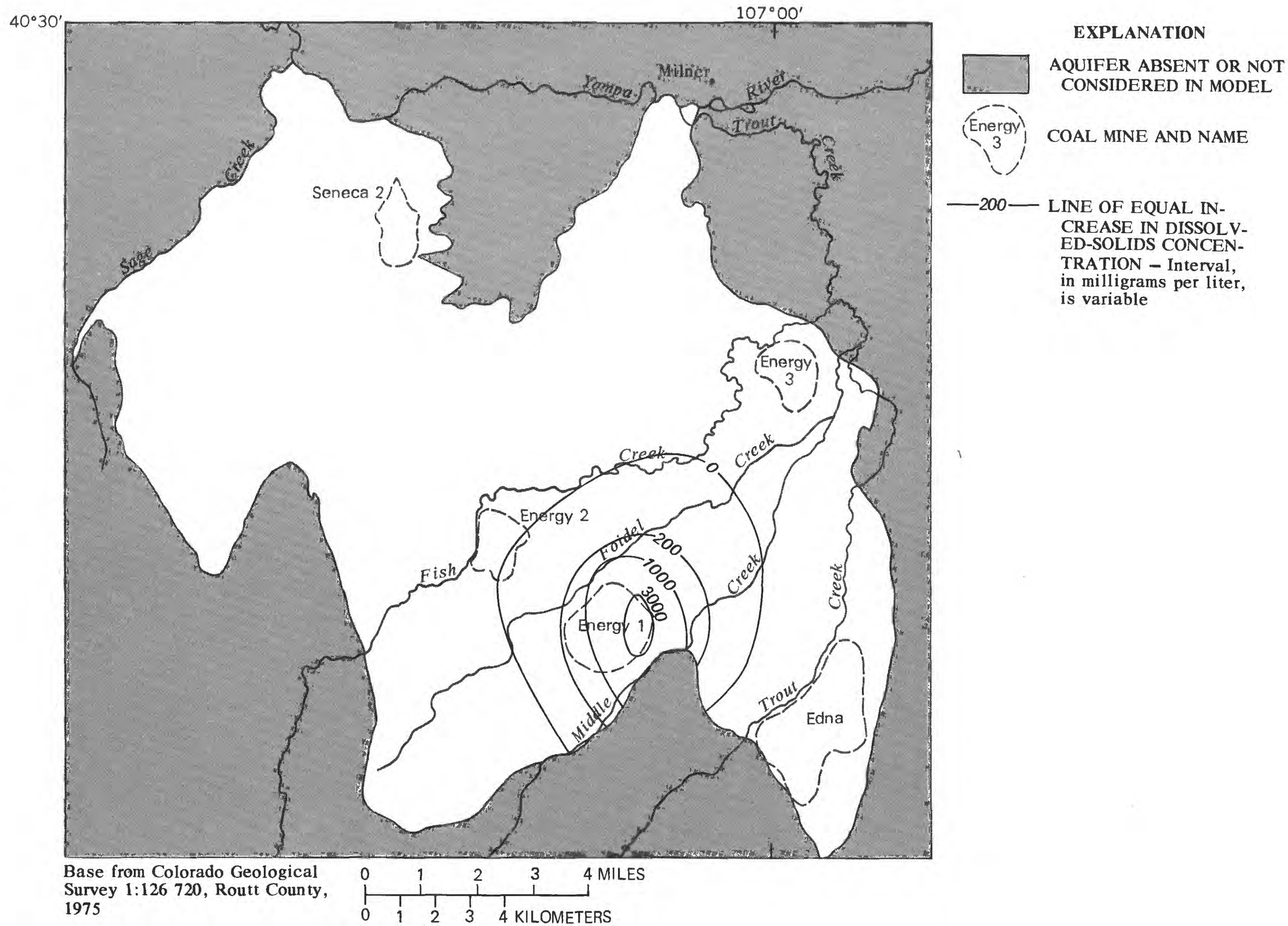


Figure 14.--Predicted increase after 20 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles at the Energy No. 1 Mine--Model simulation T2.

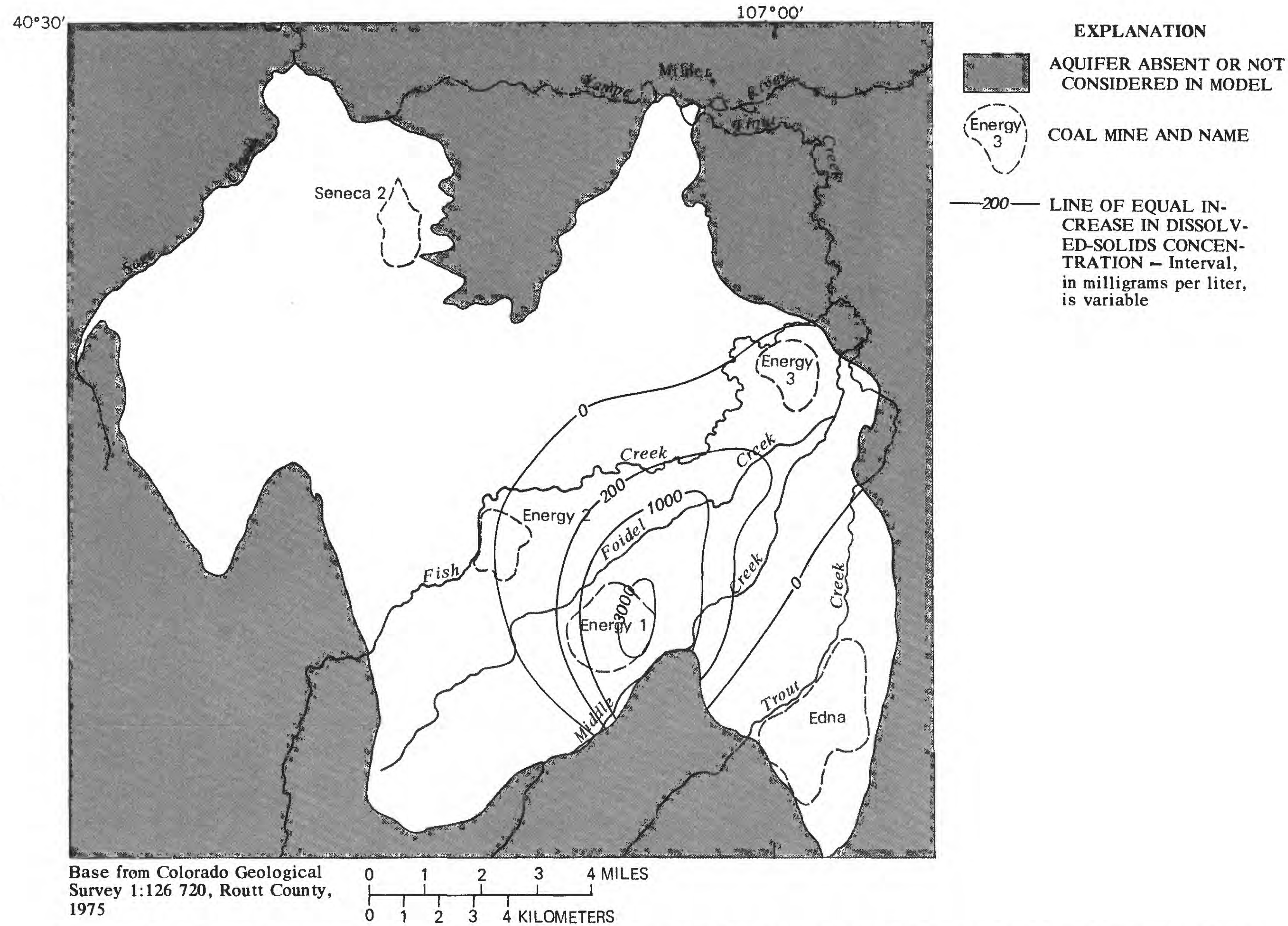


Figure 15.--Predicted increase after 60 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles at the Energy No. 1 Mine--Model simulation T2.

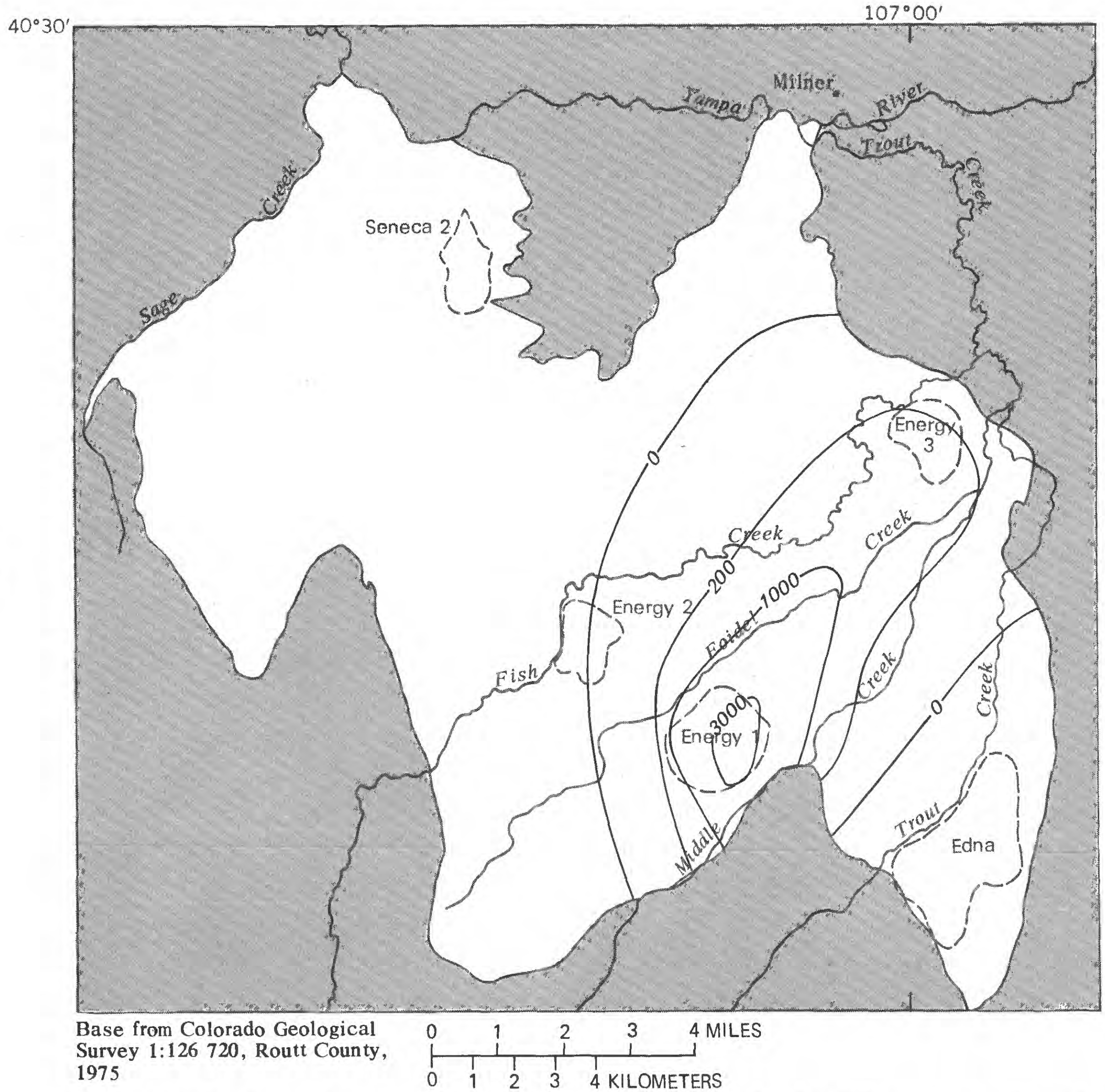
After 200 years, the plume of degraded ground water would occupy an area of about 37 mi^2 (96 km^2) (fig. 16). Most of the degraded ground water would flow northeast from the mine site before discharging into one of the nearby streams. However, some of the degraded ground water would flow north from the mine and would not be intercepted until it ultimately would discharge directly into the Yampa River. The area of ground water with an increased dissolved-solids concentration of more than 200 mg/L then would extend as much as 6 mi (10 km) from the mine site.

The dissolved-solids concentration of degraded ground-water discharge to Middle and Foidel Creeks would be about the same as after 60 years, more than a 1,000-mg/L increase, but the rate of degraded ground-water discharge to Middle Creek then would increase to about 1.0 ft^3/s (0.028 m^3/s). The rate of degraded ground-water discharge to Foidel Creek would remain at about 0.35 ft^3/s (0.010 m^3/s). This would result in an increase in dissolved-solids concentration at low flows of 280 mg/L in Middle Creek and 560 mg/L in Foidel Creek. The rate of degraded ground-water discharge to Fish Creek would increase to about 0.40 ft^3/s (0.011 m^3/s), which would result in a dissolved-solids increase of about 100 mg/L at low flow. The degraded ground-water discharge load (about 119,000 tons or 108,000 t) to these three streams represents about 85 percent of the total dissolved-solids loading leached from the Energy No. 1 Mine waste-spoil piles during the 200-year period. An estimated 21,000 tons (19,100 t) still would be in storage within the aquifer.

In summary, model simulations indicate that within 20 years, a noticeable increase in low-flow dissolved-solids concentration in Middle, Foidel, and Fish Creeks would result from the mining operations. Ultimately, an increase in low-flow dissolved-solids concentrations of 280 mg/L in Middle Creek, 560 mg/L in Foidel Creek, and 100 mg/L in Fish Creek could be expected. A plume of degraded ground water would develop in the vicinity of the mine site within 20 years and would continue to enlarge and extend as far as 6 mi (10 km) from the mine. However, most of the degraded ground water would be intercepted by one of the nearby streams after moving only a few miles from the mine site.

Model Simulation T3--Energy No. 2 and No. 3 Mines

The results of model simulation T3 predict how ground-water quality would be affected by deep infiltration of water percolating through the waste-spoil piles from both Energy No. 2 and No. 3 Mines (fig. 2). The Energy No. 2 Mine is located in the central part of the model area between Fish and Foidel Creeks. Mining at this site began in 1972. Mining is from the upper coal group which includes coals above the Twentymile Sandstone Member. Cumulative production of the Energy No. 2 Mine through 1977 totaled 3.45 million tons (3.13 million t) (Steele and others, 1979, table 3), and production in 1978 was 0.26 million tons (0.24 million t) (Colorado Division of Mines, 1979). The Energy No. 3 Mine is located in the east-central part of the model area between Fish and Middle Creeks. Mining began in 1975 and is from the middle coal group. Cumulative production of the Energy No. 3 Mine through 1977 totaled 1.43 million tons (1.30 million t) (Steele and others, 1979, table 3), and production in 1978 was 0.34 million tons (0.31 million t) (Colorado Division of Mines, 1979).



EXPLANATION

AQUIFER ABSENT OR NOT CONSIDERED IN MODEL

Energy 3 — COAL MINE AND NAME

—200— LINE OF EQUAL INCREASE IN DISSOLVED-SOLIDS CONCENTRATION -- Interval, in milligrams per liter, is variable

Base from Colorado Geological Survey 1:126 720, Routt County, 1975

Figure 16.--Predicted increase after 200 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles at the Energy No. 1 Mine--Model simulation T2.

All the preceding model and data assumptions used in the calibration procedure and in the other simulations apply to this model simulation. For simulation T3, the dissolved-solids concentrations of the ground water contacting the waste-spoil piles were assumed to increase by 5,000 mg/L, resulting in an additional dissolved-solids loading to the ground-water system of 470 tons/yr (430 t/yr) for the Energy No. 2 Mine, and 350 tons/yr (320 t/yr) for the Energy No. 3 Mine.

The predicted effects from infiltration of this degraded water on the ground-water quality after 20 years are shown in figure 17. Around the Energy No. 2 Mine, the degraded ground water would form a circular plume with a radius of about 2 mi (3 km), occupying an area of about 12 mi^2 (31 km^2). The increase in the dissolved-solids concentration of the ground water would be more than 1,000 mg/L at the Energy No. 2 Mine site and more than 200 mg/L within a 0.5- to 0.7-mi (0.8- to 1.1-km) distance of the mine. Degraded ground water from the Energy No. 2 Mine would discharge to Fish Creek with a dissolved-solids concentration increase of nearly 1,000 mg/L. The rate of this degraded ground-water discharge to Fish Creek would be very small in the reach near the Energy No. 2 Mine site and, therefore, should not observably affect the water quality in the stream. This degraded ground-water discharge load to Fish Creek would represent less than 1 percent of the total dissolved-solids loading leached from the Energy No. 2 Mine waste-spoil piles during the 20-year period. More than 99 percent of the load still would be in storage within the aquifer.

At the Energy No. 3 Mine site, the degraded ground water would have a maximum dissolved-solids concentration increase of about 700 mg/L. Degraded ground water from the Energy No. 3 Mine would discharge to Fish, Middle, and Foidel Creeks. Degraded ground water having an increase in dissolved-solids concentration of about 200 mg/L would be discharged at a rate of about 0.4 ft^3/s (0.011 m^3/s) and 0.55 ft^3/s (0.016 m^3/s), respectively, to Fish and Middle Creeks, resulting in an increase at low flows of about 30 mg/L in Fish Creek and of about 150 mg/L in Middle Creek. Degraded ground water having an increase in dissolved-solids concentration of about 50 mg/L would be discharged to Trout Creek at a rate of about 0.2 ft^3/s (0.006 m^3/s), which would not observably change the water quality in the stream. Approximate steady-state conditions in water-quality changes caused by the Energy No. 3 Mine were reached after 20 years; little change was simulated after either 60 years (fig. 18) or after 200 years (fig. 19). The combined degraded ground-water discharge load to these three streams would represent about 70, 91, and 97 percent of the total dissolved-solids loading leached from the Energy No. 3 Mine waste-spoil piles during the 20-, 60-, and 200-year periods, respectively. The remainder still would be in storage within the aquifer.

After 60 years, the plume of degraded ground water from the Energy No. 2 Mine would more than double in areal extent, enlarging to occupy an area of about 32 mi^2 (83 km^2). This plume of degraded ground water would then extend about 6 mi (10 km) to the northwest and as much as 4 mi (6 km) to the north and northeast of the mine. Due to the small ground-water discharge to streams in the vicinity of the mine, degraded ground water from the Energy No. 2 Mine should produce no observable change in water quality of streams in the model area. However, some deterioration of water quality may occur in discharge from springs located north of the mine.

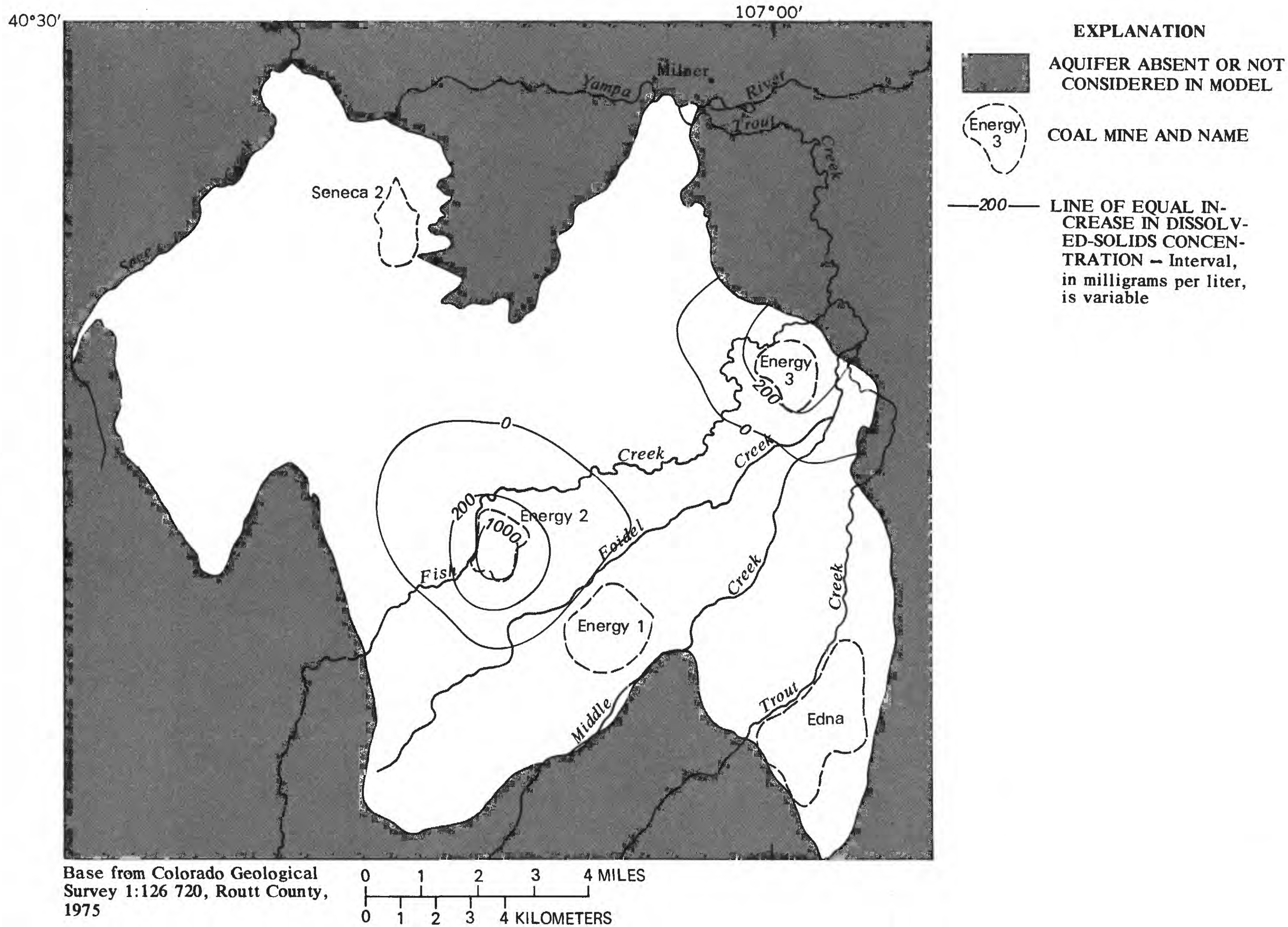


Figure 17.--Predicted increase after 20 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles at the Energy No. 2 and No. 3 Mines--Model simulation T3.

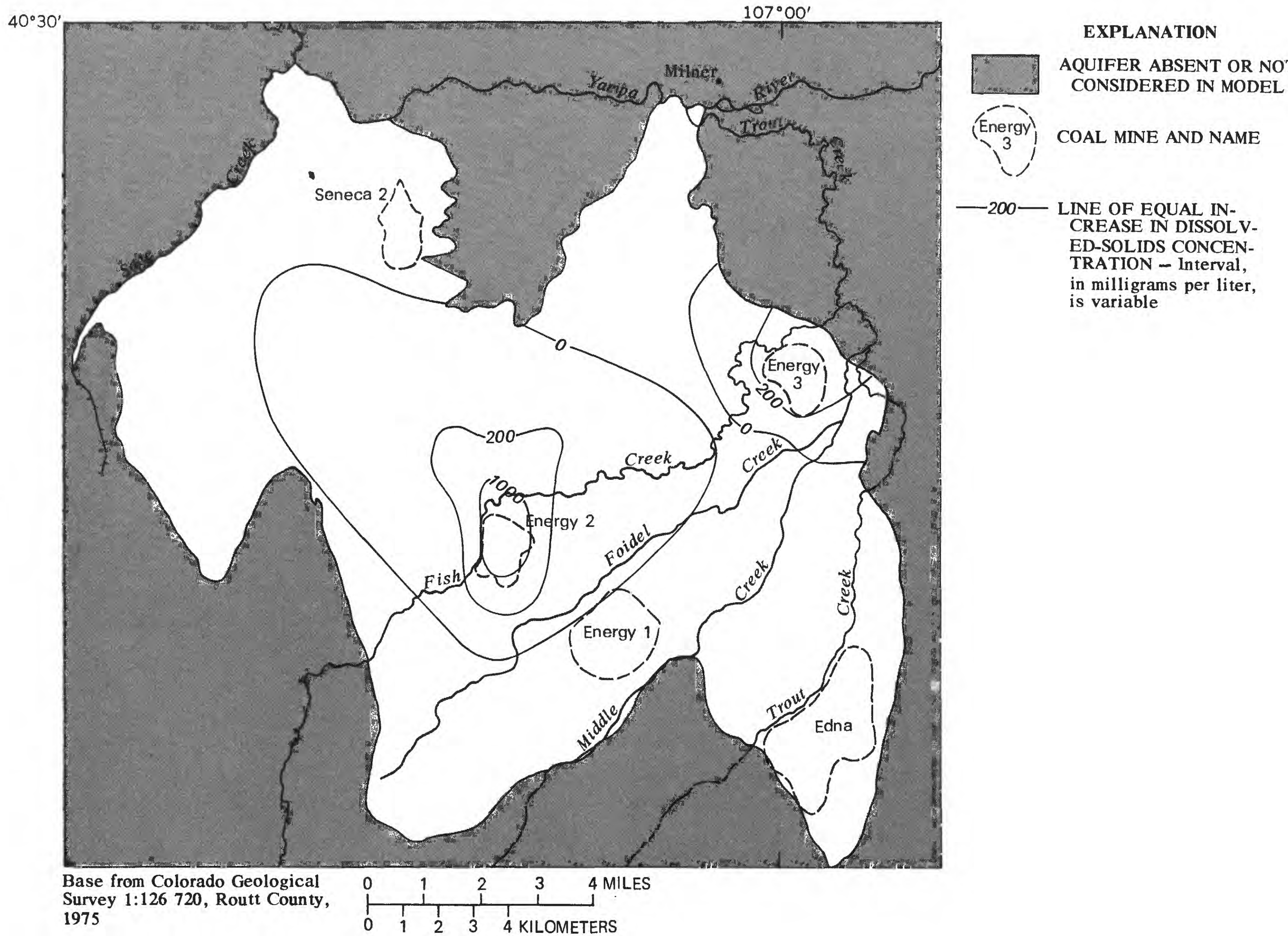


Figure 18.--Predicted increase after 60 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles at the Energy No. 2 and No. 3 Mines--Model simulation T3.

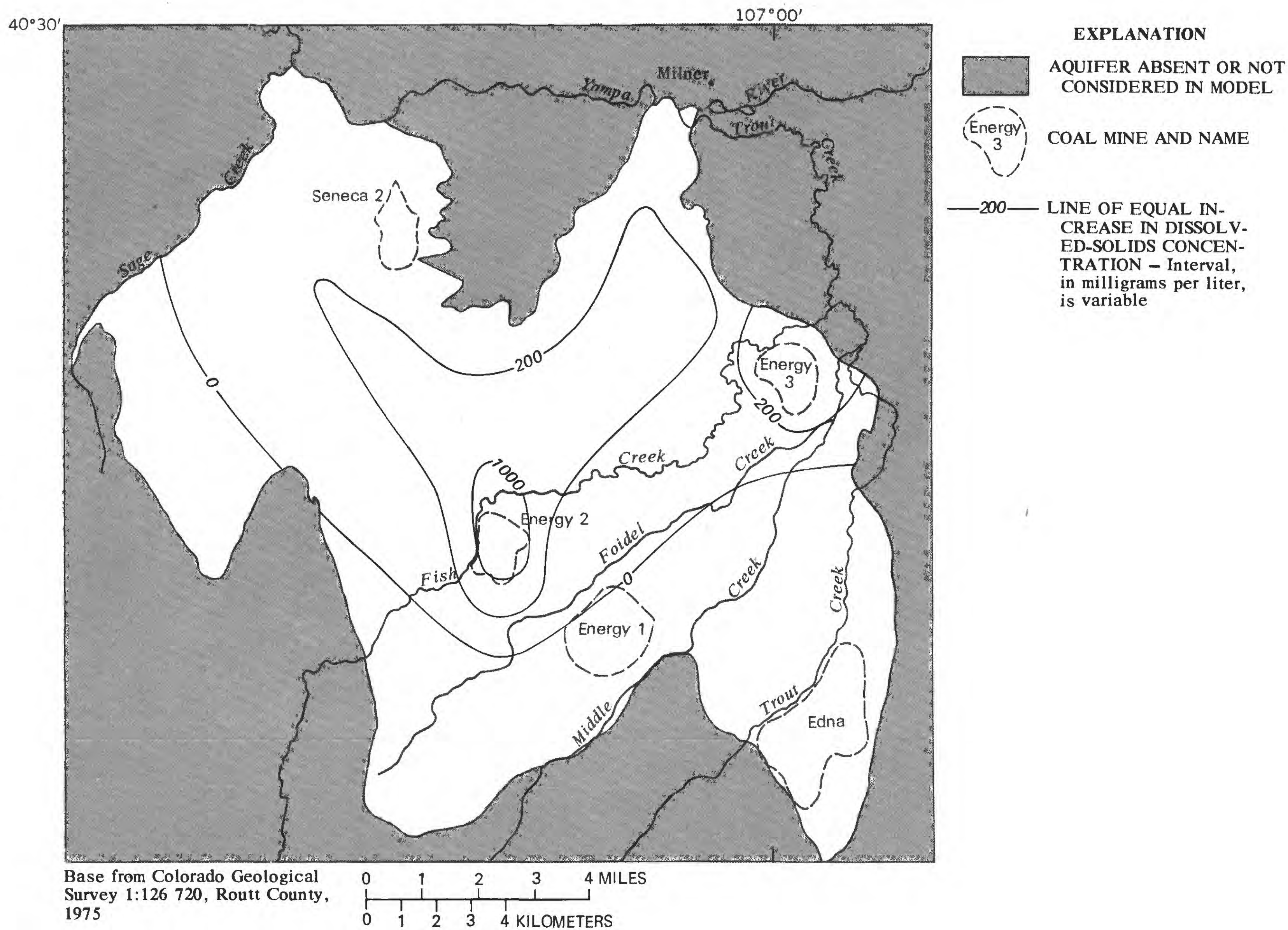


Figure 19.--Predicted increase after 200 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles at the Energy No. 2 and No. 3 Mines--Model simulation T3.

After 200 years the plume of degraded ground water from the Energy No. 2 Mine would enlarge considerably to occupy most of the northern one-half of the model area (fig. 19). Most of the degraded ground water would flow either northwestward or northeastward from the mine site towards the Yampa River, forming almost two separate plumes. Degraded ground water from the Energy No. 2 Mine would then discharge directly into the Yampa River, but this source should not significantly affect water quality in the Yampa River. The degraded ground-water discharge load to streams still would represent less than 1 percent of the total dissolved-solids loading leached from the Energy No. 2 Mine waste-spoil piles during either the 60-year or 200-year periods. Increases in dissolved-solids concentrations of 200 to 400 mg/L would be expected in discharge from springs north of the mine.

In summary, model simulations indicate that degraded ground water from the Energy No. 3 Mine would discharge into either Fish, Middle, or Trout Creeks. Near steady-state conditions in water-quality changes caused by the Energy No. 3 Mine would be reached within 20 years. Increases in low-flow dissolved-solids concentrations of 30 mg/L in Fish Creek and 150 mg/L in Middle Creek would be expected. There should be no observable changes in the quality of water in Trout Creek as the result of mining at the Energy No. 3 Mine. Degraded ground water from the Energy No. 2 Mine should not observably affect the water quality of any of the streams in the model area. However, a plume of degraded ground water would form in the vicinity of the mine and continue to enlarge, ultimately occupying most of the northern one-half of the model area. This degraded ground water may result in a deterioration of water quality in springs located north of the Energy No. 2 Mine.

Model Simulation T4--Seneca No. 2 Mine

The results of model simulation T4 predict how ground-water quality would be affected by deep infiltration of water percolating through the waste-spoil piles or from ground water contacting buried ash at the Seneca No. 2 Mine (fig. 2). The Seneca No. 2 Mine is located in the northwest part of the model area about 2 mi (3 km) south of the Yampa River. Mining at this site began in 1968 and is from the middle coal group. Cumulative mine production through 1977 totaled 7.12 million tons (6.46 million t) (Steele and others, 1979, table 3), and production in 1978 was about 1.37 million tons (1.24 million t) (Colorado Division of Mines, 1979). The entire production from the Seneca Mine is used as fuel for the Hayden Powerplant located about 5 mi (8 km) northwest of the mine site. Fly and bottom ash from the Hayden Powerplant are buried at the Seneca Mine site.

The same assumptions used in the calibration procedure and in the previous simulations apply to this model simulation. For simulation T4, an assumed increase of 5,000 mg/L in the dissolved-solids concentration of ground water contacting either the Seneca Mine waste-spoil piles or the buried ash at the mine was used, resulting in an additional dissolved-solids loading of 470 tons/yr (430 t/yr) to the ground-water system.

The predicted increase in the dissolved-solids concentration of the ground water caused by the leachate from the Seneca Mine after 20, 60, and 200 years is shown in figures 20, 21, and 22, respectively. A small plume of degraded ground water would form near the mine site. Most of the degraded ground water would flow

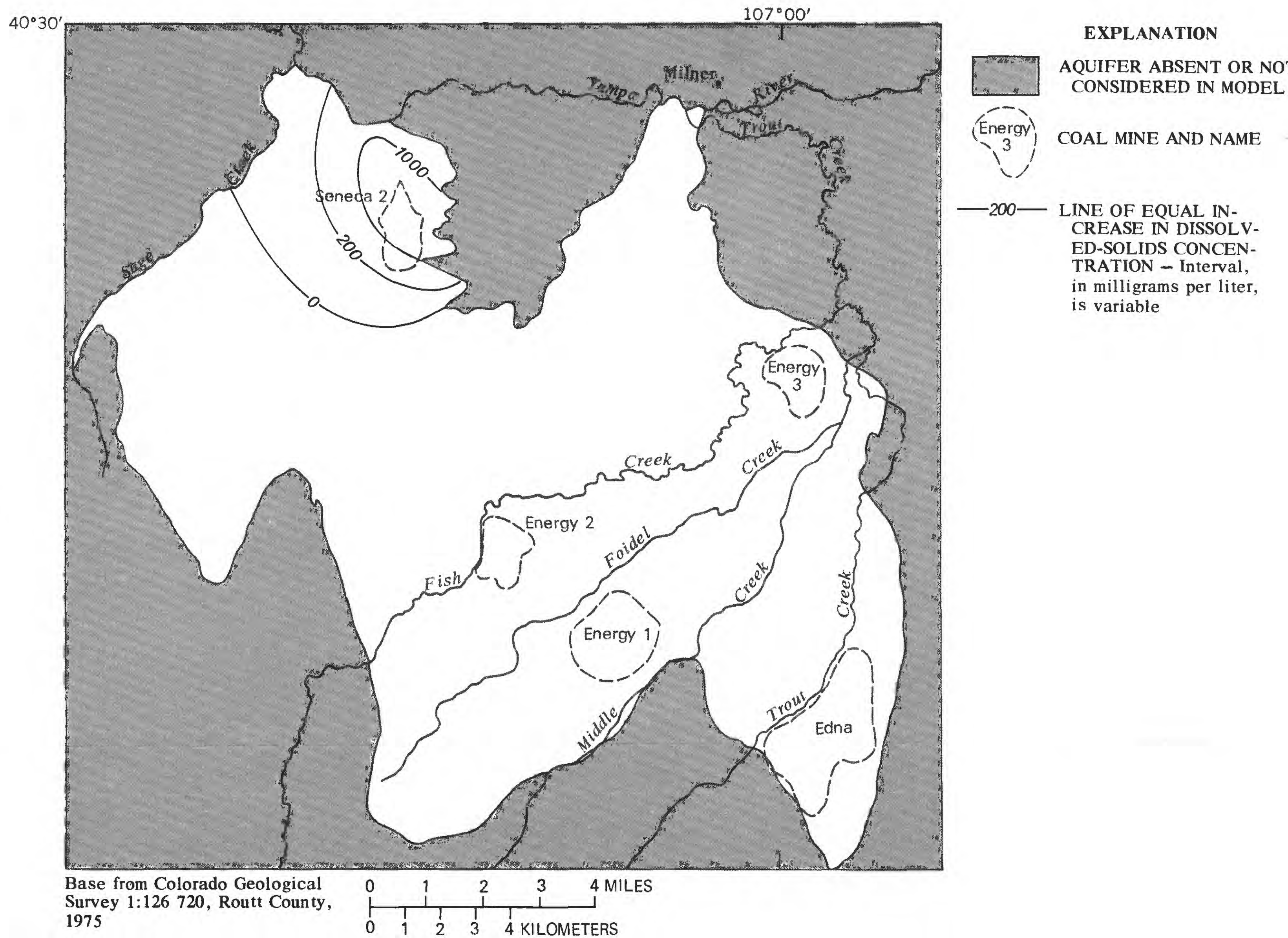


Figure 20.--Predicted increase after 20 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles and buried ash at the Seneca No. 2 Mine--Model simulation T4.

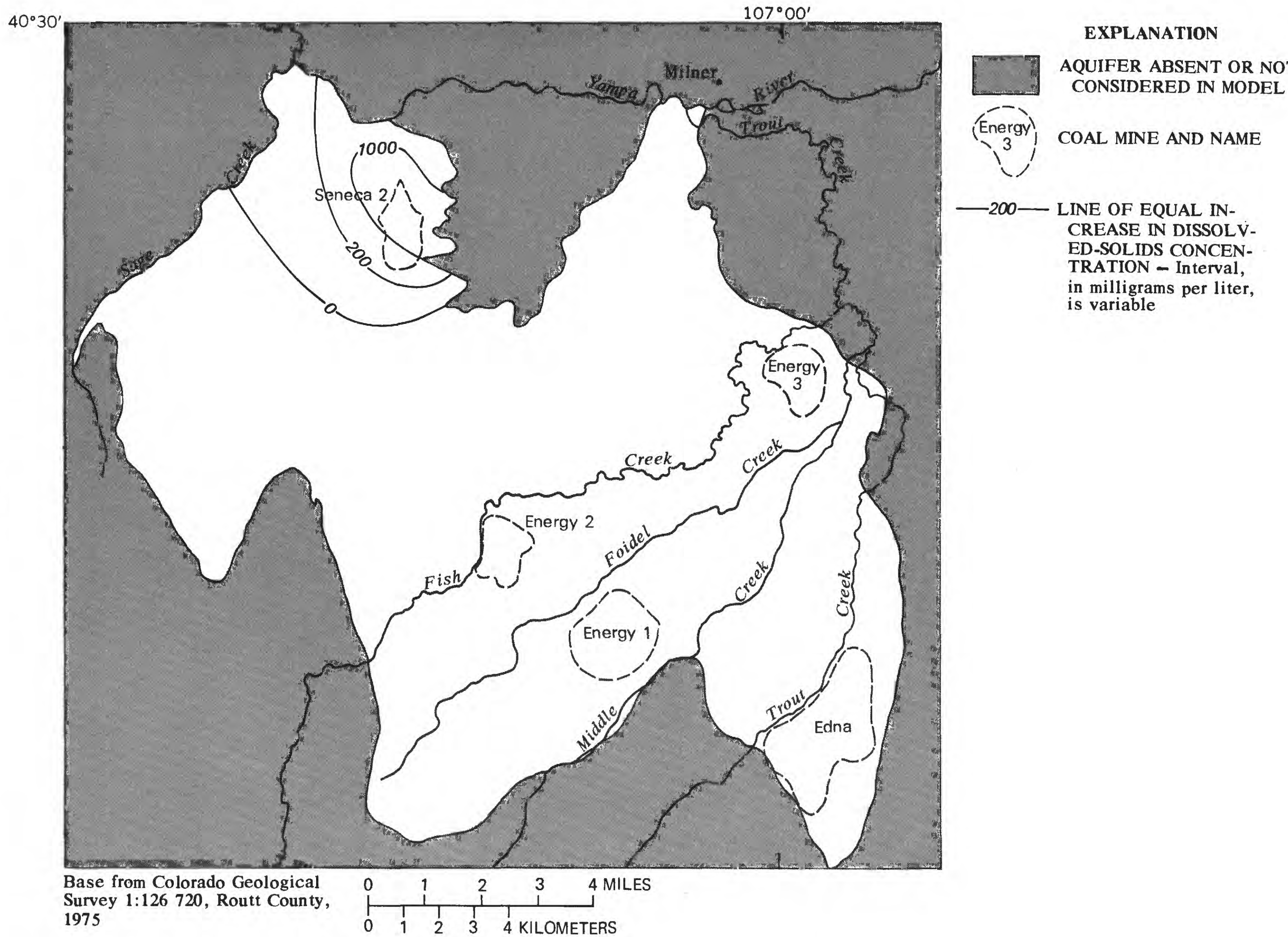


Figure 21.--Predicted increase after 60 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles and buried ash at the Seneca No. 2 Mine--Model simulation T4.

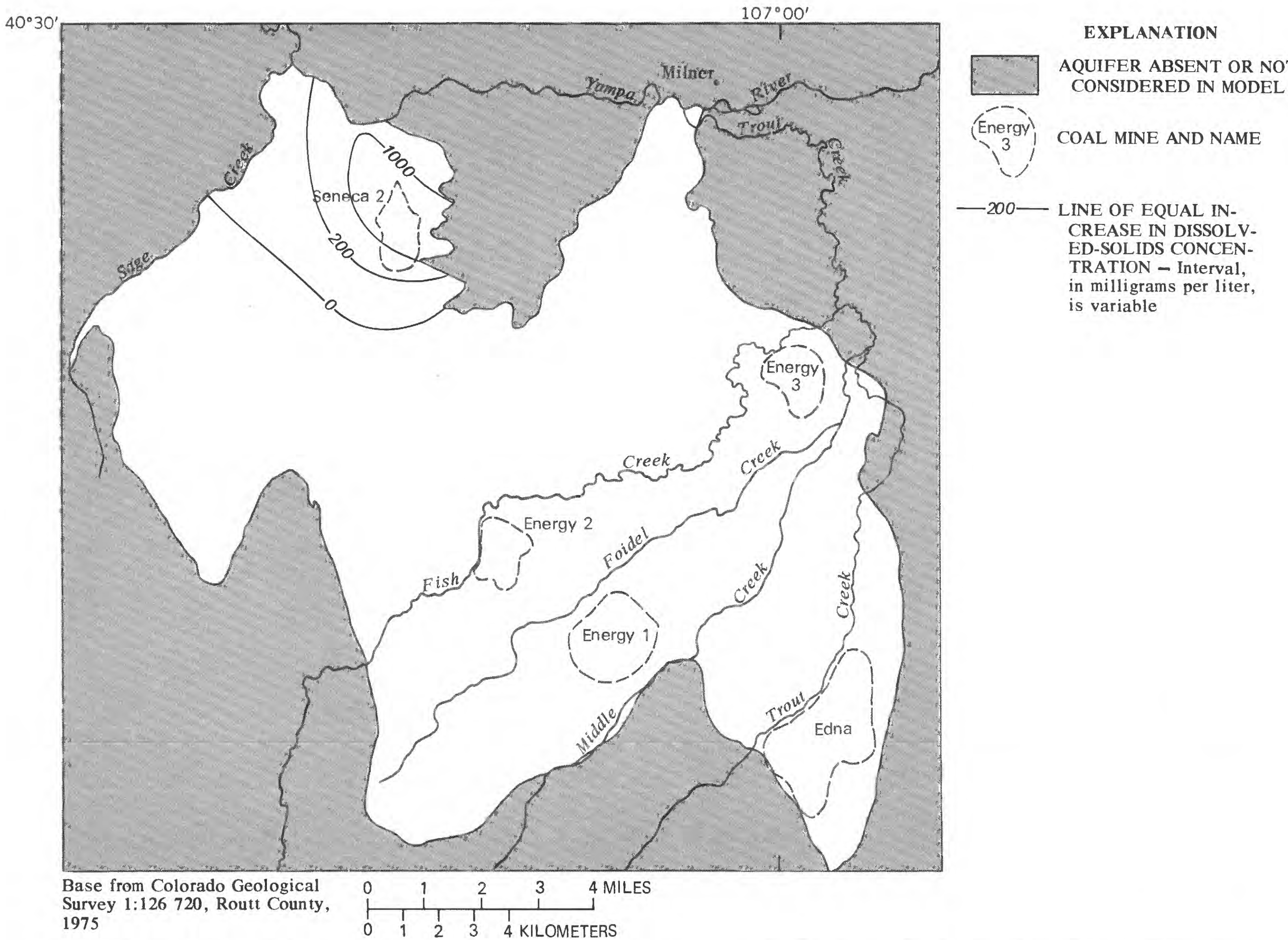


Figure 22.--Predicted increase after 200 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles and buried ash at the Seneca No. 2 Mine--Model simulation T4.

northward and discharge directly into the Yampa River while some would migrate northwestward as underflow out of the model area and down dip into the Sand Wash basin. The amount of degraded ground water discharged directly into the Yampa River would be small compared to the flow in the river and should produce no observable change in water quality of the river. This direct discharge into the Yampa River probably would occur as underflow to the alluvial deposits adjacent to the stream channel and then as discharge to the Yampa River. Thus, it is possible that the quality of ground water would be adversely affected in some wells completed in the river-channel deposits.

Comparison of figures 20, 21, and 22 indicates near steady-state conditions would be reached by 20 years and that very few water-quality changes would occur after that time. The dissolved-solids concentrations of the degraded ground-water discharge to the Yampa River would increase between 200 and 1,000 mg/L. At the mine site, the increase in the dissolved-solids concentrations of the ground water would remain in excess of 1,000 mg/L.

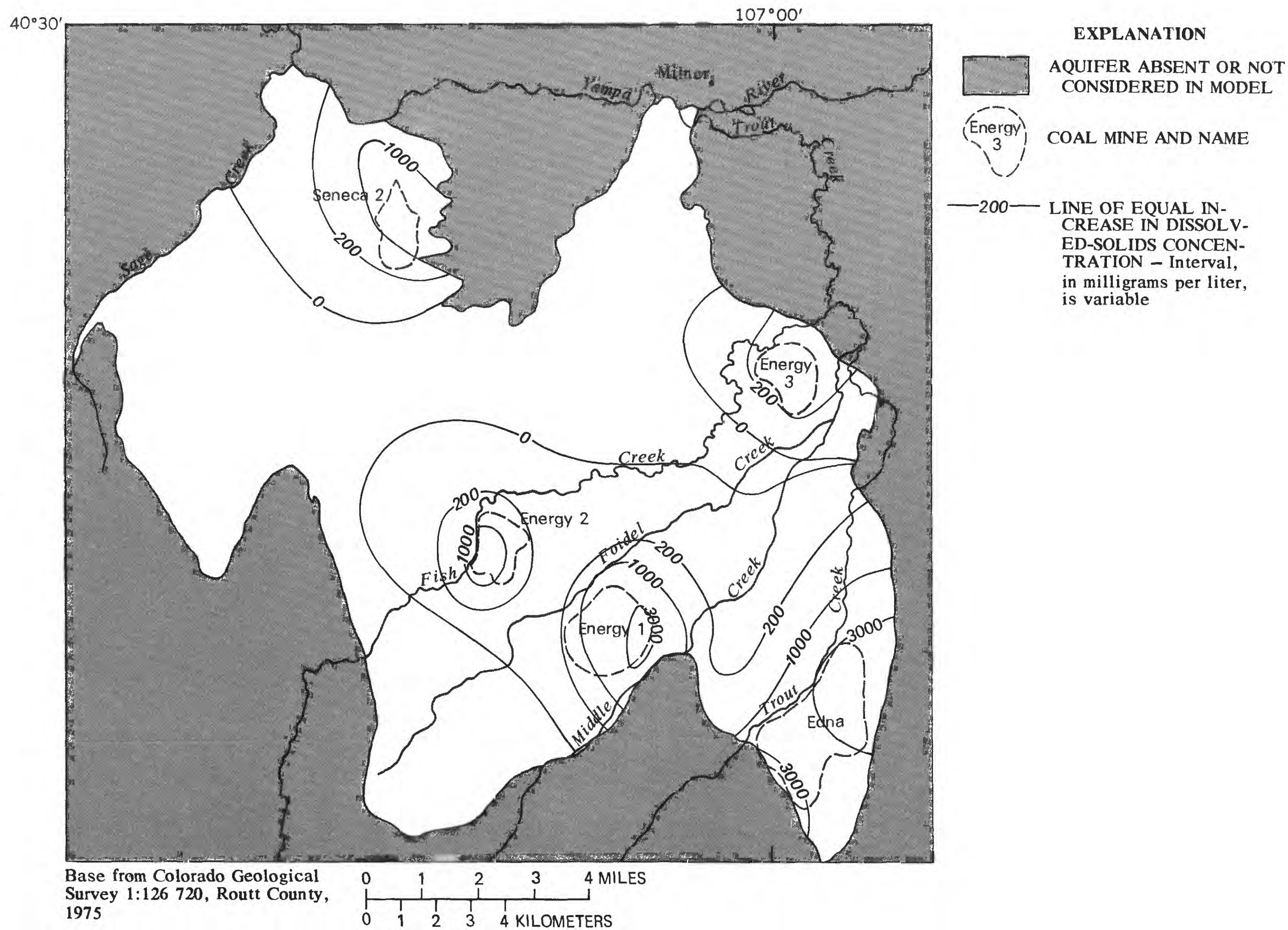
In summary, near steady-state changes in water quality caused by the Seneca Mine would be reached by 20 years. A small plume of degraded ground water would form near the mine site with most of the degraded ground water discharging directly into the Yampa River. This would cause no observable change in water quality in the Yampa River.

Model Simulations T5, T6, and T7--All Mines

The results of model simulations T5, T6, and T7 predict how ground-water quality would be affected when all of the mines in the model area are considered concurrently. Model simulation T5 virtually represents a composite of all previously presented model simulations. In these simulations the assumption was made that ground water contacting the mine waste-spoil piles would increase in dissolved-solids concentration by 5,000 mg/L. Model simulations T6 and T7 are identical with model simulation T5, except that the source concentration increase was assumed at 2,000 mg/L for model simulation T6 and 10,000 mg/L for model simulation T7. These latter two simulations reflect the uncertainty of the dissolved-solids concentration increase of leachate from the waste-spoil piles.

All of the preceding model and data assumptions apply to these model simulations. Using a source concentration of 5,000 mg/L (model simulation T5) would result in a combined total dissolved-solids loading of 3,200 tons/yr (2,900 t/yr) to the ground-water system.

The predicted increase after 20 years in the dissolved-solids concentration of the ground water caused by leachate from waste-spoil piles for the combination of all of the mines is shown in figure 23 (model simulation T5). Degraded ground water would extend over much of the southern and eastern parts of the model area, occupying an area of about 57 mi^2 (148 km^2). Concentrated plumes of degraded ground water would exist around the individual mines. An increase of at least 200 mg/L in the dissolved-solids concentration of the ground water would be typical within a 0.5- to 1.0-mi (0.8- to 1.6-km) radius of the mines. Most of the



Base from Colorado Geological Survey 1:126 720, Routt County, 1975

Figure 23.--Predicted increase after 20 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles for all of the mines with source concentration of 5,000 milligrams per liter--Model simulation T5.

degraded ground water would move only a few miles from the mine site before being intercepted by one of the streams in the model area. Within 20 years, degraded ground water would discharge to Trout, Middle, Foidel, and Fish Creeks. The degraded discharge to Trout Creek would have an increase in dissolved-solids concentrations of more than 1,000 mg/L, resulting in an increase in dissolved-solids concentration in Trout Creek of about 50 mg/L at low flow. The increase in dissolved-solids concentration of degraded ground-water discharge to the other streams in the model area would be from 500 to 1,000 mg/L, resulting in an estimated increase in the dissolved-solids concentration at low flow of 235 mg/L in Middle Creek, 70 mg/L in Foidel Creek, and with no observable change expected in Fish Creek.

After 60 years, the combined plumes of degraded ground water from all of the mines would occupy an area of about 76 mi^2 (197 km^2) and would enlarge to extend over much of the model area (fig. 24--model simulation T5). The degraded ground-water discharge to Trout Creek then would have an increase in dissolved-solids concentration of about 2,000 mg/L, resulting in an increase in dissolved-solids concentration in Trout Creek of about 100 mg/L at low flow. More than a 1,000-mg/L increase would occur in the dissolved-solids concentration of the degraded ground water discharged to the other streams, resulting in an increase in dissolved-solids concentration at low flow of 900 mg/L to Middle Creek, 400 mg/L to Foidel Creek, and with still no observable change expected in Fish Creek.

After 200 years, the combined plumes of degraded ground water would occupy almost all of the model area (fig. 25--model simulation T5). Degraded ground water with a concentration increase of more than 200 mg/L would extend almost to the Yampa River and occupy an area of about 52 mi^2 (135 km^2). The spread of these plumes of degraded ground water would be relatively slow, primarily because most of the degraded ground water generated by the mining operations would be discharged to the streams draining the model area. After 200 years, this would result in an increase in dissolved-solids concentration at low flow of 100 mg/L in Trout Creek, 930 mg/L in Middle Creek, 560 mg/L in Foidel Creek, and 100 mg/L in Fish Creek. The quality of water in the Yampa River should not be observably altered by either the dissolved-solids concentration increase of streamflow in these tributaries or by the direct discharge of degraded ground water to the Yampa River. The relatively greater base flow in the Yampa River would mask any of the water-quality effects of the mining operations.

Model simulations T6 (figs. 26, 27, and 28) and T7 (figs. 29, 30, and 31) predict how the ground-water quality would be affected when dissolved-solids increases of 2,000 and 10,000 mg/L, respectively, are used as source concentrations for leachate from the waste-spoil piles at the mines. Comparison of these figures with figures 23, 24, and 25 (model simulation T5) indicates an approximately linear relationship between the increase in the dissolved-solids concentration of the ground water and the dissolved-solids increase assumed for the source concentration. This linear relationship also extends to the resulting change in water quality of streamflow in the model areas. This indicates a relatively sensitive correlation between the assumed dissolved-solids concentration increase of leachate from mine waste-spoil piles used in the model and the predicted impact of coal mining on the environment.

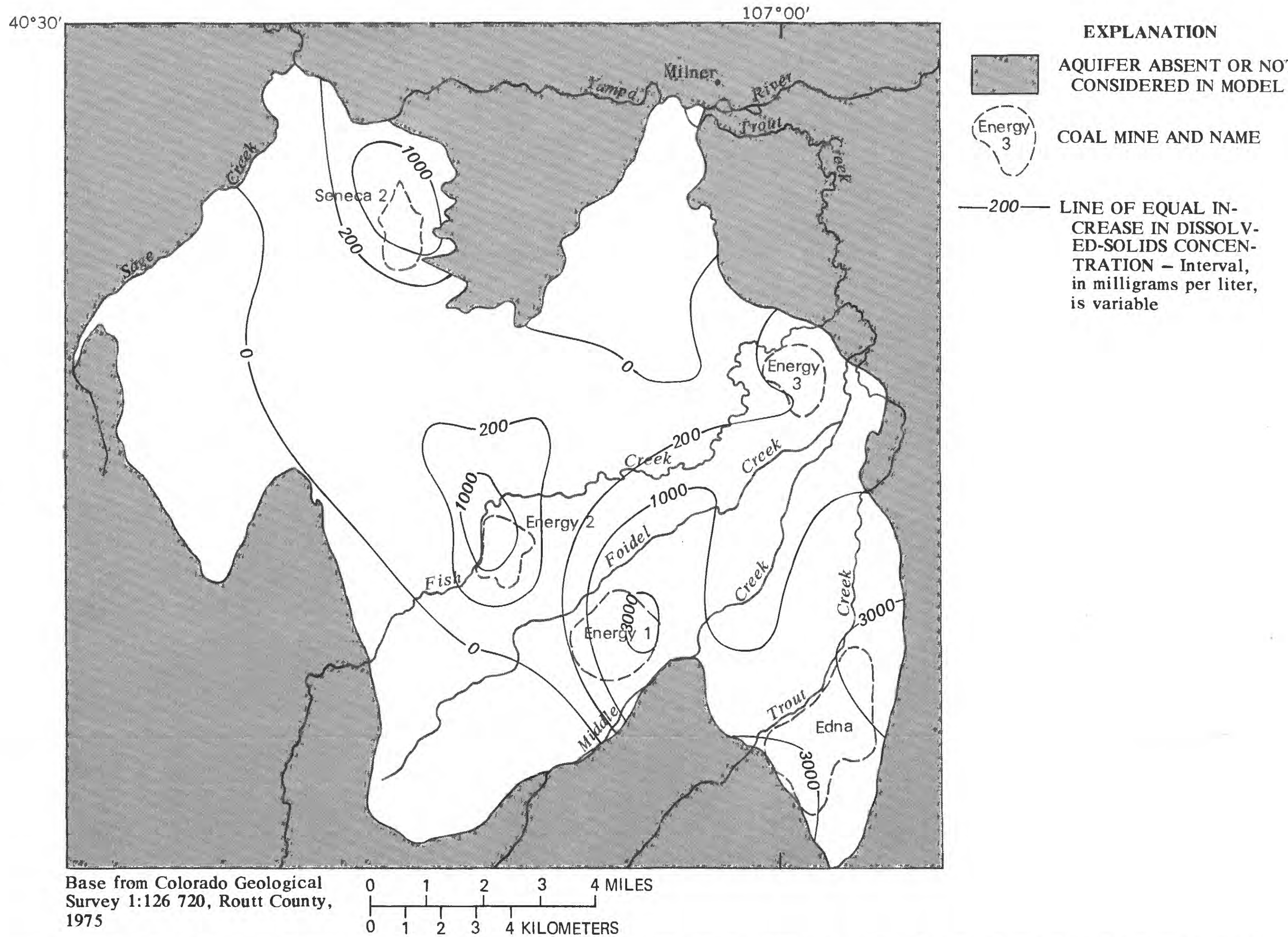


Figure 24.--Predicted increase after 60 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles for all of the mines with source concentration of 5,000 milligrams per liter--Model simulation T5.

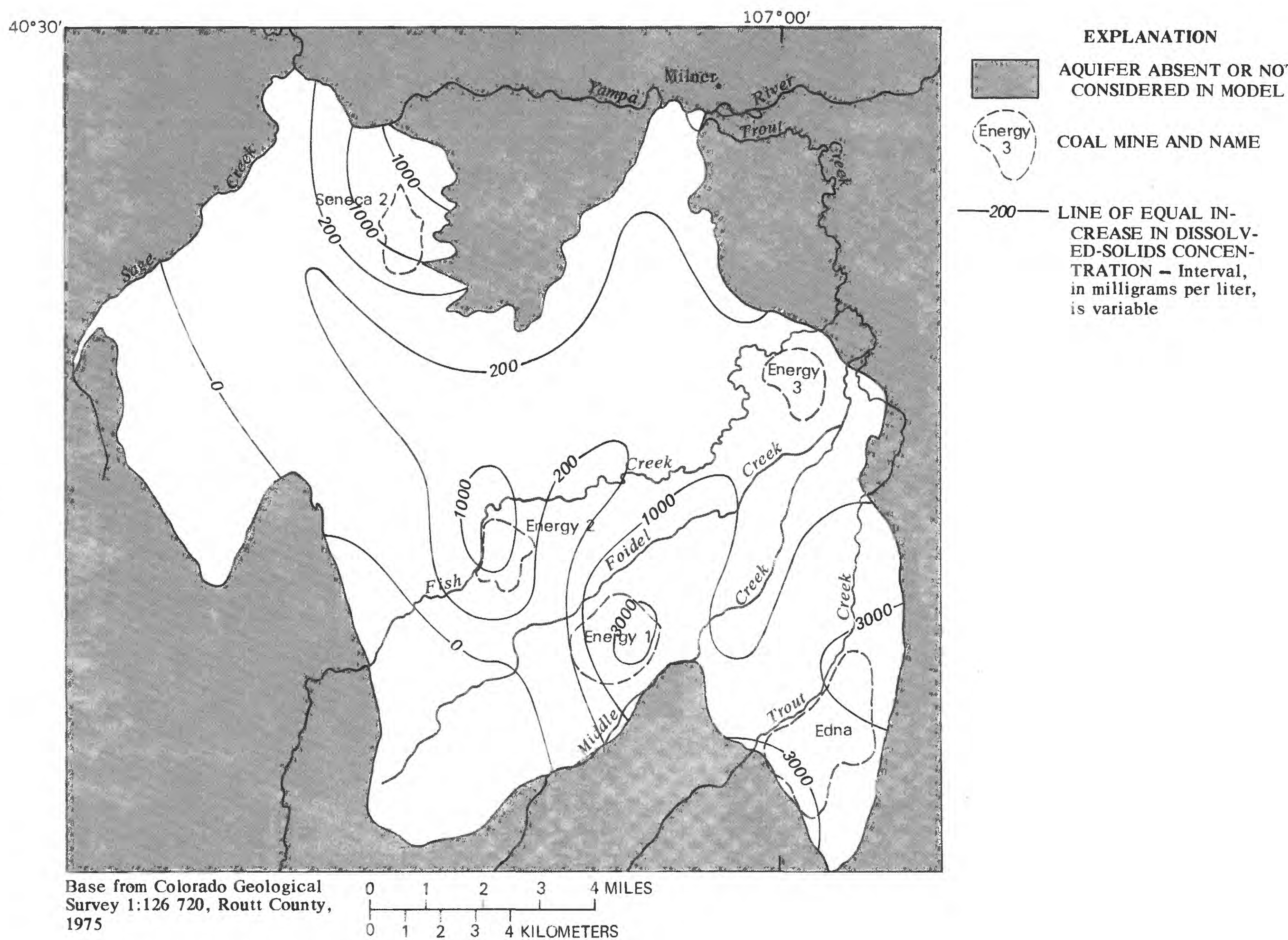


Figure 25.--Predicted increase after 200 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles for all of the mines with source concentration of 5,000 milligrams per liter--Model simulation T5.

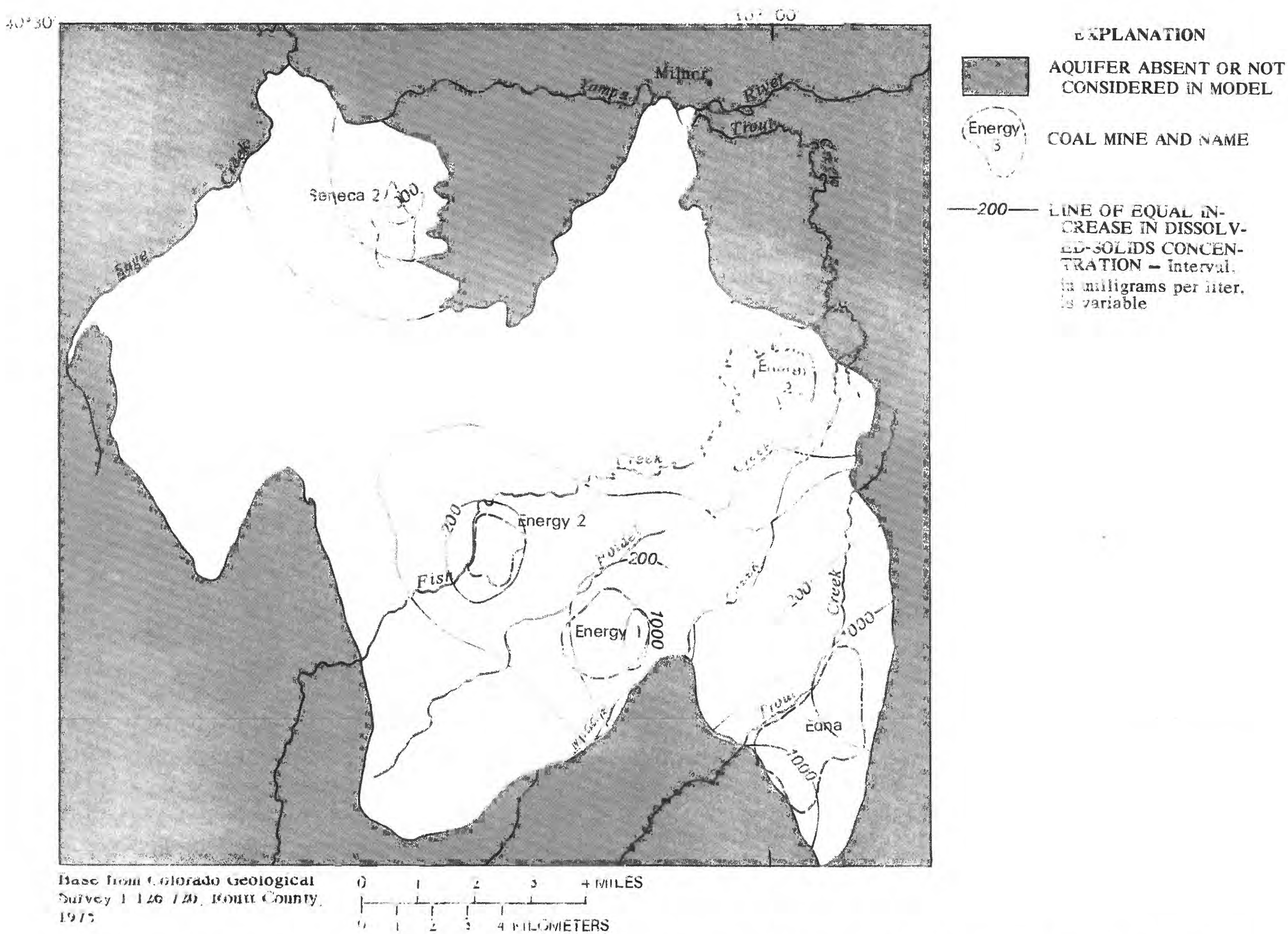


Figure 25.--Predicted increase after 20 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles for all of the mines with source concentration of 3,000 milligrams per liter for

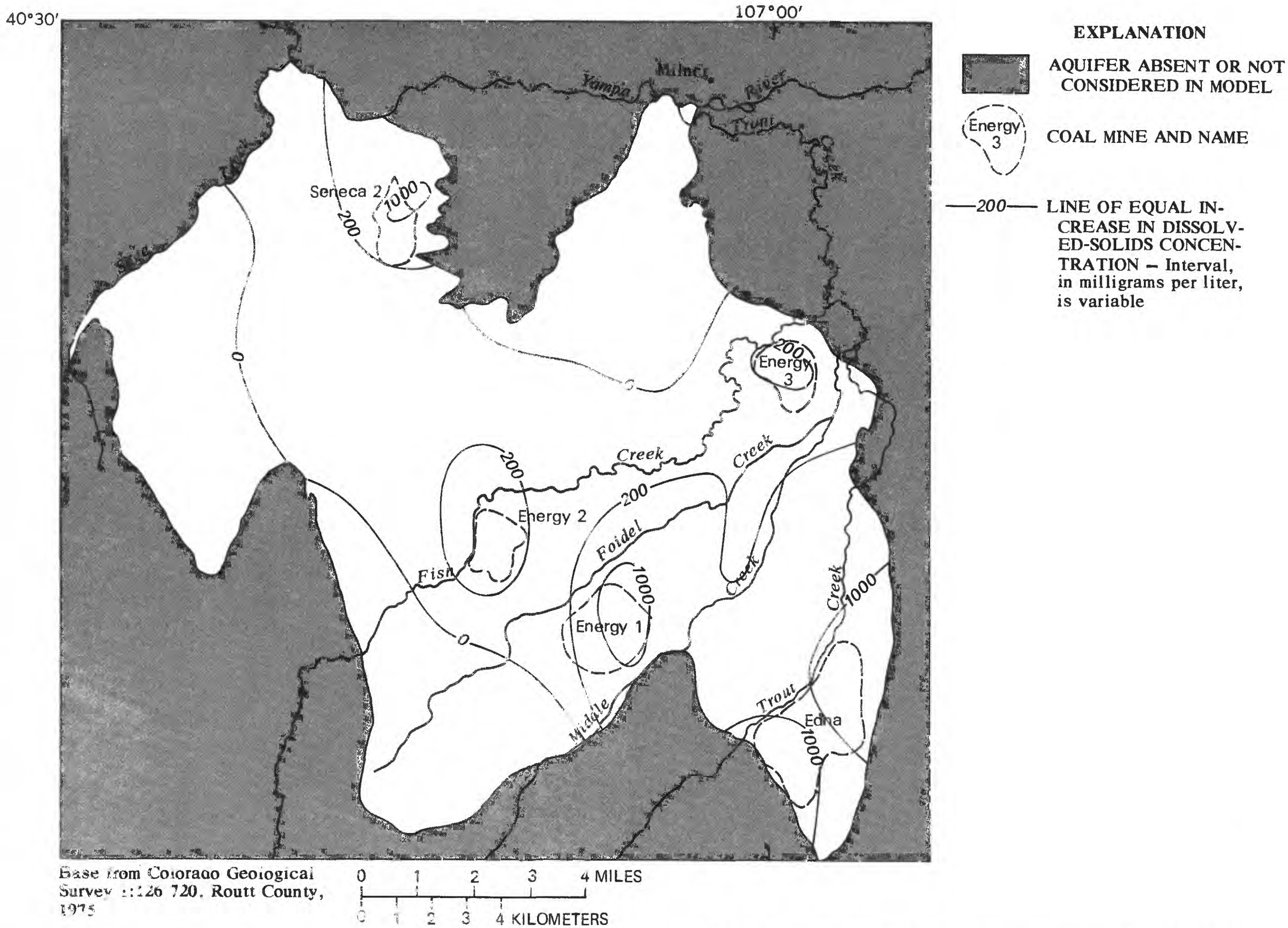
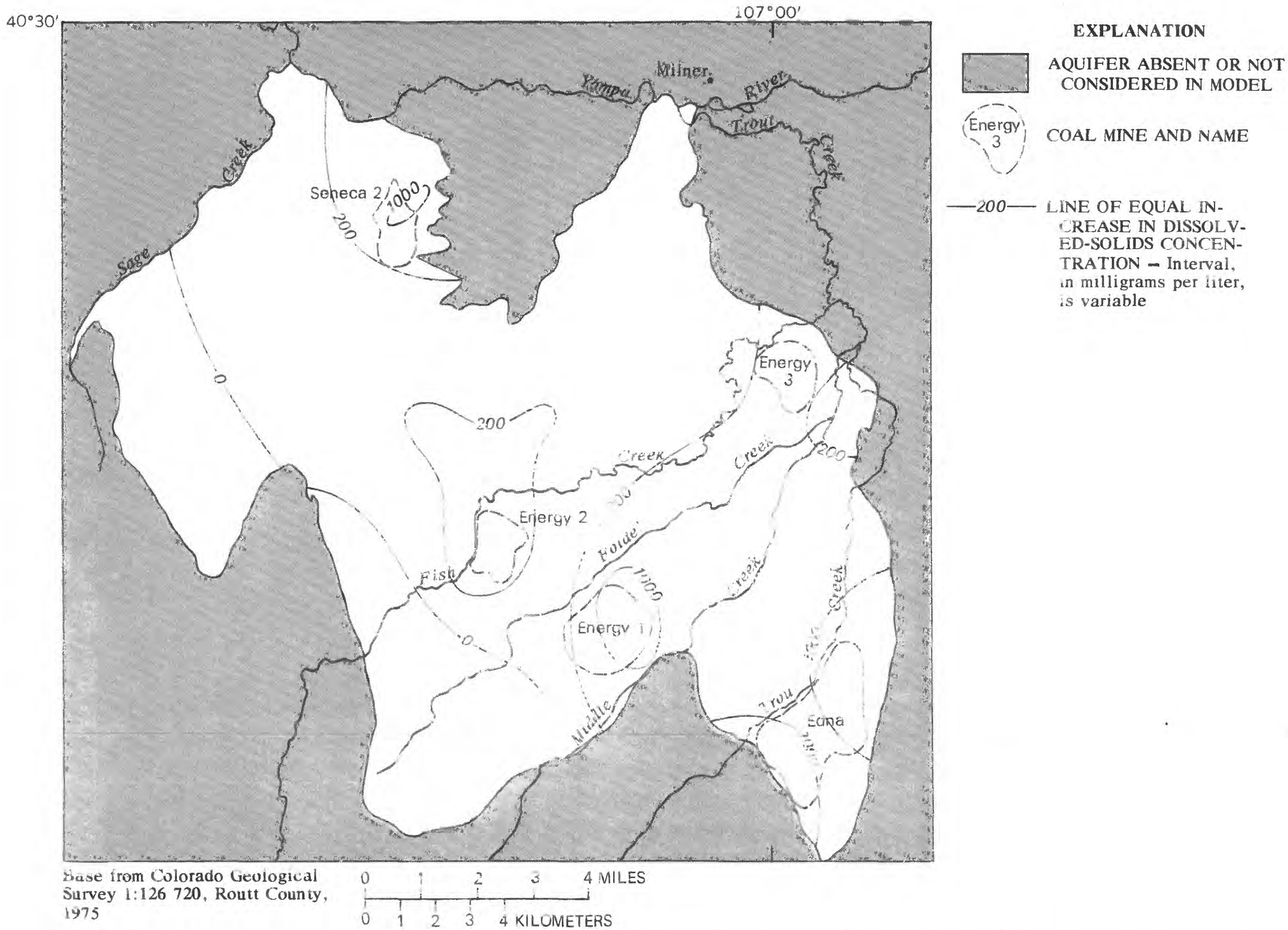


Figure 27.--Predicted increase after 60 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles for all of the mines with source concentration of 2,000 milligrams per liter--Model simulation T6.



Base from Colorado Geological Survey 1:126 720, Routt County, 1975

Figure 28.--Predicted increase after 200 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles for all of the mines with source concentration of 2,000 milligrams per liter--Model simulation T6.

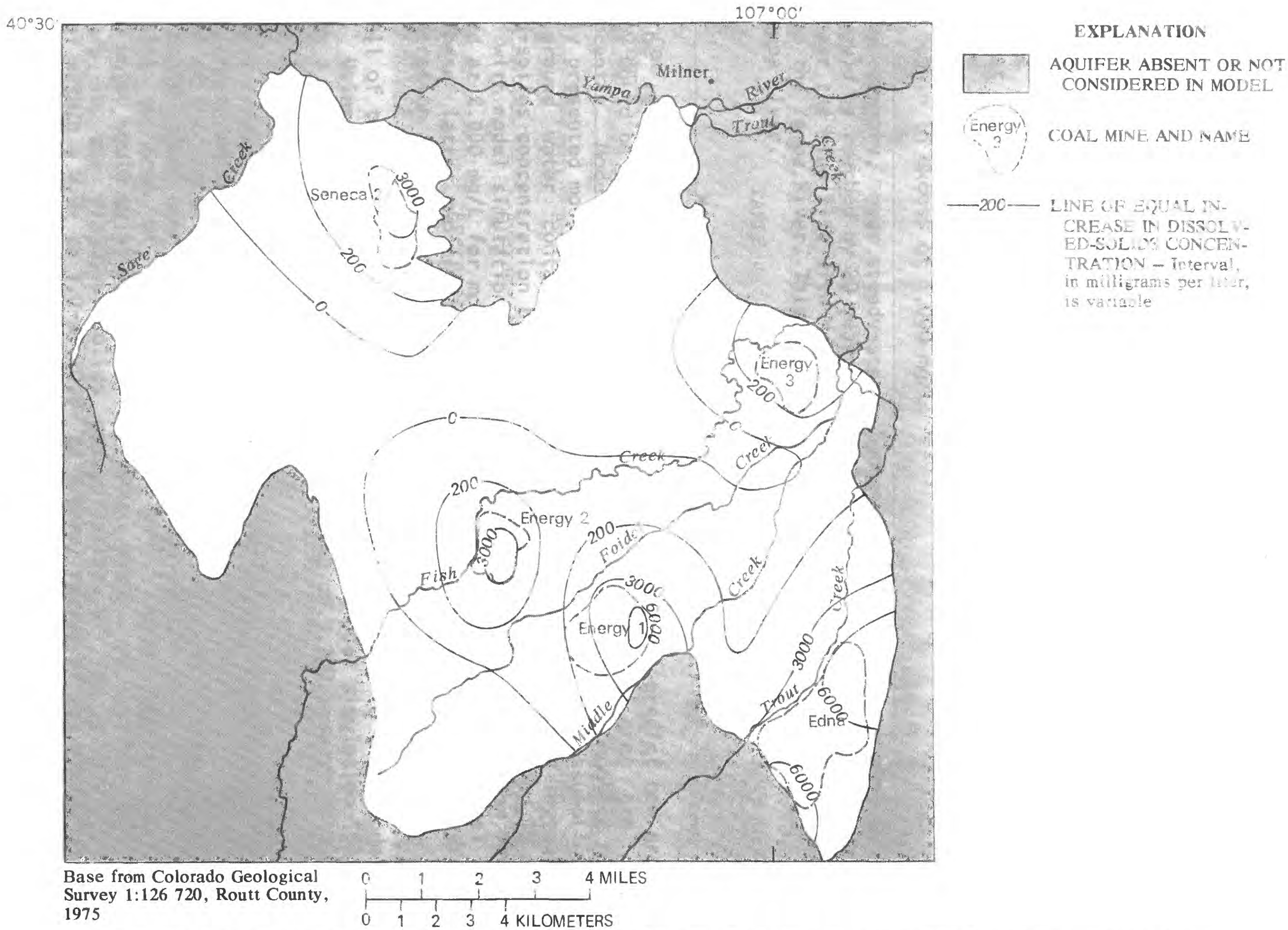
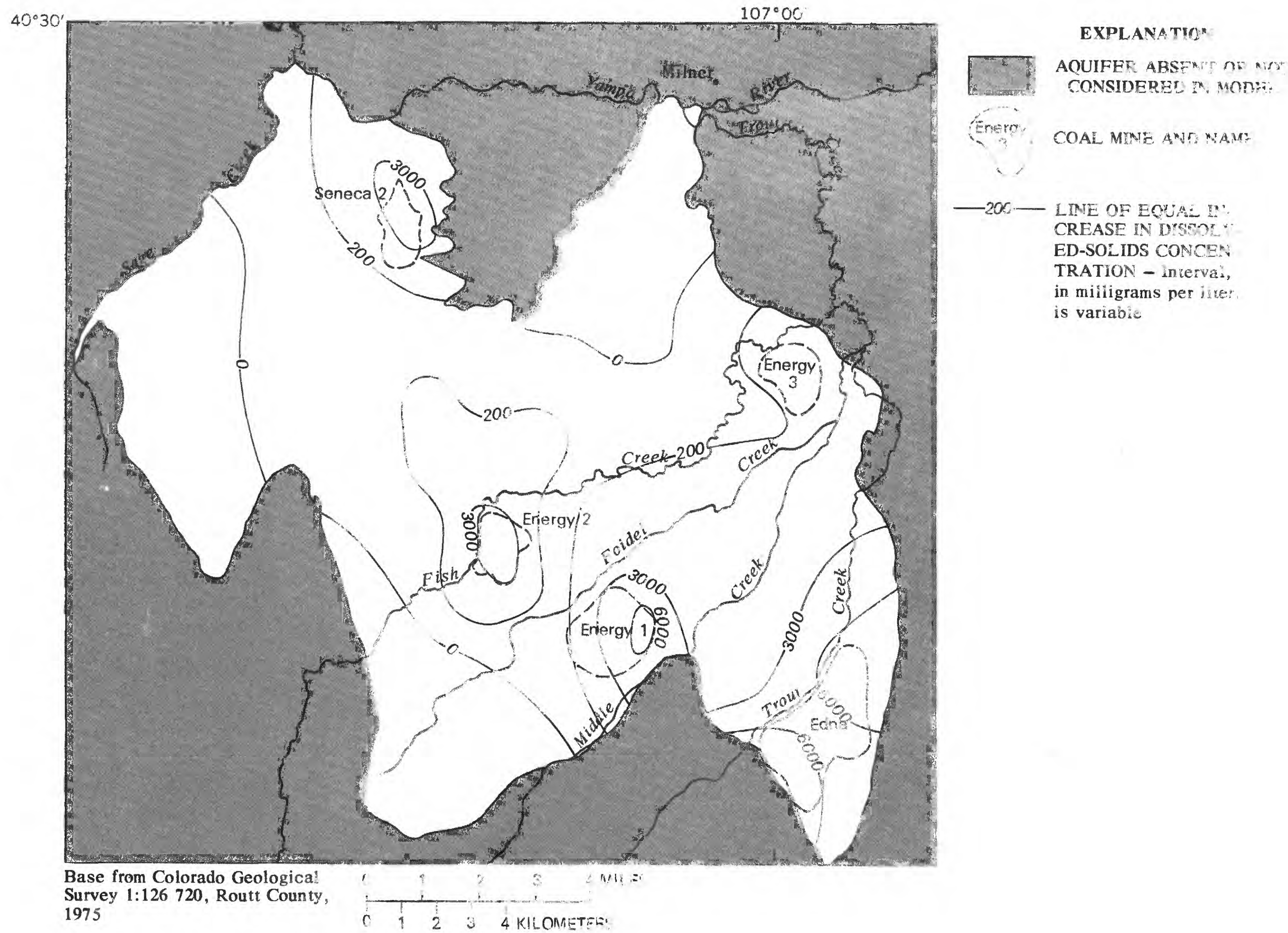
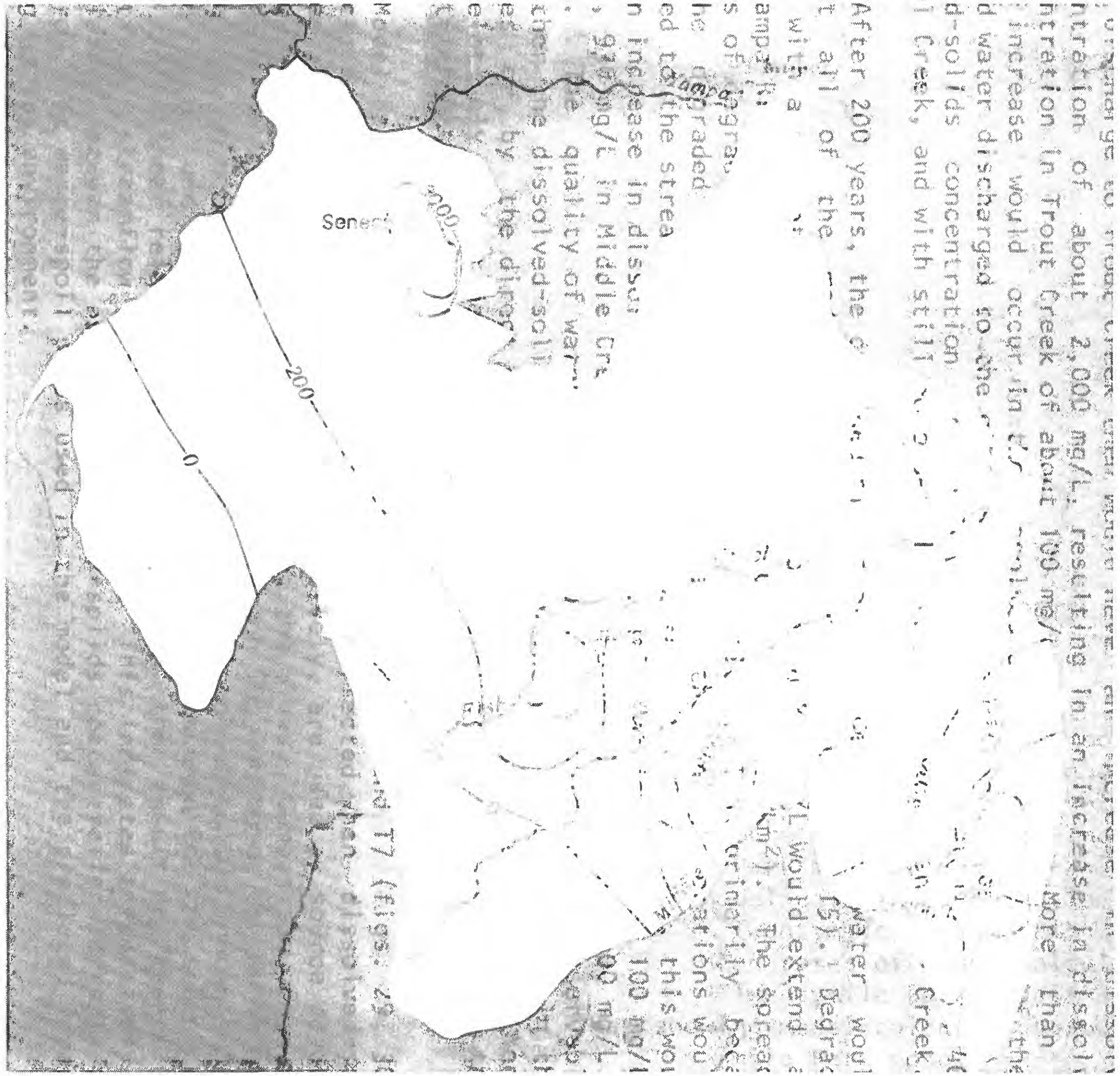


Figure 29.--Predicted increase after 20 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles for all of the mines with source concentration of 10,000 milligrams per liter--Model simulation T7.



Base from Colorado Geological Survey 1:126 720, Routt County, 1975

Figure 30.--Predicted increase after 60 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles for all of the mines with source concentration of 10,000 milligrams per liter--Model simulation T7.



Base from Colorado Geological Survey 1:126 720, Routt County, 1975

Figure 31.--Predicted increase after 200 years in [illegible] dissolved-solids concentration of ground water caused by leachate from waste-spoil [illegible] with source concentration of 10,000 milligrams per liter--Model simulation T7.

Model Simulation T8--Hypothetical Large-Scale Ground-Water Development

The results of model simulation T8 predict the impact on the ground-water system caused by mining together with a hypothetical large-scale ground-water development. The purpose of this simulation is to perform a limited feasibility test on the potential of ground-water resources to provide needed water for energy development and other uses. This might depend on the impact that mining would have on any future possible large-scale ground-water development that could be contemplated. A group of wells was simulated in the northwestern part of the model area about 4 mi (6.4 km) south of the Yampa River and about 2 mi (3.2 km) southwest of the Seneca Mine. The simulated wells were located in an area where the saturated thickness of the aquifer is large and downgradient from where most of the recharge to the aquifer occurs. The wells also were located to minimize the hydrologic and water-quality effects from a majority of the mines in the model area. Total pumpage from the wells was simulated at about 900 gal/min (0.057 m^3/s), which represents about one-third of the total recharge to the aquifer in the model area.

In this simulation, the effects of all of the mines were considered concurrently. As in most of the previous simulations the assumption was made that ground water contacting the mine waste-spoil piles would increase in dissolved-solids concentration by 5,000 mg/L. All of the preceding model and data assumptions apply to this simulation except that transient ground-water flow conditions were simulated rather than the steady-state flow conditions, as was assumed in the previous simulations.

The steady-state drawdown in the potentiometric surface is shown in figure 32. Approximate steady-state ground-water flow conditions would be reached within 20 years. Drawdowns of 0 to 300 ft (0 to 90 m) would occur over the western two-thirds of the model area. Along the northwestern model boundary located about 4 mi (6.4 km) from the pumping site, drawdowns greater than 100 ft (30 m) were predicted. In model simulation T8, this necessitated a change along the common boundary between the two models from the constant-head boundary specifications used in the previous simulations to a constant-flux boundary specification. Drawdowns in the potentiometric surface caused by this hypothetical large-scale ground-water development would be less than 5 ft (1.5 m) at the Edna and Energy No. 1 and No. 3 Mines, about 30 ft (9 m) at the Energy No. 2 Mine, and nearly 200 ft (60 m) at the Seneca Mine.

The predicted impact on the ground-water quality is shown after 20, 60, and 200 years, respectively, in figures 33, 34, and 35. During the first 20 years, the pumping depression created by the hypothetical large-scale ground-water development would have very little noticeable effect on the ground-water quality patterns in the model area. The predicted increases in the dissolved-solids concentration of the ground water near the Edna, Energy, and Seneca Mines shown in figure 33 are nearly the same as those shown in figure 23 (model simulation T5) without large-scale ground-water development. The movement of degraded ground water from the Edna and Energy Mines still would be primarily to the north and east from these mines and from the Seneca Mine still would be towards the Yampa River. However, some of the degraded ground water from the Energy No. 2 Mine would begin to move towards the pumping depression created by the hypothetical large-scale ground-water development, but as yet, insufficient time would have elapsed for any of the degraded ground water to have reached the area of ground-water development.

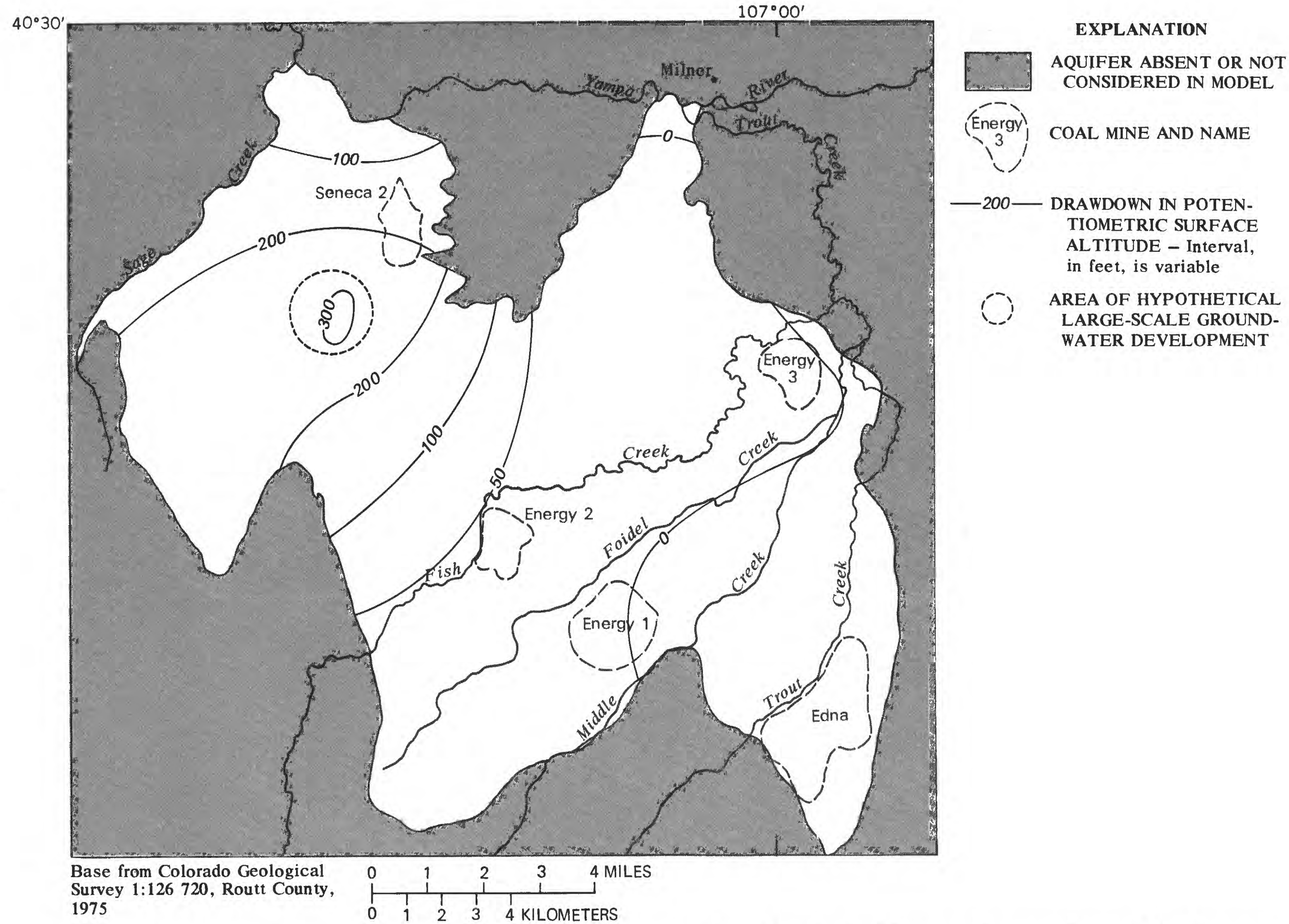


Figure 32.-- Steady-state drawdown in potentiometric surface caused by a hypothetical large-scale ground-water development-- Model simulation T8.

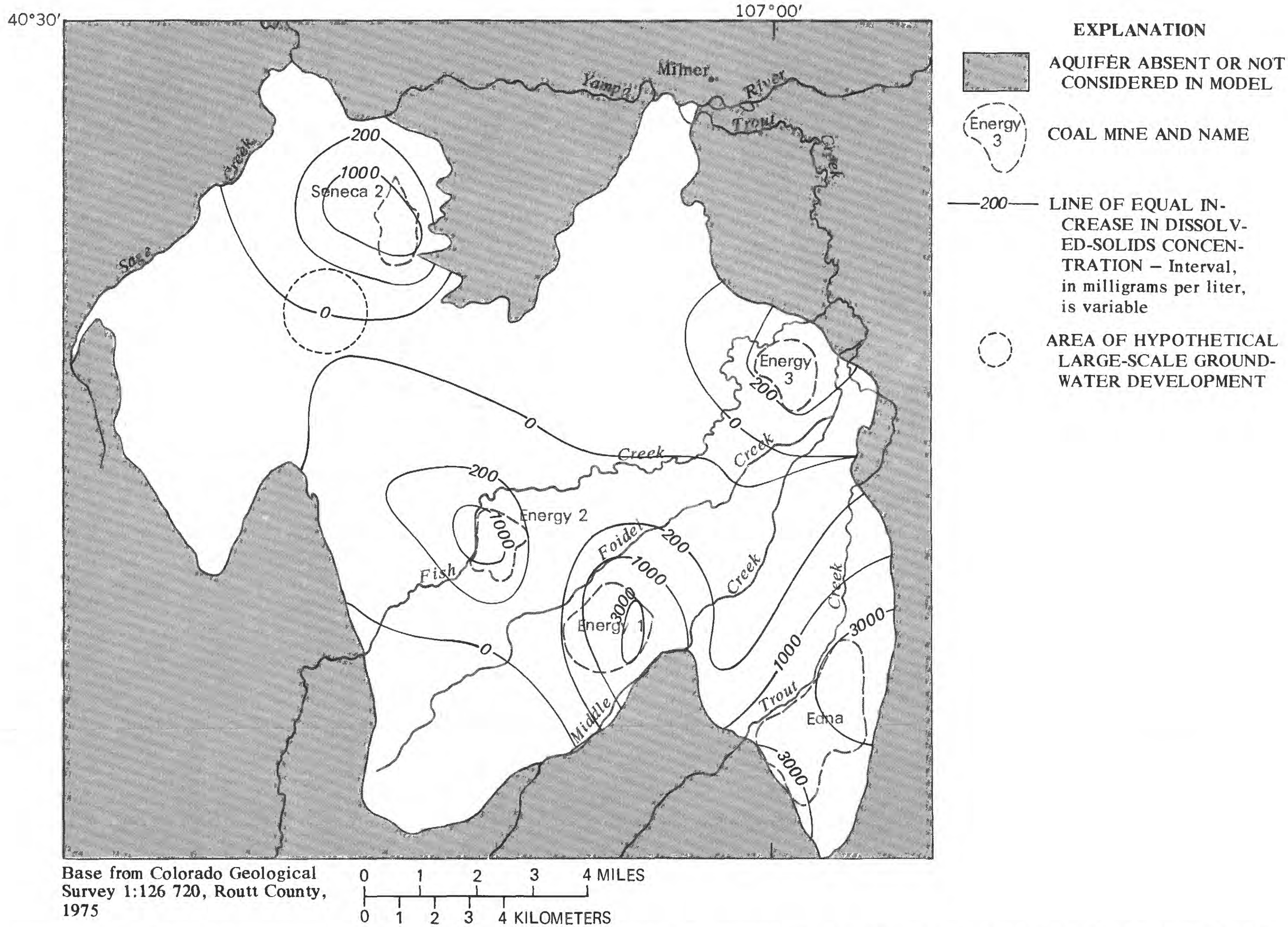


Figure 33.--Predicted increase after 20 years in the dissolved-solids concentration of ground water caused by both mining and for a hypothetical large-scale ground-water development--Model simulation T8.

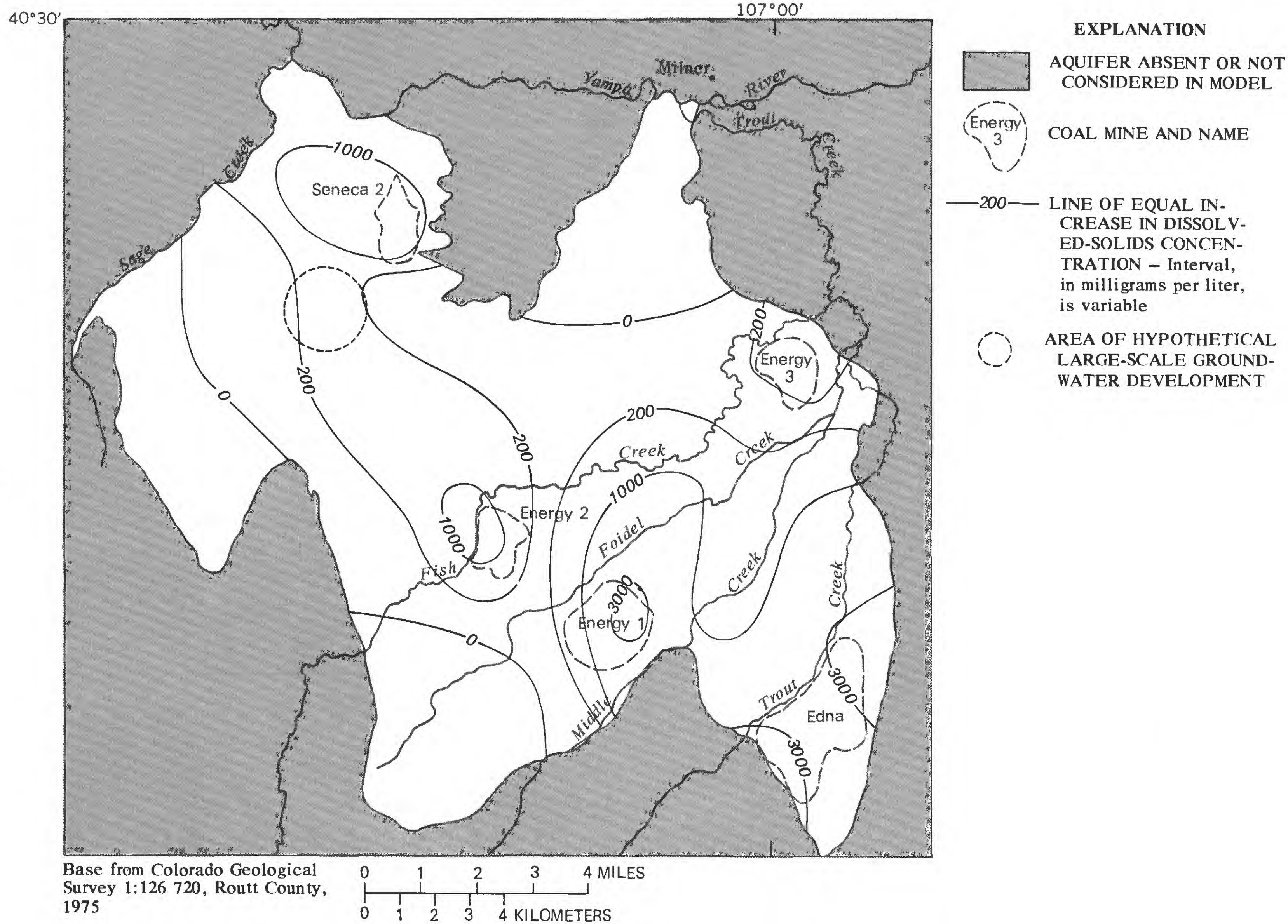


Figure 34.--Predicted increase after 60 years in the dissolved-solids concentration of ground water caused by both mining and for a hypothetical large-scale ground-water development--Model simulation T8.

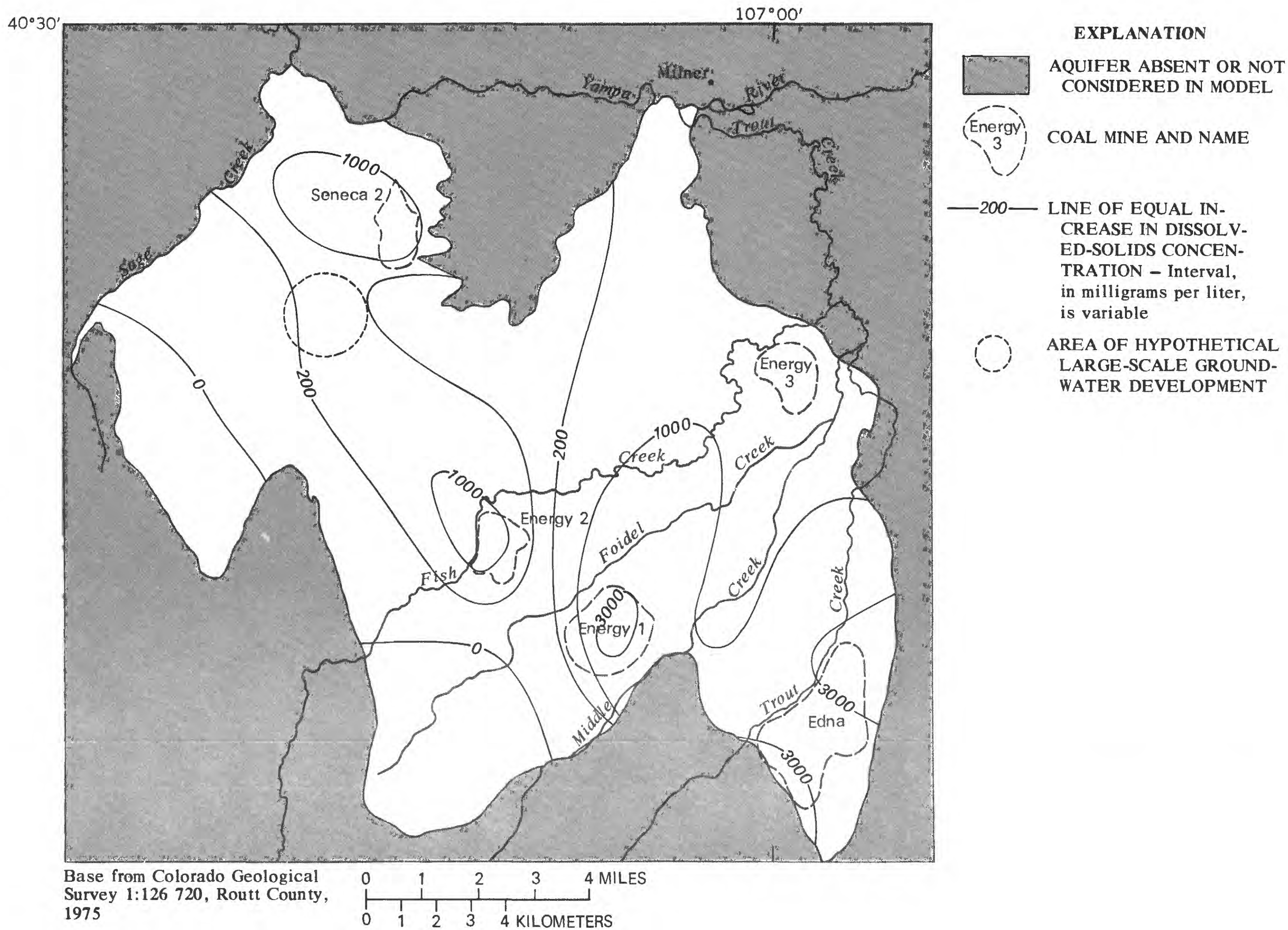


Figure 35.--Predicted increase after 200 years in the dissolved-solids concentration of ground water caused by both mining and for a hypothetical large-scale ground-water development--Model simulation T8.

After 60 years, the hypothetical large-scale ground-water development would intercept degraded ground water with dissolved-solids concentration increases of more than 300 mg/L and after 200 years, would intercept degraded ground water with dissolved-solids increases of more than 500 mg/L. Most of the degraded ground water would come from the Energy No. 2 Mine. Ground water degraded by the Edna Mine and the Energy No. 1 and No. 3 Mines would be discharged to either Trout, Middle, Foidel, or Fish Creeks before reaching the area of ground-water development. Degraded ground water from the Seneca Mine still would discharge primarily directly into the Yampa River. However, the rate of ground-water movement near the Seneca Mine would have been diminished by the ground-water development, causing a buildup of dissolved-solids concentrations in the ground water in the vicinity of this mine.

In summary, large-scale ground-water development in the model area probably would cause ground water degraded by the coal mining to move towards this area of ground-water development. The actual impact of the coal mining on any large-scale ground-water development would depend on the location and amount of the ground-water pumpage. Any large-scale ground-water development probably would intercept degraded ground water with dissolved-solids concentration increases of 500 mg/L or greater. This probably would occur in the time interval of 20 to 60 years but could occur much sooner, depending on how close the actual ground-water development was to the mines.

WILLIAMS FORK MOUNTAINS MODEL

Model-Input Data

The Williams Fork Mountains model area, shown in figure 36, was constructed for the entire Mesaverde Group, including both the Williams Fork and the Iles Formations. The model encompasses an area of about 360 mi^2 (933 km^2). The same types of data are required for this model as for the Twentymile Park model. A different size model grid was used and different boundary conditions were specified. The hydraulic characteristics of the aquifer as well as other data needed for model input were kept, with minimal differences, in close agreement between the two models.

Grid Interval

The model contained a total of 594 nodes with 355 active nodes (fig. 36). A model-grid interval of 4,500 by 4,500 ft (1,370 by 1,370 m) was used, which gave the advantage of being able to simulate aquifer conditions over a larger model area than the Twentymile Park model. However, this advantage was partly offset by the loss of resolution in this model when compared with the Twentymile Park model.

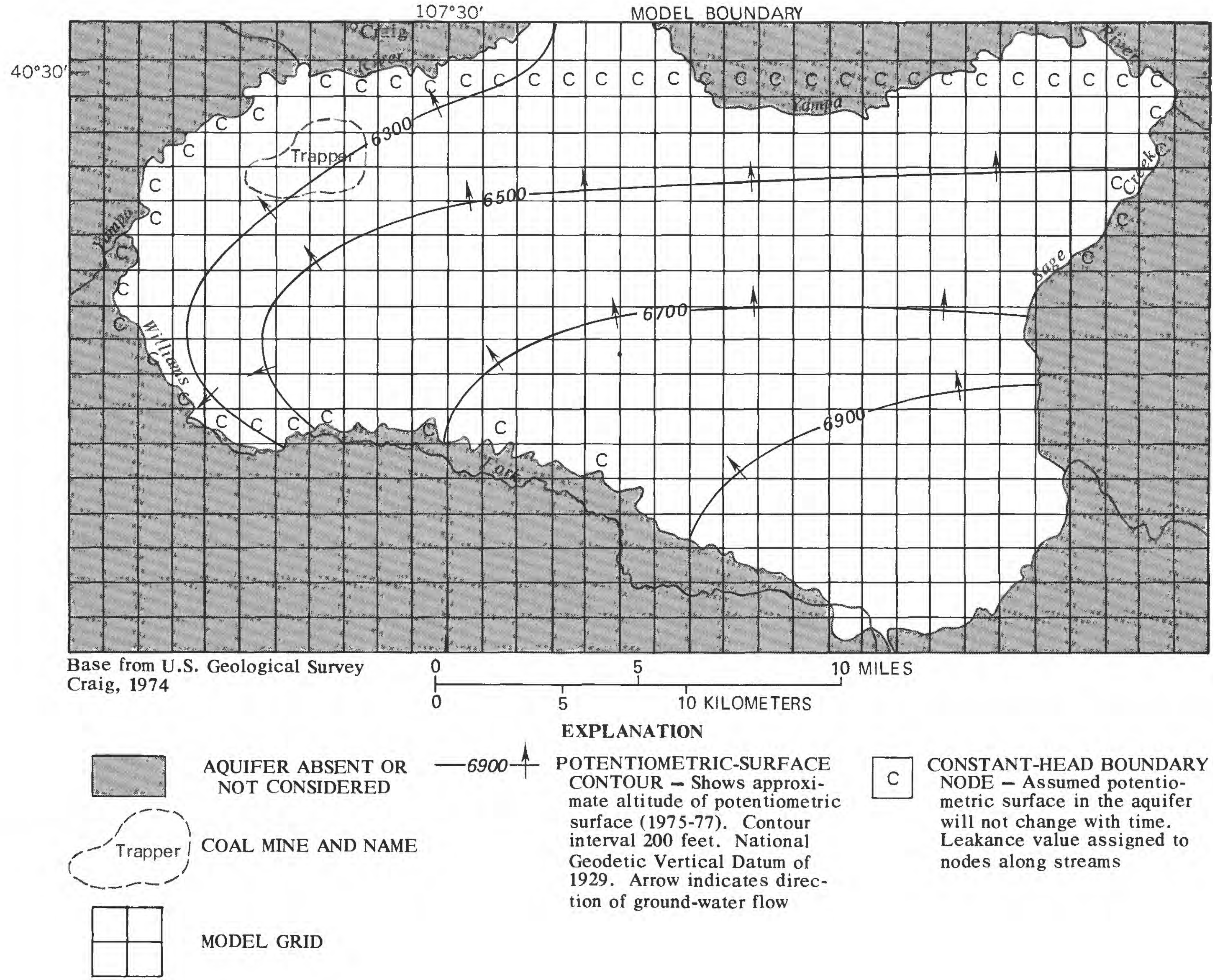


Figure 36.--Model grid, location of constant-head boundary nodes and potentiometric-surface contours for 1975-77, Williams Fork Mountains model area.

Boundary Conditions

The boundary conditions specified in the model were either constant-flux or constant-head conditions. The constant-flux condition most commonly used was a no-flow boundary condition. No-flow boundaries were simulated between the Mesaverde aquifer and the Mancos Shale by using a transmissivity equal to zero at the boundary nodes. Constant-head boundaries, shown in figure 36, were simulated where the model boundary intersected adjacent parts of the Mesaverde aquifer or where the potentiometric surface in the aquifer remained approximately constant. In the Williams Fork Mountains model, constant-head boundary nodes were specified along the intersection of the Mesaverde aquifer with the Yampa River and the Williams Fork. Along these boundaries the potentiometric surface in the aquifer was maintained at approximately the river-stage elevation. A constant-head boundary was specified along the northern edge of the model area where it intersects adjacent parts of the Mesaverde aquifer and along the common boundary between the two model areas. A constant-head boundary condition also was specified in model nodes which contained springs. There were three of these nodes in the model.

Potentiometric Surface

Steady-state ground-water flow conditions were assumed. The 1975-77 potentiometric-surface contours in the model area are shown in figure 36. In general, the direction of water movement follows the general dip of the aquifer and flow is northward in the model area. Minimal ground-water pumpage occurs in most of the model area and the assumption of steady-state ground-water flow conditions is probably valid. However, increased ground-water pumpage has occurred near the town of Craig, which might have some small local effect on the direction and rate of water movement in the vicinity of Craig. The ground-water gradient within the model area is about 68 ft/mi (139 m/km), with a total decrease in the potentiometric surface of about 930 ft (283 m) across the model area.

Recharge Rate

Most ground water occurring in the model area is derived from infiltration of rainfall or snowmelt within the model area. Some ground-water underflow enters from the northeast along the common boundary with the Twentymile Park model. Recharge from infiltration of precipitation was estimated to be the same as for the Twentymile Park model at 1 in. (25 mm) per year and was assumed uniform over the outcrop area of the Mesaverde Group. Total recharge from infiltration of precipitation to the Mesaverde Group within the model area was estimated at 11.4 ft^3/s (0.32 m^3/s). Ground-water discharge out of the model area occurs mainly to the Yampa River and the Williams Fork and as ground-water flow to the north, down dip into the Sand Wash structural basin.

Saturated Thickness and Transmissivity

The saturated thickness and transmissivity of the aquifer are needed for input to the model. The saturated thickness of the Mesaverde aquifer ranges from zero at the contact with the Mancos Shale to a maximum of 800 ft (240 m) where it is overlain by the Lewis Shale (fig. 37). Only the sandstone layers in the Mesaverde Group are included in the saturated thickness. The transmissivity of the aquifer was calculated as the product of the hydraulic conductivity and the saturated thickness. The hydraulic conductivity determined in the model calibration to give the best overall fit was 1 ft/d (0.3 m/d). This value of hydraulic conductivity was considered to be uniform in the model area. Calculated values of transmissivity of the aquifer ranged from 0 to 800 ft^2/d (0 to 74 m^2/d).

Dissolved-Solids Concentration

The initial dissolved-solids concentration in the aquifer was set equal to zero in the model. Thus, concentration values calculated by the model represent increases in concentration values expected above premining values rather than absolute concentration values.

Model Calibration

The same calibration procedure was used in this model as in the Twentymile Park model and involved a comparison of the measured potentiometric-surface altitudes in the Mesaverde aquifer with model-calculated potentiometric-surface altitudes. In addition, measurements of ground-water discharge at springs and gain-loss measurements of ground-water discharge to streams along selected reaches were compared with model-calculated ground-water discharges.

The 1975-77 potentiometric-surface altitudes in the aquifer (fig. 36) show good agreement with model-calculated steady-state potentiometric-surface altitudes (fig. 38). The greatest discrepancy between measured and model-calculated altitudes occurs in the Williams Fork Mountains in the western part of the model area. The ground-water gradients in this area are steep and, because of the large grid size used in the model, a detailed simulation of the aquifer in this area was not possible. The model calculated a quasi-average hydraulic gradient for the ground water in this area. The loss of resolution of the model in this area is thought to be insignificant when compared to the entire modeled area, and the model is thought to simulate actual conditions in the aquifer with an acceptable level of accuracy.

As another calibration check, the model-calculated ground-water discharge rates were compared with measured values. A gain-loss measurement of streamflow along the Williams Fork near its mouth indicated a gain in streamflow of 0.60 ft^3/s (0.017 m^3/s) along this reach. This compares with a model-calculated ground-water discharge rate to the Williams Fork of 0.74 ft^3/s (0.021 m^3/s) (fig. 39) along this reach. A series of springs occurs along the south side of the Williams Fork Mountains. The combined discharge rate of these springs was estimated at 0.25 ft^3/s (0.0071 m^3/s), as compared to a model-calculated spring discharge rate of 0.14 ft^3/s (0.0040 m^3/s) (fig. 39).

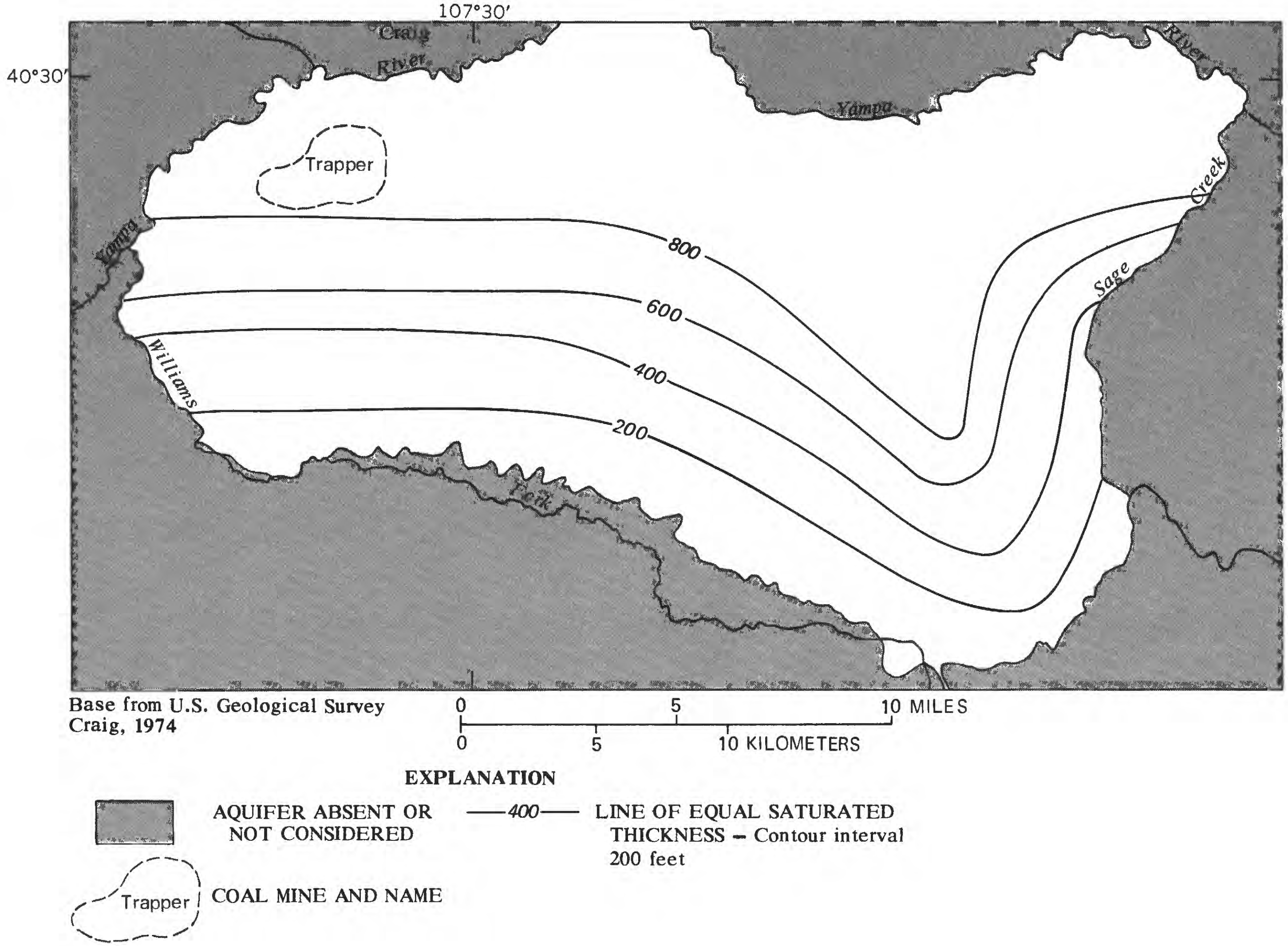


Figure 37.--Saturated thickness of Mesaverde aquifer, Williams Fork Mountains model area.

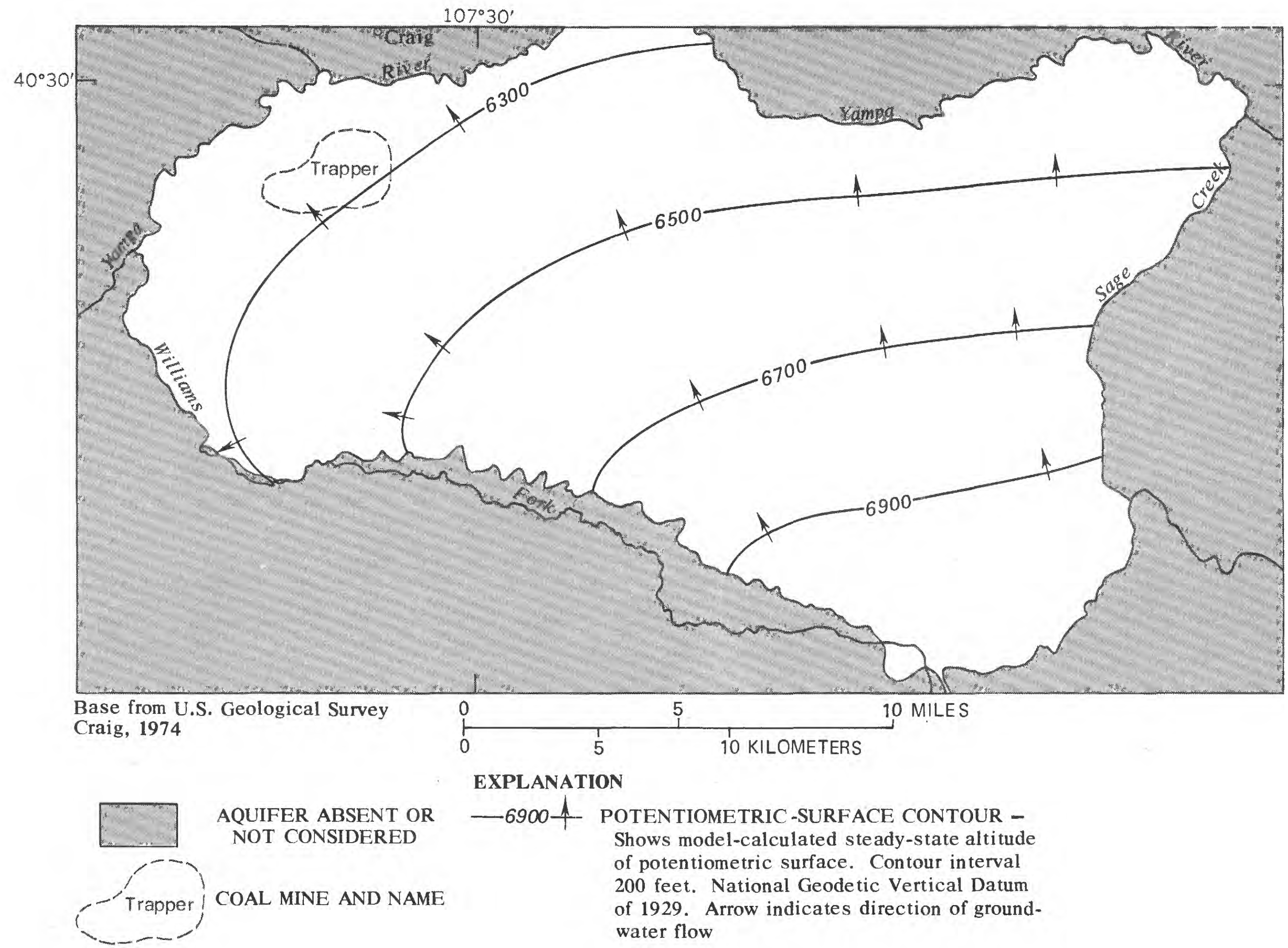


Figure 38.--Model-calculated potentiometric-surface contours, Williams Fork Mountains model.

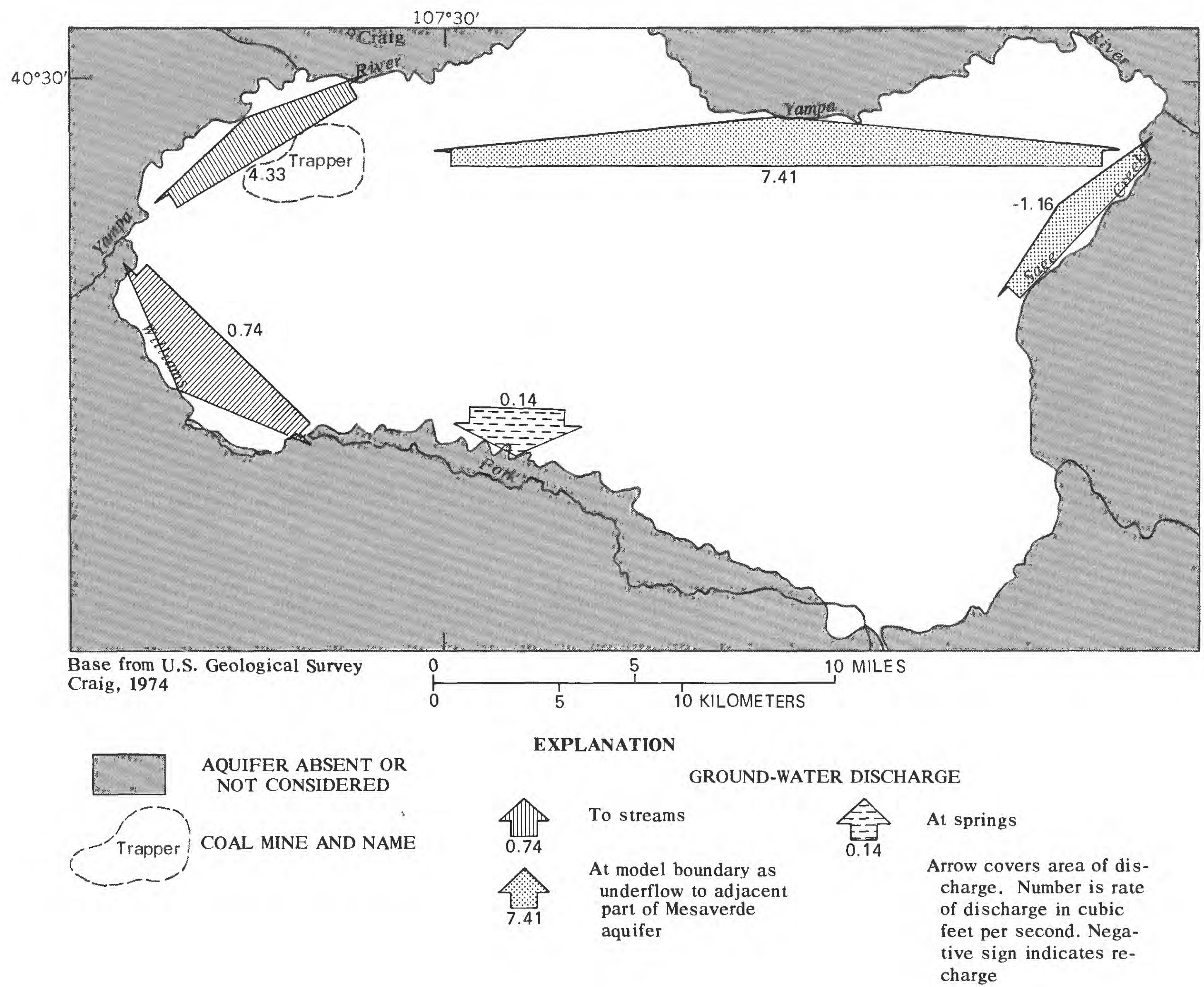


Figure 39.--Mean rates of model-calculated ground-water discharge, Williams Fork Mountains model.

The calibrated model was used to calculate the mean rate of ground-water discharge at other points as well. Ground water discharges directly into the Yampa River in the vicinity of Craig where the river flows over sandstones contained in the Williams Fork and the Iles Formations. This ground-water discharge near Craig was calculated by the model to be about 4.33 ft^3/s (0.123 m^3/s) (fig. 39). Because of the much larger flows in the Yampa River, gain-loss measurements could not be used to check this model calculation.

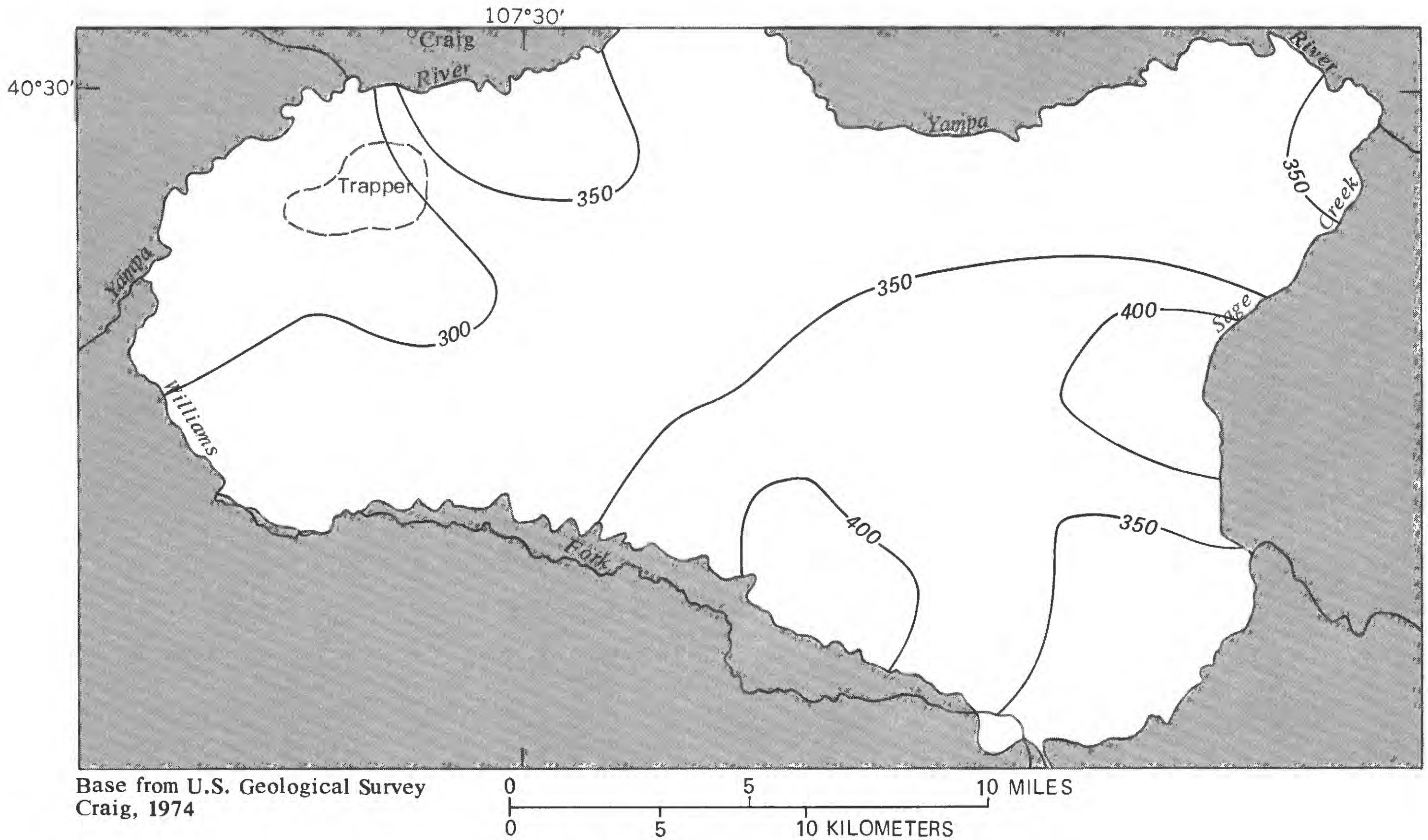
Ground water discharges as underflow to the north out of the model area and down dip into the Sand Wash structural basin. The model-calculated ground-water underflow to the north is about 7.41 ft^3/s (0.210 m^3/s), and model calculations indicate that this ground-water underflow may possibly discharge upward through the Lewis Shale into the Yampa River. A vertical hydraulic conductivity of 0.01 of the horizontal hydraulic conductivity was assigned to the aquifer along the Yampa River east of Craig where the Lewis Shale overlies the Mesaverde Group. The Lewis Shale is about 1,000 ft (305 m) thick along this reach. Model calculations indicated that upward movement of ground water through the Lewis Shale of from 5 to 8 ft^3/s (0.14 to 0.23 m^3/s) was possible along this reach of the Yampa River. Measurements of streamflow in the Yampa River could not be used to check this calculation because of the much greater comparative flows in the river. However, an independent streamflow model of the Yampa River made in another part of the Yampa River basin assessment indicated that ground-water discharges of from 5 to 10 ft^3/s (0.14 to 0.28 m^3/s) could be expected along this reach of the Yampa River (Adams and others, 1982).

The Williams Fork Mountains model calculated ground-water inflow from the Twentymile Park model at about 1.16 ft^3/s (0.033 m^3/s) (fig. 39), which compares with 1.35 ft^3/s (0.038 m^3/s) (fig. 9) outflow to the Williams Fork Mountains model as calculated by the Twentymile Park model. These calculations are sufficiently close to consider the two models to be in fairly good agreement. Part of the difference may be attributed to the differences in resolution of the two models.

The calibrated model was used to calculate the average interstitial ground-water velocities in the model area. The porosity of the aquifer was estimated to be 0.01 and assumed to be constant over the model area. In general, ground-water velocities are small, ranging from about 300 to about 400 ft/yr (90 to 120 m/yr) (fig. 40). Velocities are greatest where the ground-water gradient is the steepest, which occurs in the Williams Fork Mountains in the southern part of the model area. In general, ground-water velocities calculated by this model are similar to those calculated in the Twentymile Park model.

Model Simulation W1--Trapper Mine

Through simulations of projected conditions, the model was used to predict the potential effects of coal-resource development on the ground-water system. Data assumptions and model limitations for the previous Twentymile Park model apply to this model. Within the Williams Fork Mountains model area, the Trapper Mine is the only major coal mine. The effects on the ground-water quality as the result of leachate from the waste-spoil piles and buried bottom and fly ash at this mine were simulated.



Base from U.S. Geological Survey
Craig, 1974

EXPLANATION

AQUIFER ABSENT OR NOT CONSIDERED

Trapper — COAL MINE AND NAME

—350— LINE OF EQUAL GROUND-WATER VELOCITY MAGNITUDE — Average interstitial ground-water velocity magnitude is shown. Interval 50 feet per year

Figure 40.--Model-calculated ground-water velocities, Williams Fork Mountains model.

The results of model simulation W1 predict the effects on ground-water quality from deep infiltration of water that percolates through the waste-spoil piles at the Trapper Mine. Mining at the Trapper Mine, located in the western part of the model area about 4 mi (6 km) south of Craig, started in 1976. Mining is from the upper coal group, which includes coals above the Twentymile Sandstone Member. Production in 1978 was 1.33 million tons (1.21 million t) (Colorado Division of Mines, 1979), about a fourfold increase over 1977 production. The entire production of the mine is being used as fuel for the Craig Powerplant. Fly and bottom ash from the Craig Powerplant are buried at the Trapper Mine.

All of the preceding model and data assumptions used in the calibration procedure apply to this model simulation. For simulation W1, the dissolved-solids concentration of ground water contacting either buried fly and bottom ash or waste-spoil piles at the Trapper Mine was assumed to increase by 5,000 mg/L, resulting in an additional dissolved-solids loading of about 1,320 tons/yr (1,200 t/yr) to the ground-water system.

The effects from infiltration of this degraded water on the ground-water quality after 20 years are shown in figure 41. The degraded ground water would move northwestward from the mine site towards the Yampa River. A plume of degraded ground water occupying an area of about 28 mi^2 (73 km^2) would form around the mine site and would extend about 3 mi (5 km) to the northwest. Degraded ground water would discharge to the Yampa River along an approximate 7-mi (11-km) reach of the river. The dissolved-solids concentration increase of the degraded ground-water discharge to the Yampa River would be less than 200 mg/L and should have no observable effect on the water quality in the Yampa River.

The effect on the ground-water quality after 60 years is shown in figure 42. After 60 years, the plume of degraded ground water would occupy an area of about 40 mi^2 (104 km^2). Degraded ground water would discharge to the Yampa River along an approximate 10-mi (16-km) reach of the river near the town of Craig. The area of ground water with a dissolved-solids concentration increase of more than 200 mg/L would have enlarged to an area of about 12 mi^2 (31 km^2) downgradient from the mine site. The dissolved-solids concentration increase in ground water at the mine site would be about 1,000 mg/L.

The effect on the ground-water quality after 200 years (fig. 43) is nearly identical to that after 60 years. The area of the plume of degraded ground water would still be about 40 mi^2 (104 km^2). The concentration increase of degraded ground-water discharge to the Yampa River would then be greater than 1,000 mg/L; however, because of the much greater comparative flows in the Yampa River, this should have no observable effect on the water quality of the river. Discharge of this degraded ground water to the river-channel deposits along reaches of the river valley may cause a deterioration of water quality in some wells that derive their water supply from the deposits.

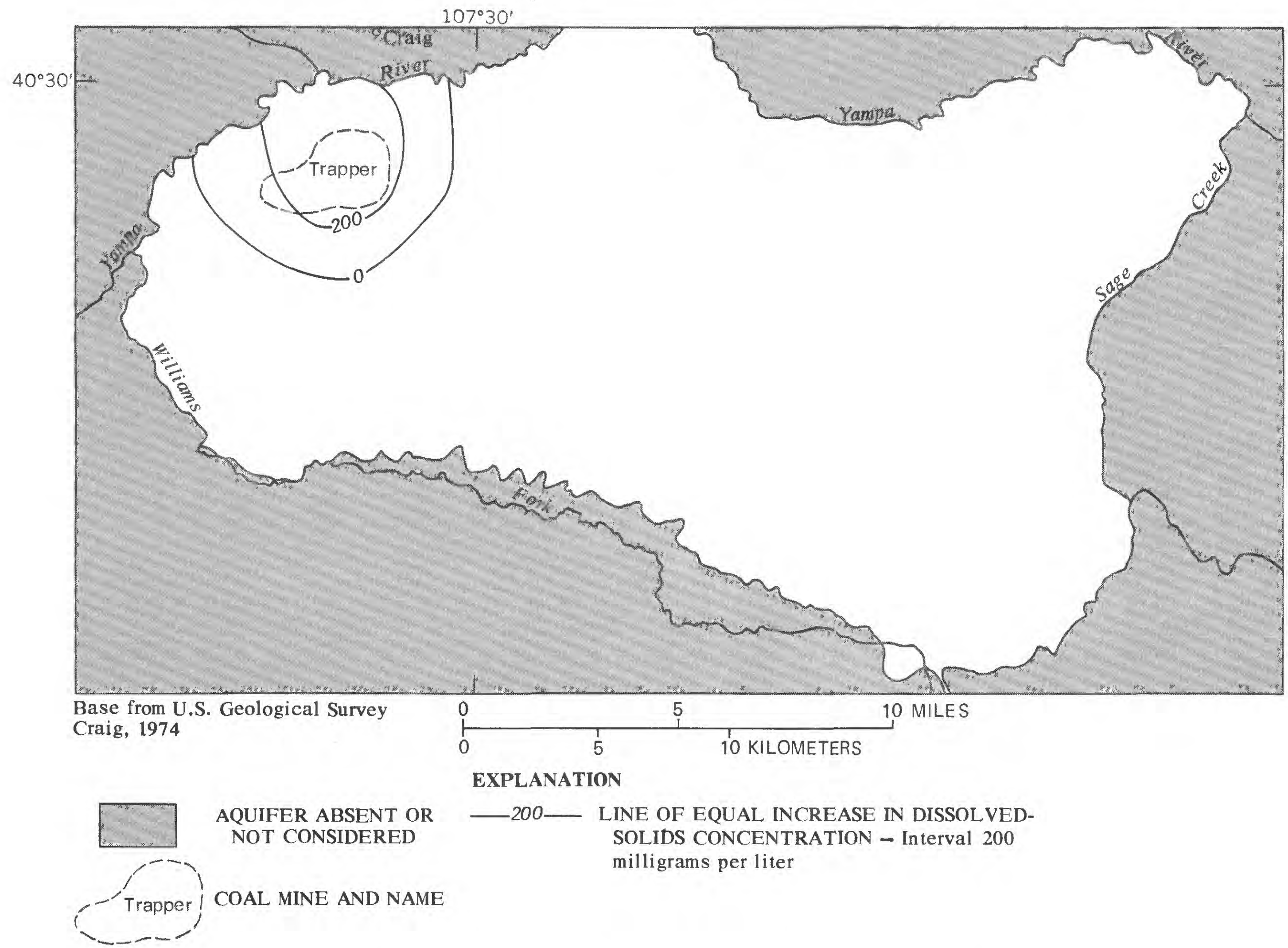
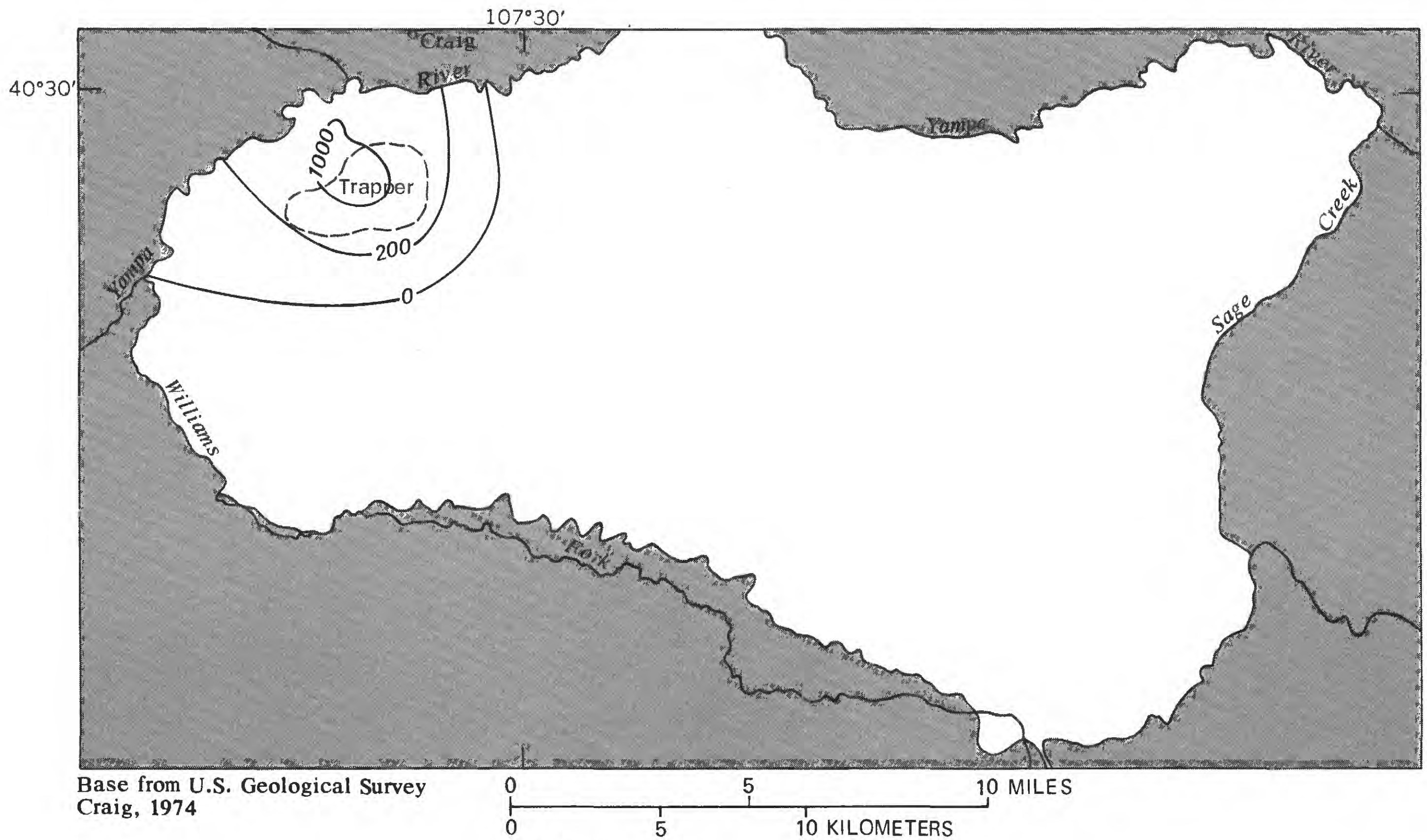


Figure 41.--Predicted increase after 20 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles and buried ash at the Trapper Mine--Model simulation W1.



Base from U.S. Geological Survey
Craig, 1974

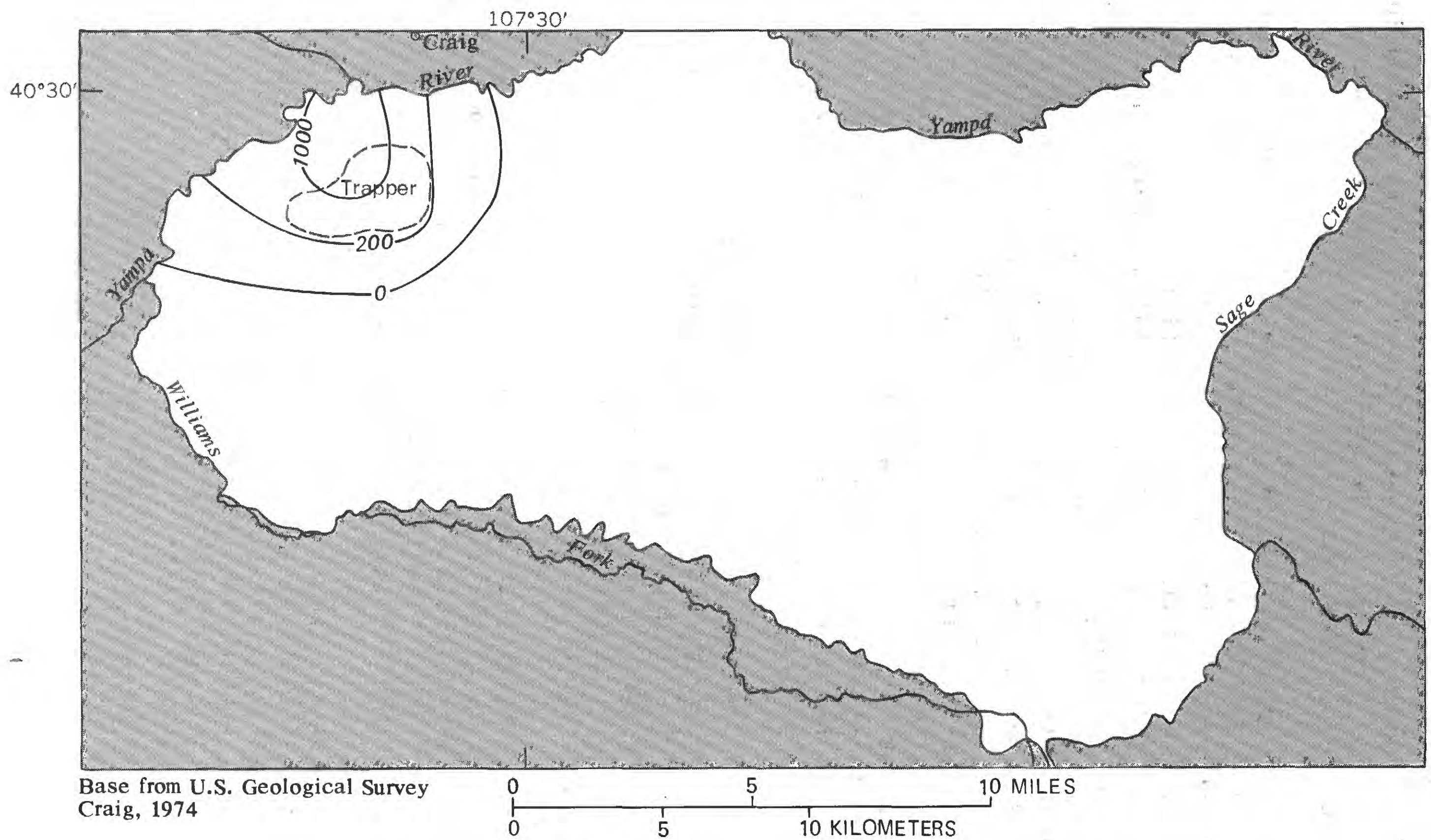
EXPLANATION

AQUIFER ABSENT OR NOT CONSIDERED

—200— LINE OF EQUAL INCREASE IN DISSOLVED-SOLIDS CONCENTRATION – Interval, in milligrams per liter, is variable

Trapper COAL MINE AND NAME

Figure 42.--Predicted increase after 60 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles and buried ash at the Trapper Mine--Model simulation W1.



Base from U.S. Geological Survey
Craig, 1974

EXPLANATION

AQUIFER ABSENT OR NOT CONSIDERED

Trapper COAL MINE AND NAME

—200— LINE OF EQUAL INCREASE IN DISSOLVED-SOLIDS CONCENTRATION – Interval, in milligrams per liter, is variable

Figure 43.--Predicted increase after 200 years in the dissolved-solids concentration of ground water caused by leachate from waste-spoil piles and buried ash at the Trapper Mine--Model simulation W1.

COMPARISON OF THE MODELS

The major difference between the two models is that the Williams Fork Mountains model included the entire Mesaverde Group (both Williams Fork and Iles Formations), whereas, the Twentymile Park model included only the Williams Fork Formation and the Trout Creek Sandstone, which is the uppermost member of the underlying Iles Formation. Another difference was the loss of resolution in the Williams Fork Mountains model as compared to the Twentymile Park model because of the increased grid size required to model the larger area.

Differences in model-input data between the two models were minimal. The hydraulic characteristics of the aquifer as well as other hydrologic data were kept in close agreement in both models. In both models, only the sandstone layers were considered in determining saturated thickness and transmissivity of the aquifer. A hydraulic conductivity of the aquifer of 1 ft/d (0.3 m/d) was determined jointly in the two models to give the best overall fit. This value of hydraulic conductivity was considered to be uniform in the Mesaverde and was used in both models to determine transmissivity as the product of hydraulic conductivity and saturated thickness. Both models assumed steady-state ground-water flow conditions. The recharge rate of 1 in. (25 mm) per year was applied uniformly in both models over the outcrop areas of the Mesaverde. Different boundary conditions were used in the two models, but in both models, constant-head boundaries were used where the model boundaries intersected adjacent parts of the Mesaverde aquifer or along the intersections of the Mesaverde with streams such as the Yampa River and the Williams Fork. Along these boundaries, the potentiometric surface in the aquifer was maintained at approximately the river-stage elevation.

The same calibration procedure was used in both models. Calibration involved a comparison of measured and model-calculated potentiometric-surface altitudes and a comparison of measurements of ground-water discharge rates at springs and ground-water discharge rates to streams with model-calculated rates. The calibration of the two models was conducted jointly, so that calibration data common to both models resulted in an overall "best fit."

Comparison of model-calculated ground-water underflow between the two models indicates fairly good agreement. Along the common boundary, a constant-head specification was used. The potentiometric-surface altitude specified along this boundary was the same in both models. The Twentymile Park model was used to calculate ground-water underflow to the Williams Fork Mountains model area of 1.35 ft^3/s (0.038 m^3/s), compared to 1.16 ft^3/s (0.033 m^3/s) for the same underflow calculated using the Williams Fork Mountains model. Part of this difference is due to a loss of resolution because of the increased grid size required for the larger area of the Williams Fork Mountains model, compared to the Twentymile Park model. The differences between the two models appear to be minor, and the overall similarity of the calibration and model-calculated quantities indicates good agreement between the two models.

SUMMARY AND CONCLUSIONS

Large increases in coal mining currently (1979) taking place in the Yampa River basin are expected to continue during the 1980's and may adversely impact both the ground-water and surface-water quality in the basin. One potential source of adverse impact is the dissolution of soluble minerals contained in overburden material disturbed during the mining. Ground-water degradation is anticipated from deep infiltration of water percolating through the waste-spoil piles at the mines. Digital-transport modeling techniques were used to evaluate the potential effects of this anticipated ground-water degradation.

Two digital models of the Mesaverde aquifer in the Twentymile Park and the Williams Fork Mountains areas were used to simulate the effects of coal development on ground-water movement and chemical quality in these major coal-mining areas. The Mesaverde aquifer was modeled as a single-aquifer system. Steady-state flow conditions in the aquifer also were assumed. The calibration procedure involved a comparison of measured and model-calculated potentiometric-surface altitudes. In addition, measurements of ground-water discharge at springs and gain-loss measurements of ground-water discharge to streams along selected reaches were compared with ground-water discharges calculated by the model. The calibration of the two models was conducted jointly so that calibration data common to both models resulted in an overall "best fit." The data assumptions and model limitations were thought not to be significant and considered not to limit the validity of the model results.

The models were shown to be a valuable technique in the evaluation of the potential hydrologic impacts of coal mining. One of the major contributions of the models was a better understanding of the ground-water flow system in the basin. The calibrated models were used to estimate the recharge and discharge rates for the Mesaverde aquifer. Recharge to the Mesaverde aquifer in the Twentymile Park model area was 6.0 ft^3/s (0.17 m^3/s), and the recharge rate in the Williams Fork Mountains model area was 11.4 ft^3/s (0.32 m^3/s). It was shown that, in general, ground water moves only short distances--less than a few miles--before being discharged at the surface, either at springs or to streams.

In the Twentymile Park model, approximately 77 percent of the flow in the aquifer was discharged at springs or to streams draining the area. The remainder, approximately 23 percent, was discharged as underflow across the common boundary of the two models. In the Williams Fork Mountains model, approximately 35 percent of the flow in the aquifer was discharged at springs or to streams. The remainder, approximately 65 percent, was discharged as underflow to the north out of the model area and down dip into the Sand Wash structural basin. Model calculations indicated that the ground-water underflow to the north may possibly discharge upward through the Lewis Shale into the Yampa River.

The calibrated models also were used to calculate the average interstitial ground-water velocities in the model areas. The porosity of the Mesaverde aquifer was estimated to be 0.01 and assumed constant over the model areas. In general, ground-water velocities are small, ranging from about 200 to 1,000 ft/yr (60 to 300 m/yr).

Through simulations of projected conditions, the models were used to predict the potential impacts on the regional ground-water quality for each major coal strip mine in the model areas. These model simulations indicate the effect that coal mining would have on the regional ground-water system in the Yampa River basin. These results do not eliminate the need for site-specific studies to evaluate the effect coal mining will have on local ground water in individual aquifer units. A general increase in all major ionic constituents in the water is anticipated from infiltration through the waste-spoil piles created by the mining. Data are generally lacking on the magnitude of this anticipated increase. In the models, dissolved-solids concentrations of leachate from the waste-spoil piles of 2,000, 5,000, and 10,000 mg/L were simulated. The models simulated conservative (nonreactive) mass transport.

Almost no data exist to evaluate the ground-water impact of earlier mining in the basin, but the impact was probably small and certainly much less than that caused by present-day (1979) mining activity. The assumption was made that the earlier impact on the ground water was negligible and initial dissolved-solids concentrations of the ground water were assigned a value of zero in the model. Thus, concentration values calculated by the models represent increases in dissolved-solids concentrations above premining values, rather than absolute concentrations.

Assuming a dissolved-solids increase of 5,000 mg/L for leachate from the waste-spoil piles, an additional loading to the ground-water system of 4,500 tons/yr (4,100 t/yr) would occur for all of the mines considered. Increases in dissolved-solids concentrations of as much as 3,000 mg/L in the ground water could be expected at some of the mine sites. Increases in dissolved-solids concentrations of 200 mg/L would be typical within an 0.5- to 1.0-mi (0.8- to 1.6-km) radius of the mine sites. The ground-water degradation would result in an increase in dissolved-solids concentrations of 200 to 400 mg/L in water from springs near some of the mines.

Development of the plumes of degraded ground water created by mining would be slow, because much of the degraded water would be intercepted by nearby streams within only a few miles of the mine sites. This degraded ground-water discharge could cause increases in dissolved-solids concentrations of as much as 900 mg/L at low flow in some of the tributary streams but should not cause any observable change in the water quality of the Yampa River because of the much greater comparative flow. This sequence of events generally will occur during a 20- to 60-year period.

Model simulations using 2,000 and 10,000 mg/L as source concentrations for leachate from the mine waste-spoil piles indicate an approximately linear relationship exists between the increase in the dissolved-solids concentration of the ground water and the dissolved-solids increase assumed for the source concentration. This linear relationship also extends to the resulting change in water quality of streamflow in the model areas. This indicates a relatively sensitive correlation between the assumed dissolved-solids concentration increases of leachate from mine waste-spoil piles used in the model and the predicted impact of coal mining on the environment. The consequence of the differing levels of assumed source concentrations may or may not be significant, depending upon permissible impact levels determined by applicable Federal, State, and local regulations.

Digital ground-water transport modeling provides quantitative answers to the difficult question of what the potential hydrologic impacts of coal mining may be. This study provides insight as to which areas are most severely impacted, where data should be collected, the magnitude of this impact, and the expected timing of this impact. The techniques used in this study may be applied in varying degrees to other areas of surface-mined coal in the Rocky Mountain region.

REFERENCES

Adams, D. B., Bauer, D. P., Dale, R. H., and Steele, T. D., 1982, Reservoir-development impacts on surface-water quantity and quality in the Yampa River basin in Colorado and Wyoming: U.S. Geological Survey Water-Resources Investigations 81-30 [in press].

Bredehoeft, J. D., and Pinder, G.F., 1973, Mass transport in flowing ground water: Water Resources Research, v. 9, no. 1, p. 194-210.

Colorado Division of Mines, 1979, A summary of mineral industry activities in Colorado, 1978: Colorado Department of Natural Resources, Part I, Coal, 46 p.

Konikow, L.F., and Bredehoeft, J. D., 1978, Computer model of two-dimensional solute transport and dispersion in ground water: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 7, Chapter C2, 90 p.

McWhorter, D. B., Skogerboe, R. K., and Skogerboe, G. V., 1975, Water quality control in mine spoils, Upper Colorado River Basin: U.S. Environmental Protection Agency, Technical Series EPA-670/2-75-048, June 1975, 99 p.

Miller, A. E., 1975, Geologic, energy, and mineral resources maps of Routt County, Colorado: Colorado Geological Survey, Map Series 1, scale 1:126,720, 2 pl.

_____1977, Geology of Moffat County, Colorado: Colorado Geological Survey, Map Series 3, scale 1:126,720, 2 pl.

Pinder, G. F., and Bredehoeft, J.D., 1968, Application of the digital computer for aquifer evaluation: Water Resources Research, v. 4, no. 5, p. 1069-1093.

Reddell, D. L., and Sunada, D. K., 1970, Numerical simulation of dispersion in ground-water aquifers: Fort Collins, Colorado State University, Hydrology Paper 41, 79 p.

Steele, T. D., Bauer, D.P., Wentz, D.A., and Warner, J.W., 1976a, An environmental assessment of impacts of coal development on the water resources of the Yampa River basin, Colorado and Wyoming--Phase-I work plan: U.S. Geological Survey Open-File Report 76-367, 17 p.

_____1979, The Yampa River basin, Colorado and Wyoming--A preview to expanded coal-resource development and its impacts on regional water resources: U.S. Geological Survey Water-Resources Investigations 78-126, 133 p.; available from U.S. Department of Commerce, National Technical Information Service, Springfield, VA 22161, as Report PB-300 815.

Steele, T. D., James, I. C., II, Bauer, D. P., and others, 1976b, An environmental assessment of impacts of coal development on the water resources of the Yampa River basin, Colorado and Wyoming--Phase-II work plan: U.S. Geological Survey Open-File Report 76-368, 33 p.

Tweto, Ogden, 1975, Preliminary geologic map of east half of Vernal 1° by 2° quadrangle, Colorado: U.S. Geological Survey Open-File Report 75-588, scale 1:250,000, 8 p., 1 pl.

_____1976, Geologic map of Craig 1° by 2° quadrangle, northwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map MI-972, scale 1:250,000, 1 pl.

VanVoast, W.A., and Hedges, R.B., 1975, Hydrogeologic aspects of existing and proposed strip coal mines near Decker, southeastern Montana: Montana Bureau of Mines and Geology Bulletin 97, 31 p.

Warner, J. W., and Brogden, R. E., 1976, Geohydrological effects of coal-resource development in the Yampa River basin, Colorado and Wyoming [Abs.]: Boulder, Colo., Abstracts with Programs, Geological Society of America, Hydrogeologic Division, Special Symposium on Hydrologic and Engineering Problems Related to Coal Mining, Denver, Colo., p. 1162-1163.

Warner, J. W., Dale, R. H., and Steele, T. D., 1978, Potential effects of coal-resource development on the ground-water resources of the Yampa River basin, Colorado and Wyoming [Abs.]: American Geophysical Union Transactions, Miami Beach, Fla., Symposium on Ground-Water Effects of Power Production Activities, v. 59, no. 4, April 1978, p. 278.

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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