SOLUTE-TRANSPORT SIMULATION

Mathematical models provide a means of simulating processes occuring in hydrologic systems. Models of ground-water flow, for example, can provide information about the water budget, potentiometric surface, and direction of ground-water movement. Solute-transport models commonly incorporate a flow model and thus provide the information typical of a flow model in addition to information about the rate of ground-water movement and the concentration of dissolved chemical constituents. The added simulation capability of a solute-transport model makes it a particularly useful tool for evaluating the effects of mining on the head and water quality in an aquifer.

Selection of a Model Computer Code

Computer programs currently (1988) are available for many different types of solute-transport models that have a wide range of simulation capabilities. Bachmat and others (1980), Science Applications Inc. (1981), and Thomas and others (1982) present evaluations of numerous computer codes for use in ground-water management. Kincaid and others (1982-86) expanded and updated these previous works in order to evaluate the suitability of solute-transport codes for application to subsurface waste-disposal issues associated with coal-fired electric generating plants. Kincaid's work indicated that of the hundreds of codes potentially applicable to such issues, only three were considered suitable for final testing and evaluation. These three codes, available in the public sector, can be used for steady- or transient-state simulations of saturated, single-phase, two-dimensional flow of water through an isothermal, nonhomogeneous, anisotropic porous medium using distributed parameters and varied spatial and temporal boundary conditions. The method of characteristics solute-transport model (Konikow and Bredenhoeft, 1978) code was chosen for use in this study because of: (1) Kincaid's favorable rating of the code with respect to other codes; (2) the extensive history of successful application of the code to real-world solute-transport problems; (3) the continuing support and updating of the code provided by the authors; and (4) the acceptance by the U.S. Geological Survey and the U.S. Environmental Protection Agency of the code as a tool suitable for analysis of ground-water solute-transport problems.

Simulation Procedures

The objectives of the solute-transport modeling in this study are similar to those of the flow modeling in that both models are intended to provide basin-wide evaluations of the geohydrology of the aquifers rather than mine-specific or site-specific evaluations. As a result, solute transport modeling was undertaken using the same grid network used in the flow modeling. This allowed direct incorporation of flow-model data into the solute-transport model without redefining a grid or redigitizing distributed-parameter data. Model evaluation of the water-quality changes in the aquifer can be achieved by simulating the movement of a conservative tracer. Dissolved-solids concentrations commonly are used for this purpose and are better defined by field data in the model area than other chemical constituents.

The use of transient- or steady-flow and transient- or steady-transport simulation procedures are determined in part by the scale of the simulations. In the eastern part of the study area, lateral ground-water velocities range from less than 1 ft/yr to more than 30 ft/yr. Traveltimes for water to move the 2,000-ft distance between node centers of the model grid range from about 10 to 2,000 years. These traveltimes indicate that the solute transport model must compute changes during time periods of at least tens to hundreds of years, rather than short-term changes of a few years, if useful model simulations are to be achieved. Steady-flow, transient-transport simulations are appropriate for such conditions. Simulations of this type are based on the long-term, unvarying flow of ground water. The ground-water velocities produced by the steady flow are used to control the rate and direction of movement of water of differing chemical quality. Thus, the model-computed water quality in the aquifer changes through time (transient transport), even though the heads and rates of flow are invariant (steady flow).

If effects of transient ground-water flow are to be disregarded in the solute-transport model, the water-quality changes produced in the undisturbed aquifer during the transient period must be relatively small. In open-pit -and underground mines, an initial period of transient ground-water flow occurs during the several-year interval when the mine is active and is totally or partly dewatered. During this period, ground-water movement is toward the mine, and any poor quality leachate generated in the mine would be unable to move beyond the pit or workings. Water-quality changes in the undisturbed aquifer during this first period of transient flow likely are negligible.

A second period of transient flow occurs once mining is completed, or when the pit or workings begin to flood. The water levels in the mine or spoils will rise until an equilibrium level is reached with heads in the surrounding undisturbed aquifer. Transient-flow conditions cease once approximate equilibrium conditions are achieved. Poor quality leachate in the mine may begin to move beyond the mine during this transient period if the water level in the mine or spoils exceeds the head in the adjacent undisturbed aquifer. This second period of transient flow is relatively brief. Springs have been observed to develop near the low wall of the open-pit, dip-slope mines within a period of a few months to about 3 years following the completion of nearby mining. Water-quality changes in the undisturbed aquifer resulting from this brief period of transient ground-water flow are likely to be insignificant in comparison to the 10 to 100 years of water-quality changes that will be considered in the solute-transport model. Thus, for most simulations, the effects of transient ground-water flow may be disregarded without introducing serious error.

Multiple single-layer models provide an appropriate means of simulating solute transport. Results from the multilayer flow model indicate that downward components of flow exist across confining layers between the principal aquifers near the margins of the basin; upward components of flow exist across confining layers near the central parts of the basin. Traveltime required to move water from one aquifer to another across the intervening confining layers was shown to be on the order of 1,000 to 200,000 years. If a multilayer solute-transport model of the aquifer system were constructed, it would not indicate movement of poor quality water from one aquifer to another within the simulation time period. Both single-layer and multilayer models will correctly simulate the required lateral movement of contaminant in an aquifer, but a single-layer

model is less complex, more computationally efficient, and is easier to build and operate than a multilayer model. The Twentymile aquifer and the basal Williams Fork aquifer are of principal concern in mine impact analyses. A single-layer solute-transport model of each aquifer was built. Additional information about the design of these models is contained in the "Supplemental Information" section at the back of this report.

Model Calibration

Large-scale solute-transport models require large-scale historical changes in ground-water quality for use in model calibration. Movement of poor quality water from spoils in several open-pit mines apparently has caused the degradation of ground-water quality at numerous observation wells completed in the basal Williams Fork aquifer. However, virtually all of these wells are located within 1,000 ft of the spoils, a distance too small to provide useful data for calibration of a 2,000-ft grid-interval model. This limited historical movement precludes transport calibration of the solute-transport model. Thus, steady-flow, transient-transport simulations to be made with the model are based on a calibrated steady-state flow model and an uncalibrated transport model.

Transport calibration primarily enables adjustment of model dispersivity and porosity to values that are compatible with other model parameters so that the model-calculated changes in concentration will agree with observed changes in concentration. Dispersivity primarily affects the amount of dispersion, or spreading out, of a zone of poor quality water caused by nonuniform ground-water velocities in the aquifer. Porosity primarily affects the rate of movement of a degraded zone caused by the average ground-water veolocities in the aquifer. Even in fully calibrated models, some uncertainty exists as to the best value for any particular model parameter. The best values for dispersivity and porosity are more uncertain because of the lack of transport calibration. Sensitivity analysis provides a means of determining the relative importance of a parameter value. If the model results are little affected by a large change in a parameter value, the model is said to be insensitive to that parameter. Conversely, if the model results change markedly in response to a small change in a parameter, the model is sensitive to the parameter.

Sensitivity Analyses

The solute-transport model of the basal Williams Fork aquifer was used to simulate contaminant movement by using a range of values for dispersivity and porosity. Concentration profiles calculated by the model at the end of 100-year simulations of contaminant migration away from areas of degraded water quality in spoil aquifers at the Edna mine are shown in figures 45 and 46. Effects of varying transverse and longitudinal dispersivity are shown to produce minimal changes in the concentration profiles (fig. 45, graphs A and B). Porosity values that range from 5 to 15 percent are shown to produce more substantial changes in the concentration profile (fig. 45, graph C). The results of the sensitivity analyses indicate that the model-calculated dissolved-solids concentrations are relatively insensitive to dispersivity but more sensitive to porosity.

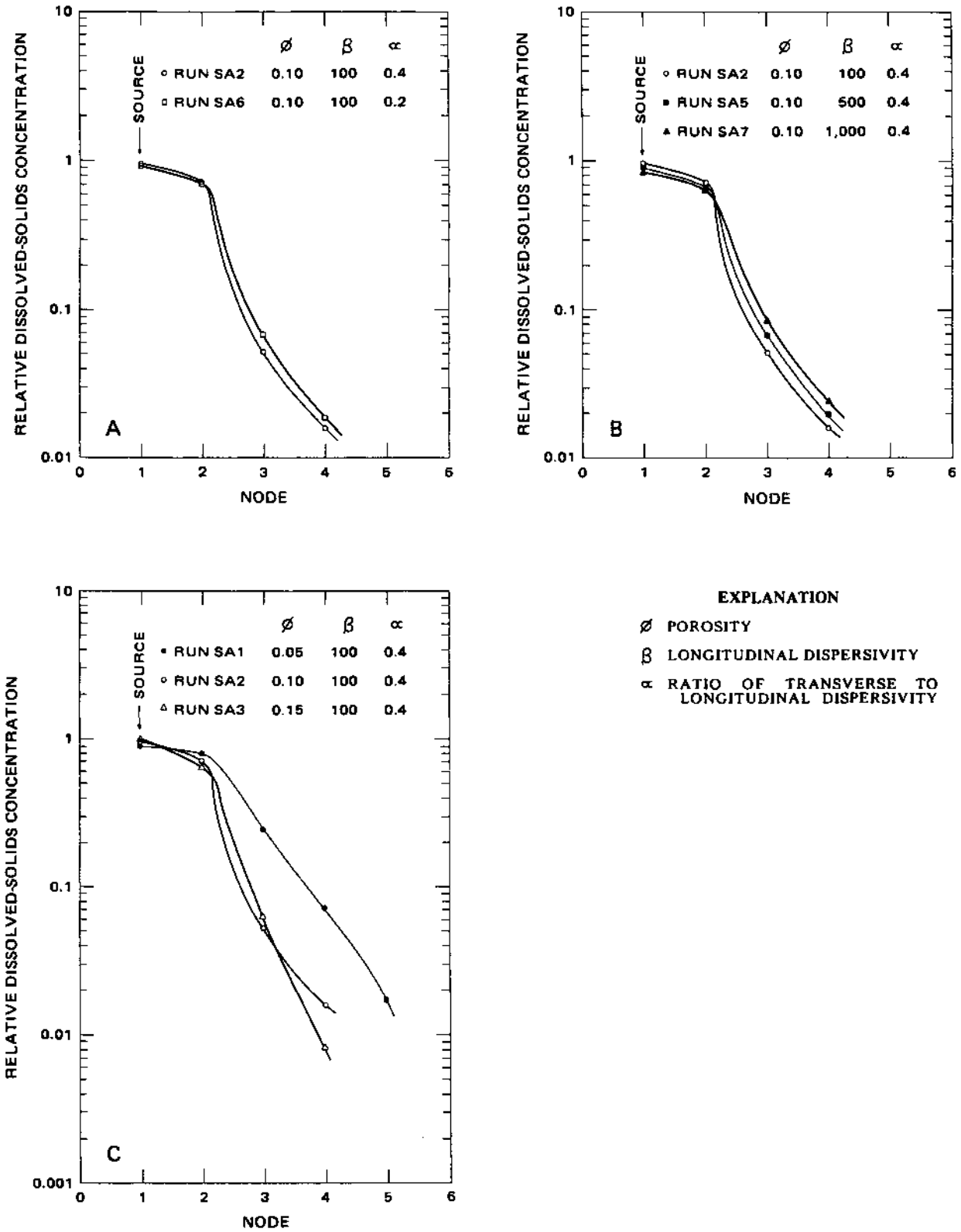


Figure 45.--Sensivity of model-calculated concentration profiles to changes in model parameters.

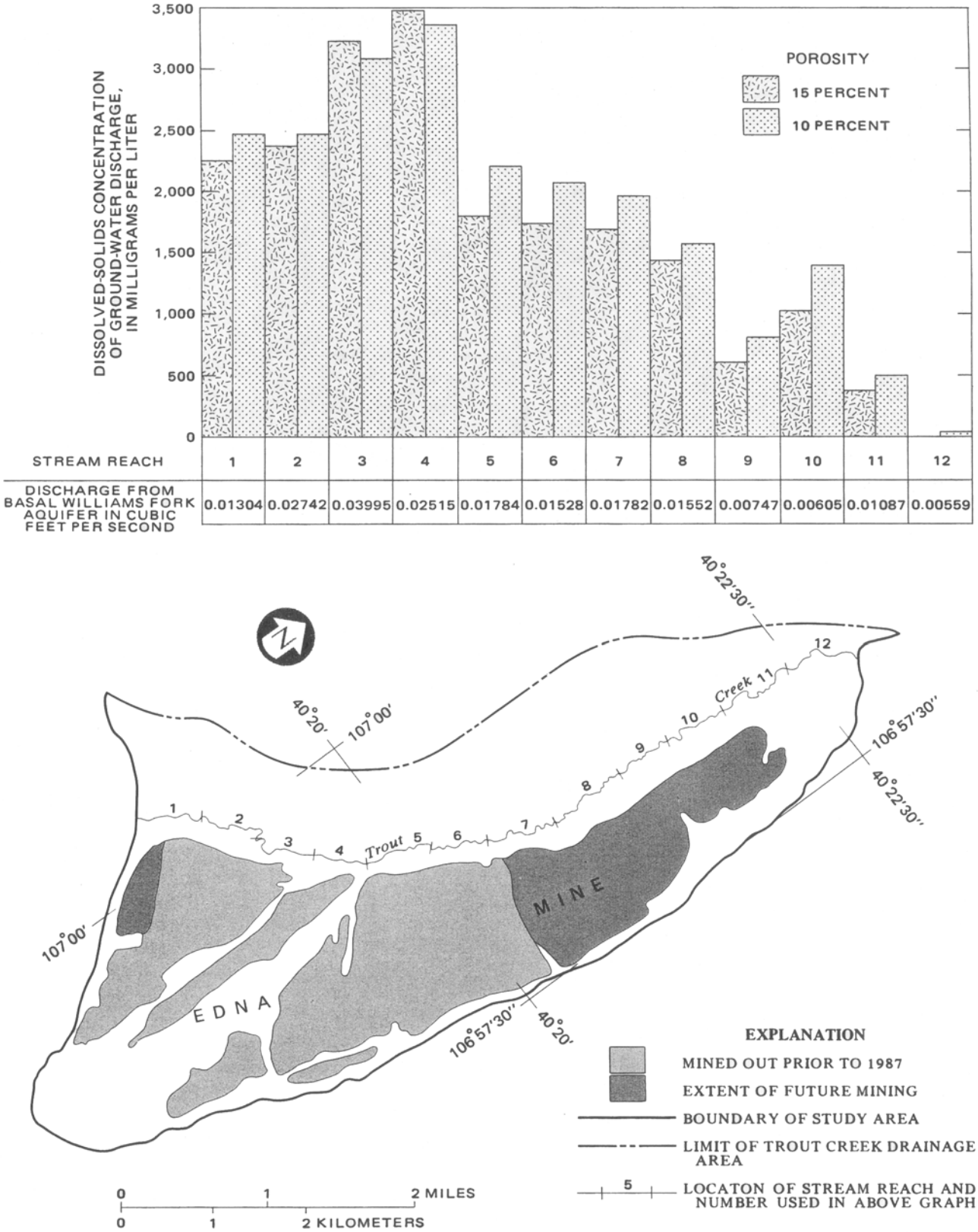


Figure 46.--Changes in simulated concentration of ground-water discharge to Trout Creek.

The dispersivity of the uniform, fine-grained sandstone in the study area likely is less than the dispersivity measured in alluvial aquifers (generally 50 to about 200 ft), which commonly consist of heterogeneous mixtures or interbedded layers of gravel, sand, silt, and clay. This sensitivity analysis (fig. 45) and similar sensitivity analyses of solute-transport models of alluvial aquifers (Robson, 1974) indicate that model results are relatively insensitive to dispersivity values that are much smaller than the dimensions of the model grid. Although the dispersivity of the aquifer in this study likely is smaller than 200 ft, a value of 200 ft was used in the model in order to avoid underestimation of the rate of dispersion in the aquifer. Numerical dispersion produced by the mathematical approximations used in the computer code also is present in model results. The two forms of dispersion likely have only a small effect on model results but would tend to make the model slightly overestimate the rate of contaminant movement rather than underestimate the rate of contaminant movement.

Model simulations that use 10 and 15 percent porosity span the 14-percent mean porosity of the basal Williams Fork aquifer indicated by laboratory analysis of rock samples (table 7). The use of either 10 or 15 percent porosity in the model produces changes in the calculated concentration distribution and also affects the concentration of ground-water discharge to streams. Dissolved-solids concentration of ground water discharging to Trout Creek generally increases in response to the larger ground-water velocities produced by smaller porosity, as shown in figure 46. In the southeastern part of the model area, a 33-percent decrease in porosity (a change in model porosity from 15 to 10 percent) causes an approximately 13-percent increase in the dissolved-solids concentration of ground-water discharge to Trout Creek. If porosity is known within an uncertainty of ±20 percent, then the concentration of ground-water discharge to Trout Creek and possibly other streams in the area will have an uncertainty due to porosity of about ±10 percent.

Previous discussion of the effects of secondary permeability and porosity indicated that fracturing in the aquifer could not be shown to have produced a statistically significant change in hydraulic conductivity of fractured versus unfractured samples. It is unlikely that a significant increase in secondary porosity caused by fracturing could occur without a corresponding and much larger increase in hydraulic conductivity. However, no data were available to make a comparison of the porosity of fractured and unfractured rocks. The sensitivity analyses provide one means of indicating how changes in porosity caused by fracturing could affect the solute-transport simulations. If the porosity of fractured rock is assumed to be about 20 percent larger than that of unfractured rock (17 percent compared with 14 percent porosity) lateral ground-water velocity will decrease by about 17 percent and the dissolved-solids concentration of ground-water discharge to Trout Creek (for example) will be about 10 percent less than that indicated in subsequent simulations.

The model sensitivity to changes in porosity primarily occurs as the result of changes in ground-water velocity. Identical changes in ground-water velocity and model response can be produced by changes in hydraulic conductivity. (However, changes in hydraulic conductivity will cause changes in the water budget.) For example, a 17-percent decrease in lateral ground-water velocity can be produced by a 20-percent increase in porosity or a 17-percent decrease in

hydraulic conductivity. Thus, the sensitivity of the model to changes in porosity also provides information on the sensitivity of the model to changes in hydraulic conductivity.

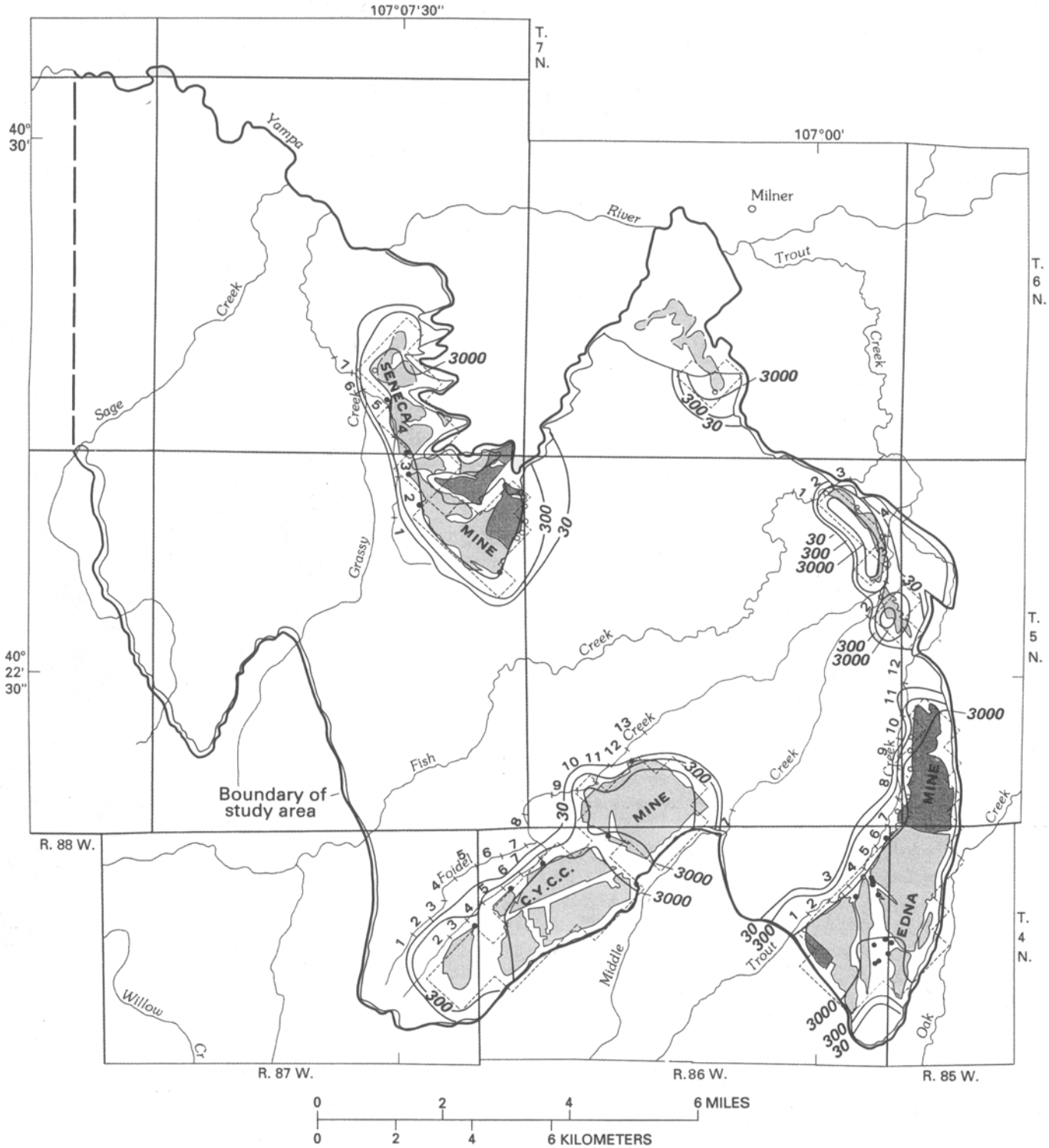
Model Simulations

Three sets of simulations were made using the solute-transport models of the basal Williams Fork and Twentymile aquifers. Set I simulated the effects on the basal Williams Fork aquifer of movement of poor quality water from spoil aquifers at inactive open-pit mines in the lower member of the Williams Fork Formation. Set II simulated the effects on the Twentymile aquifer of migration of poor quality water from spoil aquifers at inactive open-pit mines in the upper member of the Williams Fork Formation. Set III simulated the effects on the basal Williams Fork aquifer of migration of poor quality water from an inactive underground mine in the lower member of the Williams Fork Formation.

Flow of poor quality water from spoil aquifers in mined-out areas of open-pit, dip-slope mines was investigated by use of the first two sets of model simulations. For these simulations, the extent of the spoil aquifers was assumed to include both the present mined-out areas and the areas proposed for future open-pit mining. It also was assumed that heads in the spoil aquifers at the downdip contact with the basal Williams Fork or Twentymile aquifers would be controlled by the altitude of springs that have developed, or likely will develop, along the downdip edge of the spoils. The location (fig. 47) and altitude of these springs was used to determine the head relation between the spoil aquifer and the bedrock aquifers. In some areas, the head in the spoil aquifer was shown to be higher than the head in the adjacent basal Williams Fork or Twentymile aquifer, and poor quality water in the spoil aquifer could move directly into the adjacent bedrock aquifers. In other areas, heads in the spoil aquifers were shown to be lower than the heads in the adjacent bedrock aquifers, and water movement from the spoil to the bedrock would not occur in the local area.

A 30-year simulation period was assumed to begin at the close of open-pit mining in the local area. Mine plans submitted to State reglatory agencies by the local coal companies indicate that all future open-pit mining in the area will be complete prior to 1998. Any transient water-level or water-quality conditions in the aquifers prior to the close of mining are assumed to be negligible, as discussed previously in the "Simulation Procedures " section.

The dissolved-solids concentration of water in the spoil aquifers was assumed to remain constant at 4,500 mg/L. This concentration represents a "worst case"—that is, the largest concentration that Colorado State regulatory agencies assumed could conceivably occur (for purposes of this study) in the spoils during the simulation periods. It further was assumed that the 4,500-mg/L concentration in the spoils represents a 3,500-mg/L increase over the background concentration in the basal Williams Fork and Twentymile aquifers.



EXPLANATION

SOURCE OF POOR QUALITY WATER IN SPOIL AQUIFERS

Open-pit mining completed prior to 1987 in the lower member of the Williams Fork Formation. Boundary dashed where location is approximate

Proposed area of future open-pit mine in the lower member of the Williams Fork Formation

BOUNDARY OF SIMULATED MINE

BOUNDARY OF MODELED PART OF BASAL WILLIAMS FORK AQUIFER

STREAM REACH AND NUMBER

300 LINE OF EQUAL INCREASE IN DISSOLVED-SOLIDS CONCENTRATION IN THE BASAL WILLIAMS FORK AQUIFER—Interval, in milligrams per liter, is variable

SPRING ASSOCIATED WITH DISCHARGE FROM SPOIL AQUIFER

PROBABLE LOCATION OF FUTURE, OR PRESENTLY CONCEALED, DISCHARGE FROM SPOIL AQUIFER

Figure 47.--Simulated changes in dissolved-solids concentrations near open-pit mines after 30 years of solute movement.

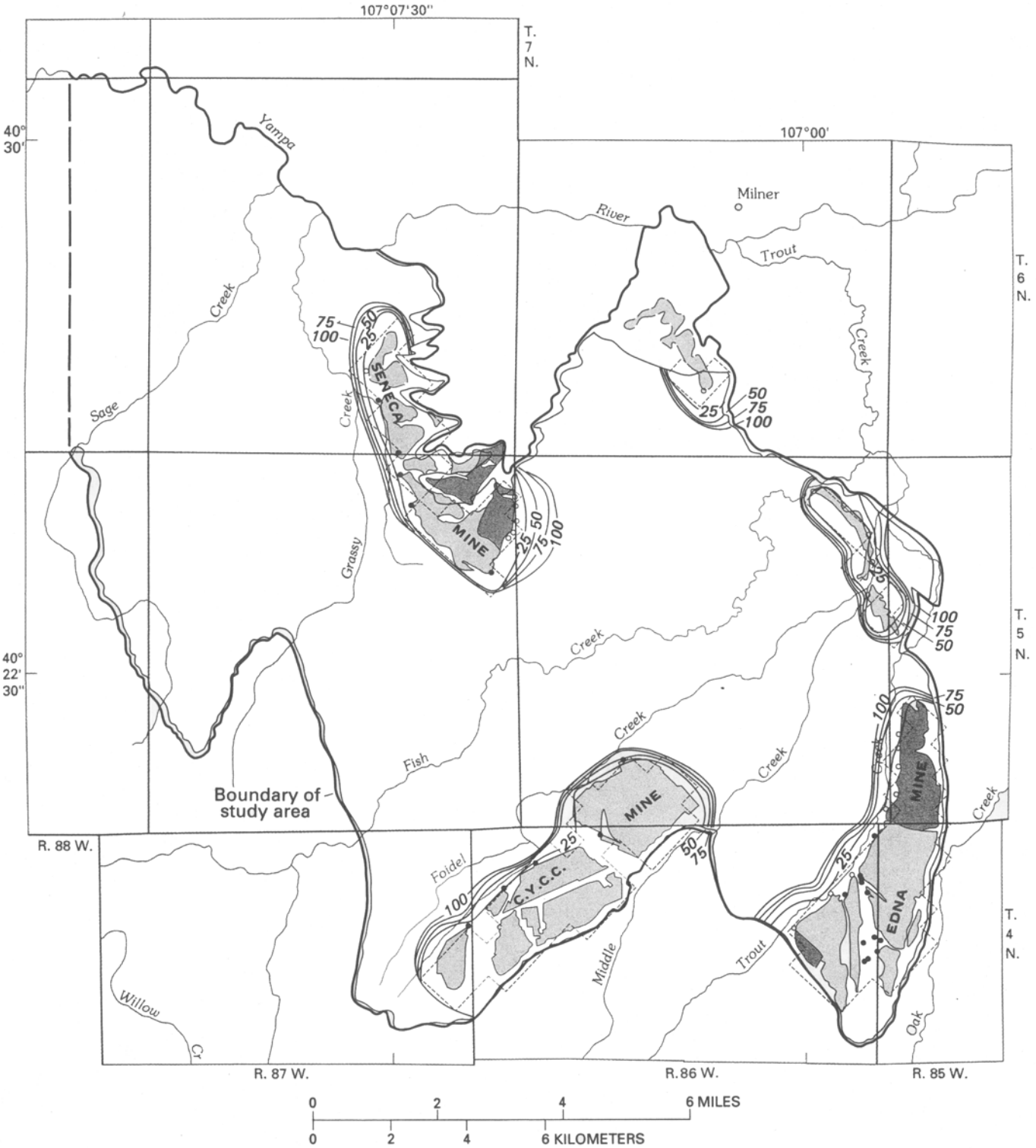
Simulations of the basal Williams Fork aquifer are based on a porosity of 14 percent, longitudinal dispersivity of 200 ft, and a transverse to longitudinal dispersivity ratio of 0.4. Simulations of the Twentymile aquifer are based on a porosity of 20 percent, longitudinal dispersivity of 200 ft, and a transverse to longitudinal dispersivity ratio of 0.4.

Simulation Set I

The increase in dissolved-solids concentration in the basal Williams Fork aquifer caused by 30 years of inflow of poor quality water from spoil aquifers in the lower member of the Williams Fork Formation is shown in figure 47. The spoil water is shown to cause an increase in concentration in the basal Williams Fork aquifer ranging from more than 3,000 mg/L near the spoil aquifer-bedrock aquifer interface, to less than 30-mg/L increase at distances generally less than 0.5 mi from the spoil aquifer. The limited movement of the degraded ground water in the 30-year simulation period primarily is the result of small rates of lateral ground-water movement in the basal Williams Fork aquifer. Simulations of up to 100 years of movement indicate a similar small rate of ground-water movement (fig. 48). In some areas, the movement of the degraded water is restricted further by the proximity of a spoil aquifer to a stream valley. Ground-water discharge to the stream valley may intercept all or part of the degraded water that moves toward the valley, thereby restricting, or terminating, the lateral movement of the degraded water in the aquifer.

Degraded water discharging from the aquifer in stream valleys also can affect the quality of surface flow in the stream. The three largest mines in the model area have the largest effect on the quality of the ground-water discharge. About 0.2 ft^3/s of simulated discharge to Trout Creek undergoes a 1,785-mg/L increase in dissolved-solids concentrations downgradient from the Edna Mine (table 11). The CYCC Mine produces a l,54l-mg/L increase in 0.35 ft^3/s of simulated discharge to Foidel Creek, and the Seneca Mine produces a 2,639-mg/L increase in 0.24 ft^3/s of discharge to Grassy Creek. Changes in streamflow quality produced by the simulated rates of ground-water discharge likely will not be significant because much larger rates of flow from spoil-aquifer springs directly enter the streams, or the stream-valley alluvium, and provide a means for much more rapid and direct change in the chemical quality of the streamflow. In Trout Creek, the 0.2 ft^3/s of simulated ground-water discharge will be greatly diluted by the 10 to 20 ft^3/s of measured base flow in the stream.

Near the southwestern ends of the CYCC and Edna Mines, ground water near the spoil aquifers (figs. 47 and 48) has been diluted by simulated inflow of small dissolved-solids concentration water from parts of the basal Williams Fork aquifer located upgradient of the spoil aquifer. Near the smaller mines in the northeastern part of the area, the concentration changes shown by the model (figs. 47 and 48) do not correspond well to the shape of the spoil aquifer due to the limited resolution of the 2,000-ft grid interval model.



EXPLANATION

SOURCE OF POOR QUALITY WATER IN SPOIL AQUIFERS

Open-pit mining completed prior to 1987 in the lower member of the Williams Fork Formation. Boundary dashed where location is approximate

Proposed area of future open-pit mine in the lower member of the Williams Fork Formation

BOUNDARY OF SIMULATED MINE

BOUNDARY OF MODELED PART OF BASAL WILLIAMS FORK AQUIFER

—100— LINE OF 500 MILLIGRAMS PER LITER DISSOLVED-SOLIDS CONCENTRATION IN THE BASAL WILLIAMS FORK AQUIFER—Time interval 25 years

• SPRING ASSOCIATED WITH DISCHARGE FROM SPOIL AQUIFER

○ PROBABLE LOCATION OF FUTURE, OR PRESENTLY CONCEALED, DISCHARGE FROM SPOIL AQUIFER

Figure 48.--Extent of movement of poor quality water away from open-pit mines during a 100-year simulation period.

Table 11.--*Increase in dissolved-solids concentration of ground-water discharge to streams produced by model simulation set I*

[ft^3/s, cubic feet per second; mg/L, milligrams per liter]

Reach (fig. 47)	Affected ground-water discharge to creek (ft^3/s)	Increase in dissolved-solids concentration in ground-water discharge due to effects of spoil aquifers (mg/L)
	Trout Creek	
1	0.0130	844
2	0.0274	1,892
3	0.0400	3,395
4	0.0252	3,477
5	0.0178	741
6	0.0153	1,034
7	0.0178	770
8	0.0155	1,069
9	0.0075	29
10	0.0061	423
11	0.0109	193
Total discharge	0.1965	
		Discharge-weighted mean concentration = 1,785
	Grassy Creek	
1	0.0149	3,428
2	0.0060	57
3	0.0813	2,432
4	0.0468	3,477
5	0.0133	604
6	0.0667	3,106
7	0.0086	1
Total discharge	0.2376	
		Discharge-weighted mean concentration = 2,639
	Foidel Creek	
1	0.0206	7
2	0.0390	414
3	0.0447	904
4	0.0237	161
5	0.0180	340

Table 11.--*Increase in dissolved-solids concentration of ground-water discharge to streams produced by model simulation set I*--Continued

Reach (fig. 47)	Affected ground-water discharge to creek (ft^3/s)	Increase in dissolved-solids concentration in ground-water discharge due to effects of spoil aquifers (mg/L)
	Foidel Creek --Continued	
6	0.0195	2,105
7	0.0400	2,557
8	0.0543	2,592
9	0.0036	275
10	0.0366	3,425
11	0.0110	434
12	0.0253	2,060
13	0.0102	1
Total discharge	0.1092	
		Discharge-weighted mean concentration = 1,541
	Middle Creek	
1	0.0771	12
2	0.0102	2,280
3	0.0149	56
4	0.0070	29
Total discharge	0.0192	
		Discharge-weighted mean concentration = 231
	Fish Creek	
1	0.0049	4
2	0.0282	25
3	0.0088	54
Total discharge	0.0419	
		Discharge-weighted mean concentration = 29

Simulation Set II

The change in dissolved-solids concentrations in the Twentymile aquifer caused by poor quality water in spoils in the upper member of the Williams Fork Formation was examined in this set of simulations. The only local mines that worked coal seams in this unit were located between Fish Creek and Foidel Creek in the west-central part of Twentymile Park. Heads in the

spoil aquifers again were estimated as the basis of the altitudes of springs at the downdip edge of the spoil aquifers. The altitude of these springs and the resulting estimated heads in the spoil aquifers were determined to be critical to the model simulations because heads in the Twentymile aquifer are at or above land surface in most of the area Of the spoils. In all but the southeasternmost part of the spoils, the spoil-aquifer heads were 0 to 130 ft below heads in the Twentymile aquifer. This head relation would prevent any significant movement of poor quality water from the spoil aquifer into the bedrock aquifer; model simulations were similar, indicating minimal effect of these spoil aquifers on the Twentymile aquifer.

If the head relation had allowed migration of poor quality water, the effect on the Twentymile aquifer still likely would have been small because Fish Creek valley is the local ground-water discharge area for the aquifer and would have intercepted almost all of the degraded water entering the Twenty-mile aquifer. Under existing conditions, the spoil aquifers discharge at springs and seeps, or by underflow into the alluvium, and contribute dissolved solids to the streamflow more directly than would be possible by means of flow through the bedrock aquifer. The quantity of direct discharge to Fish Creek is not known but likely is small in comparison to the 1 to 5 ft^3/s of base flow normally present in this reach of Fish Creek.

Simulation Set III

This set of simulations was designed to investigate the changes in ground-water quality in the basal Williams Fork aquifer caused by movement of poor quality water away from an inactive and flooded underground mine located in the central part of Twentymile Park. Mine development plans submitted by the coal company indicate that mining would be completed by 2017. Mine flooding probably would continue for several years after the workings were abandoned. A steady-flow, transient-transport simulation was used to investigate 30 years of movement of poor quality water away from workings flooded to the same level of head as had existed in the aquifer prior to mining. A transient-flow, transient-transport simulation was used to investigate 30 years of movement from workings flooded to the level of the average premining head at the margin of the mined area. The former conditions are more representative of a mined-out area that has hydraulic conductivity similar to that of the original premined materials, such as might occur following the collapse of the workings. The latter conditions are more representative of a 'mined-out area that has an extremely large hydraulic conductivity due to water flow through uncollapsed mine workings. The principal hydrologic difference between these two conditions is that in the first example head gradients at the boundary of the mined area are identical to the premining gradients, whereas head gradients in the second example generally are larger because of the assumption of a uniform average head throughout the mine.

The water-quality results of the steady-flow, transient-transport simulation (fig. 49) are not markedly different from the results of the transient-flow, transient-transport simulations (fig. 50). This indicates that the rate of lateral movement of degraded water away from the inactive underground mine will not be seriously affected by the collapsed or uncollapsed condition of

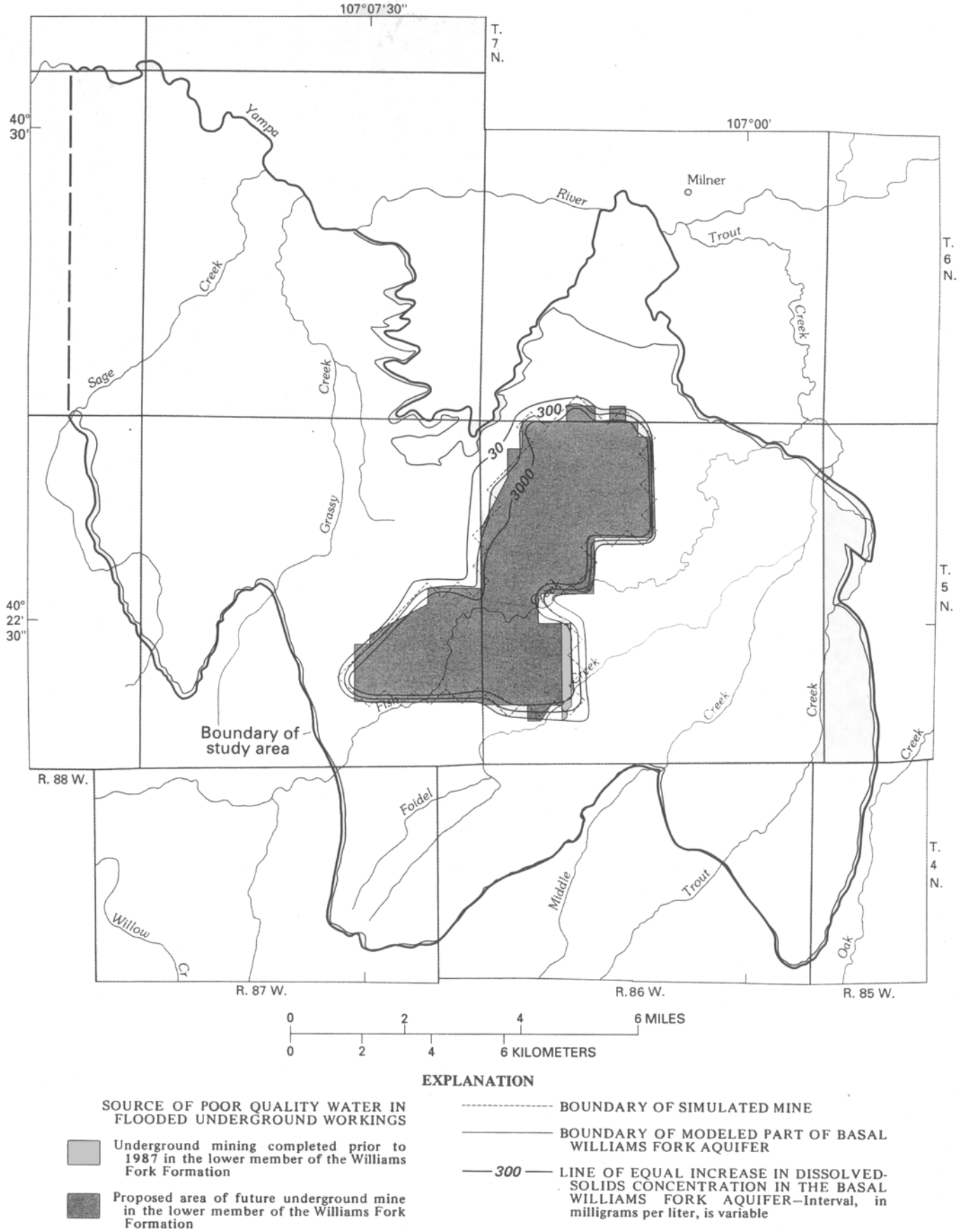


Figure 49.--Thirty-year simulated change in dissolved-solids concentrations near an underground mine using steady-flow, transient-transport conditions.

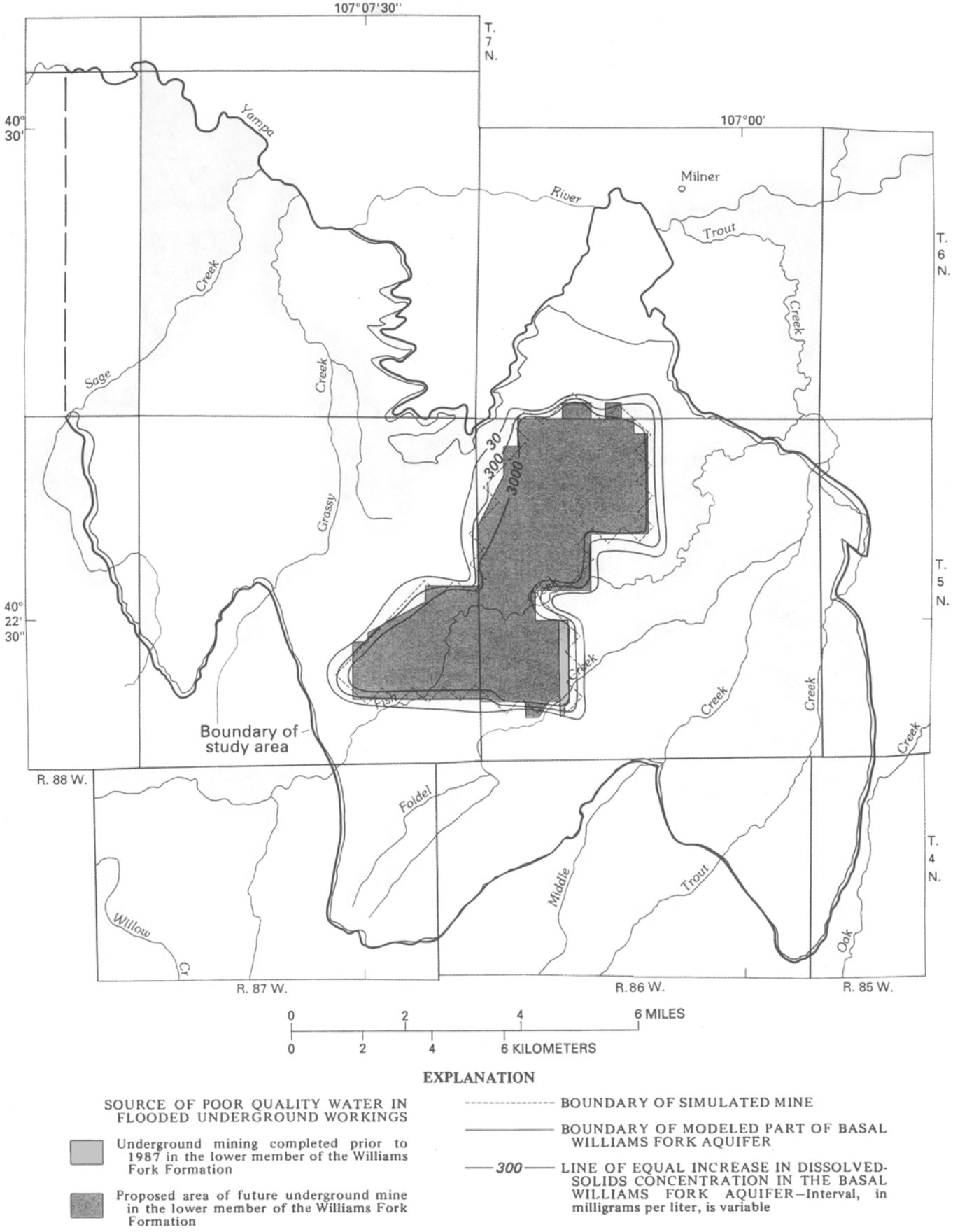


Figure 50.--Thirty-year simulated change in dissolved-solids concentrations near an underground mine using transient-flow, transient-transport conditions.

the mine workings. As in previous simulations, the relatively small movement of the degraded water during the simulation period is due to the small ground-water velocities in the aquifer. The model-simulated effects of hydrodynamic mixing (dispersion) cause simulated changes in concentration upgradient and downgradient from the mine.

SUMMARY AND CONCLUSIONS

The bedrock geohydrologic system in the upper part of the Mesaverde group of northwestern Colorado consists of two regional aquifers separated by three principal confining layers. The confining layers, consisting primarily of marine shale, underlie the Trout Creek Sandstone Member of the Iles Formation (the deepest regional), separate the Trout Creel Member from the younger Twentymile Sandstine Member of the Williams Fork Formation (the second regional aquifer), and overlie the Twentymile Sandstone Member. Numerous aquifers of local extent are present in sandstone beds and coal seams of the middle confining layer in dandier lithology of the western part of the study area. In the eastern part of the study area, the only local aquifer (the basal Williams Fork aquifer) consists of sandstone and coal within the basal part of the Williams Fork Formation.

The basal Williams Fork aquifer has greater water-yielding potential that either of the two regional aquifers in the eastern area. Sandstones in the Trout Creek and Twentymile aquifers are similar in appearance, composition, grain size, sorting, and thickness (about 10 to 150 ft) but differ in average hydraulic conductivity; the hydraulic conductivity of the Trout Creek aquifer is about one-third that of the Twentymile aquifer. The basal Williams Fork aquifer generally contains more sandstone (100 to 200 ft) and has an average hydraulic conductivity about eight times larger than that of the Twentymile aquifer. The resulting mean transmissivity is about 20 ft^2/d for the basal Williams Fork aquifer, 4 ft^2/d for the Twentymile aquifer, and 0.0 ft^2/d for the Trout Creek aquifer. Fractured coal seams may contribute to the larger average hydraulic conductivity of the basal Williams Fork aquifer.

Infiltration of precipitation is the principal source of recharge to bedrock aquifers in the study area. Precipitation generally increase with altitude because of orographic effects associated with up-valley and cross-valley movement of storms. The upper reaches of the Yampa River valley is an exception in that lesser mean annual precipitation occurs at higher altitudes upstream from Steamboat Springs because of rain-shadow effects of cross-valley tracking storms. The mean annual precipitation of 14 to 25 in. in the study area is much less than potential evaporation, which exceeds 40 in/yr. As a result, excess surface water is available to recharge the aquifers only during periods of snowmelt or intense rainfall. Of approximately 150 ft^3/s of mean annual precipitations that falls on the eastern part of the study area, only about 2 percent recharges the bedrock aquifers,

Geologic structure and the resulting topography of the formations have an important bearing on the ground-water recharge, discharge, and flow system in the aquifers. Structure in the study area has marked similar eastern and western tectonic forms. In the eastern part of the area, complex deformation associated with the Laramide orogeny has produced a series of four plunging synclinal and anticlinal features that resulted in structural basins southeast of Hayden