# GROUND-WATER HYDROLOGY AND SIMULATED EFFECTS OF DEVELOPMENT IN THE MILFORD AREA, AN ARID BASIN IN SOUTHWESTERN UTAH

REGIONAL AQUIFER-SYSTEM ANALYSIS


USGS
science for a changing world

U.S. Department of the Interior
U.S. Geological Survey

PROFESSIONAL PAPER 1409–G

USGS
science for a changing world

## SIMULATION OF HYPOTHETICAL DEVELOPMENT ALTERNATIVES

### CRITERIA

The calibrated flow model for the Milford area was used to project the long-term effects of ground-water withdrawals under different applied stresses. Alternatives were designed to test the effects of withdrawals at a rate equal to the "sustained" yield of the ground-water system and to simulate development necessary for the capture of natural discharge. In most cases, the pumping distributions do not have practical applications. The concept of "sustained" yield is used by the States of Nevada and Utah, by which water rights generally are allocated on the basis of the estimated, average annual recharge to the basin in order to prevent long-term "mining" of ground water. Model-simulated responses of water-level declines and recovery and changes in discharge and storage were used to compare the effect of different applied stresses on the ground-water system.

Each development alternative was simulated for an arbitrary period of 600 years. The first 300 years simulated pumping, followed by 300 years of recovery. The long simulation period allowed the system to respond to the new stress and to approach a new equilibrium.

Each hypothetical development alternative was constrained by the following arbitrary requirements: Pumping wells were not located (1) where the depth to water exceeds 200 ft, (2) where land-surface slopes are larger than 200 ft/mi, (3) where the saturated thickness in any model cell is less than 200 ft, and (4) where cells are bounded on two sides by consolidated rocks. Within the simulated area, no cells had transmissivity values that were considered to be too small for pumping (less than $1.2 \times 10^{-2}$ ft$^2$/s). Pumping requirements included (1) one well per 160 acres, (2) a maximum average rate of 0.552 ft$^3$/s (400 acre-ft/yr) for each well, and (3) withdrawals equally divided between the upper two model layers. All simulations assumed net ground-water withdrawal, so it was not necessary to simulate the recirculation of pumped water to the aquifer.

Hypothetical development alternatives simulated for the basin were as follows:

A. Concentrated pumping centers, withdrawing ground water at a rate equal to the estimated average annual recharge—Alternative A1 concentrated pumping in the southern one-half of the simulated area; alternative A2 concentrated pumping in the northern one-half of the simulated area; and alternative A3 concentrated pumping in two equal centers, one in the south and one in the north.

B. Strategically placed distribution of withdrawals that efficiently captured natural discharge, which includes evapotranspiration and basin outflow—Alternative B1 maintained pumping at a rate equal to the estimated average annual recharge; alternative B2 maintained pumping at 1.25 times the estimated average annual recharge; and alternative B3 maintained pumping at 1.75 times the estimated average annual recharge for the first 50 years and then at a rate equal to the estimated annual recharge for the remaining 250 years.

Specific economic considerations were not addressed, but were indirectly considered when placing constraints on the model simulations. Possible degradation of water quality due to recirculation of pumped water was not considered in the simulations.

For each development alternative, a set of four plots was made to graphically portray the response of the ground-water system to the applied stress. The first plot shows the average water-level decline within all pumped cells at the end of each stress period. The second plot shows the change in basin inflow and outflow through the two general-head boundaries. In the other two plots, the net change in storage and natural discharge at the end of each stress period are divided by total recharge. Total recharge was calculated at the end of each stress period by adding any increase in basin inflow entering through the southwest general-head boundary to the other sources of recharge that remain constant throughout the simulation. Natural discharge includes evapotranspiration and basin outflow. If the ground-water gradient was reversed due to declining water levels in the northern one-half of the basin, the computed basin inflow from the northwest general-head boundary was subtracted from the basin outflow to get the net basin outflow that was then used to determine natural discharge. The simulated inflow at the north end of the basin was not added to the total recharge because it was accounted for by reducing outflow. During the recovery phase of each simulation, steady-state ground-water withdrawal, which was defined as part of the steady-state conditions, was included with natural discharge; otherwise, the potentiometric surface at the end of each simulation would be higher than the original steady-state potentiometric surface.

Plots of storage versus recharge and natural discharge versus recharge can be used to evaluate the effectiveness of each development alternative to approach a new equilibrium condition, to capture natural discharge, and to let ground-water levels recover. Ideally, if a new equilibrium condition is achieved during the 300 years of pumping, then the ratio of water removed from storage to recharge and the ratios of natural discharge to recharge would stabilize. If all natural discharge was captured during pumping, then the ratios would equal zero. If full recovery was achieved at the end of the 600-year simulation, then the ratio of water entered into storage to recharge would equal zero and the ratio of natural discharge to recharge would equal one.

All hypothetical simulations used calibrated, steady-state conditions for the initial conditions. The simulations were designed to test the effects of hypothetical ground-water development patterns and did not incorporate the present pattern.

## DEVELOPMENT ALTERNATIVE A1

In this simulation, net ground-water withdrawals were held equal to the estimated annual recharge. Ground water was withdrawn from a concentrated pumping center covering 105 cells that was located in the southern one-half of the simulated area (fig. 19). Withdrawals were divided evenly between the upper two model layers. The withdrawal for each cell depended on its size and ranged from 0.552 $ft^3/s$ (400 acre-ft/yr) to 0.828 $ft^3/s$ (599 acre-ft/yr).

After 300 years of pumping, a distinct cone of depression had developed covering the entire southern one-half of the simulated area and extending into the northern one-half (fig. 19). Computed water-level declines at the basin boundaries were locally more than 100 ft. The average water-level decline within the pumped area was about 160 ft (fig. 20). Boundary effects at both general-head boundaries began to occur after 25 years of pumping (fig. 21). Basin inflow from the Beryl-Enterprise area increased from 2.65 $ft^3/s$ (1,920 acre-ft/yr) as pumping began, to about 4.65 $ft^3/s$ (3,370 acre-ft/yr) by 300 years. Although the computed basin outflow did not decrease substantially, the net basin outflow at the northwest general-head boundary decreased 7.60 $ft^3/s$ (5,500 acre-ft/yr) because of the reversal of the hydraulic gradient at the southern end of this boundary.

After pumping ended at 300 years, water levels initially recovered rapidly with most of the water recharging the basin going into storage (figs. 20, 22). After the full 300 years of recovery, water levels had returned to within 3 ft of the original level throughout most of the basin. Only in the extreme southeast part were residual water-level declines more than 5 ft; in this area, only a small quantity of water was entering the basin fill from the consolidated rocks (fig. 23).

This development alternative is not the most efficient for capturing natural discharge—only 80 percent was eliminated (fig. 24). With water-level declines of less than 25 ft for most of the northern one-half of the basin, evapotranspiration was not completely eliminated. Although net basin outflow through the general-head boundary was reduced, the computed basin outflow was reduced only slightly. A new equilibrium condition was not reached as shown in figures 20, 21, 22, and 24; therefore, water was removed from storage throughout the 300 years of pumping. As a result, almost 25 years of recovery were required to replenish the ground-water system before natural discharge began to increase.

## DEVELOPMENT ALTERNATIVE A2

The net ground-water withdrawals for development alternative A2, like development alternative A1, were held equal to the estimated annual recharge. Ground water was withdrawn from a concentrated pumping center in the northern one-half of the simulated area. As shown in figure 25, 55 cells were pumped at a rate of 1.104 $ft^3/s$ (799 acre-ft/yr) per cell, evenly divided between the upper two layers.

As with development alternative A1, 300 years of pumping produced a cone of depression that enveloped the entire northern one-half of the basin (fig. 25). Because of smaller transmissivity values in this part of the basin, the water-level declines were much larger, averaging nearly 220 ft in the pumped area (figs. 25, 26). After 25 years, large boundary effects began to occur along the northwest general-head boundary (fig. 27). After 300 years of pumping, the hydraulic gradient had been reversed along part of this boundary so that basin inflow was approaching basin outflow, thus making net basin outflow small.

In the initial stages of recovery, water levels began to rise rapidly with most of the water going into storage (figs. 26, 28). In this development alternative, more water than usual went into storage due to the increased basin inflow along the northern general-head boundary. At the end of the full recovery period, water levels had returned to within 5 ft of the starting level throughout most of the pumped area (fig. 29); however, residual water-level declines were larger than 30 ft in the northeast corner where the Cove Creek drainage enters the basin. The eastern model boundary in this area has a fixed flow rate while the northern boundary has no flow entering the ground-water system. The boundary conditions as defined might be unrealistic; but the lack of data prevents the use of any other type of boundary. The residual water-level declines for this simulation probably represent a worst-case situation.

Like development alternative A1, this development alternative is not efficient at capturing natural discharge, eliminating only 80 percent (fig. 30). Although basin outflow through the general-head boundary was reduced and evapotranspiration eliminated in the northern one-

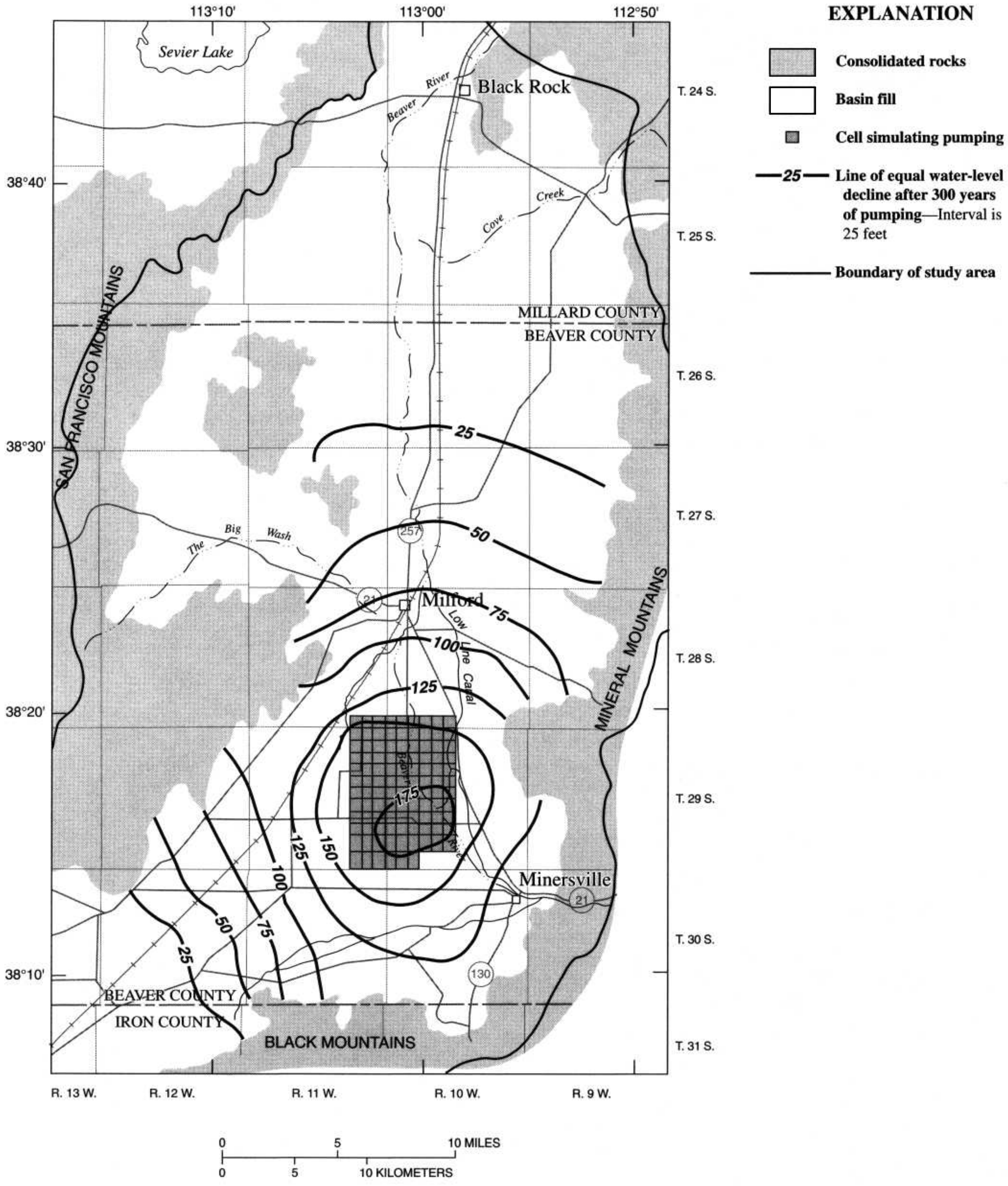


FIGURE 19.—Simulated water-level declines after 300 years of pumping and areal distribution of cells simulating pumping for development alternative A1.

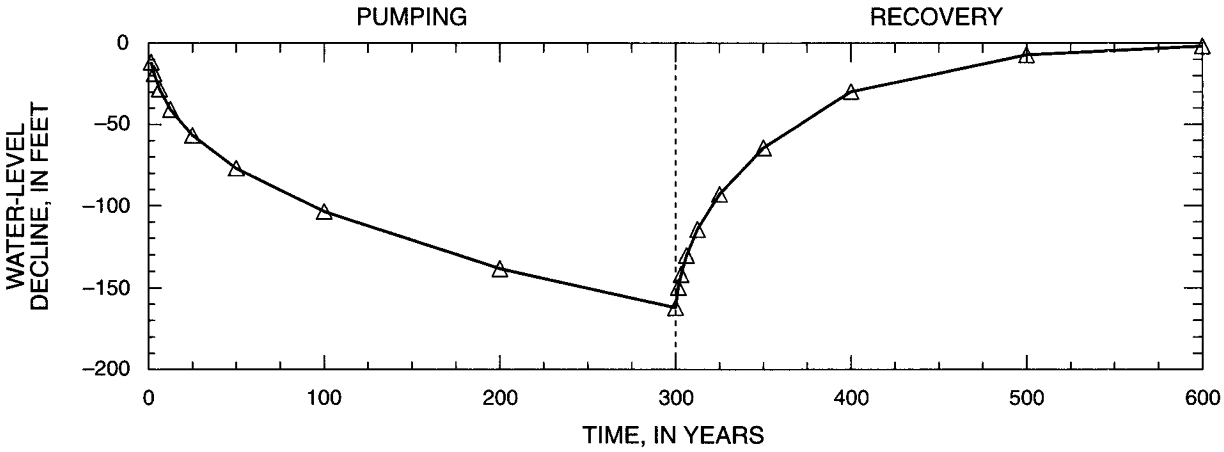


FIGURE 20.—Simulated average water-level decline and recovery in model cells containing pumped wells for development alternative A1.

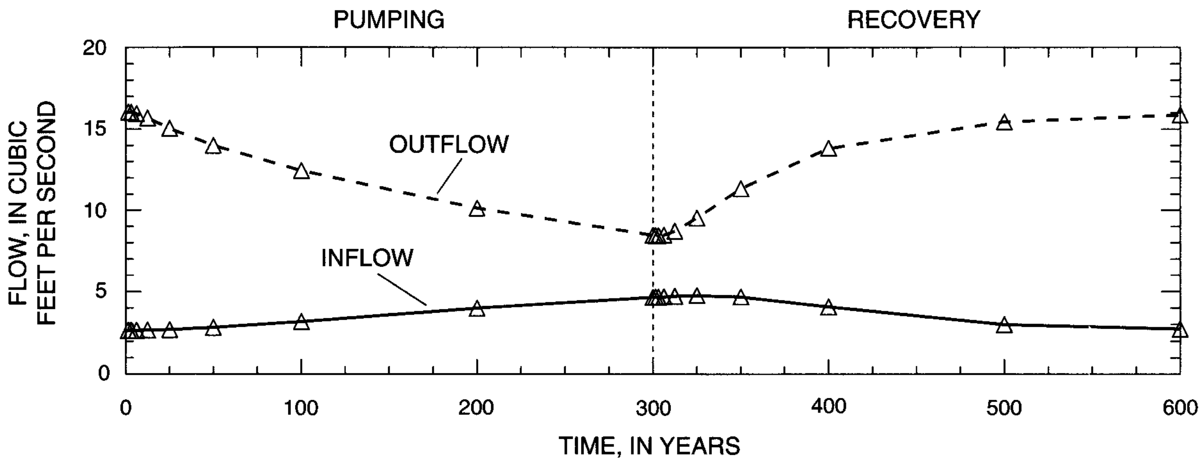


FIGURE 21.—Simulated changes in basin inflow and net outflow at general-head boundaries during pumping and recovery for development alternate A1.

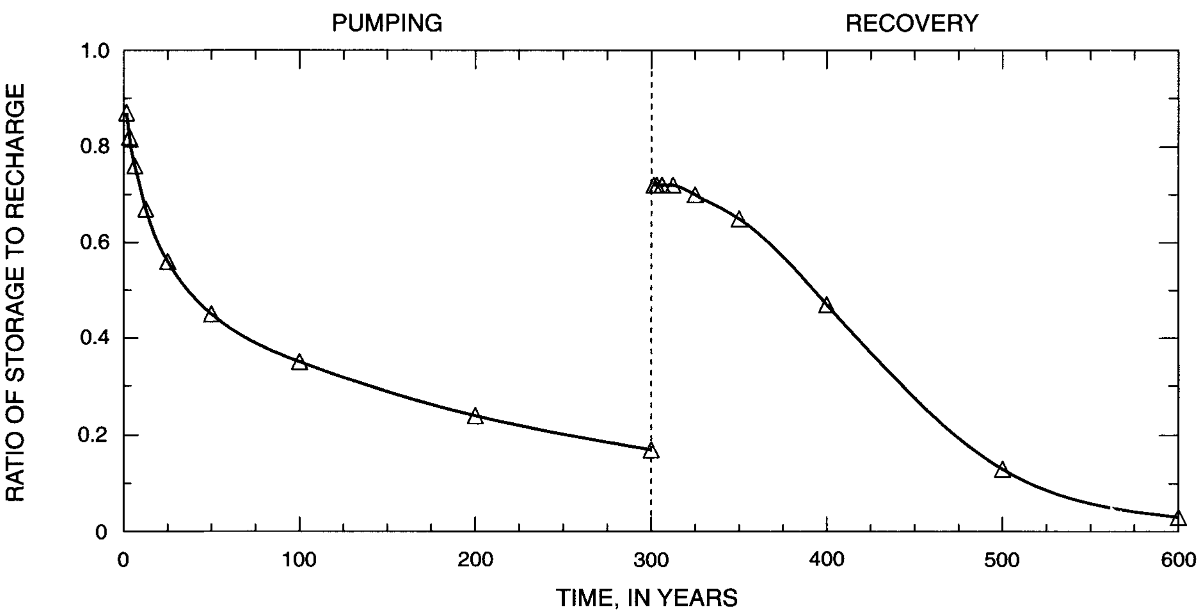


FIGURE 22.—Simulated changes in the ratios of water removed from storage during pumping to recharge and water added to storage during recovery to recharge for development alternative A1.

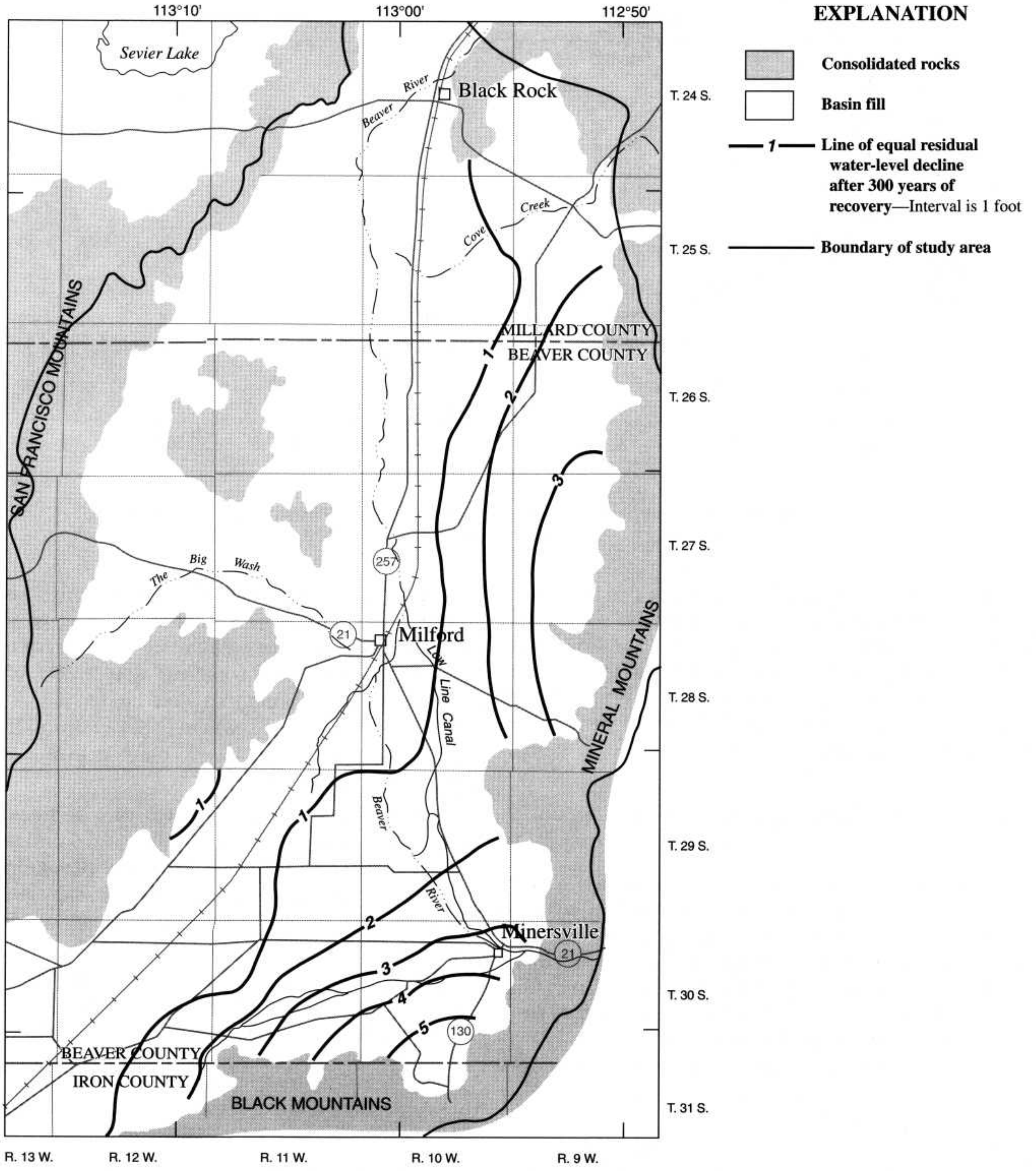


FIGURE 23.—Simulated residual water-level declines after 300 years of recovery for development alternate A1.

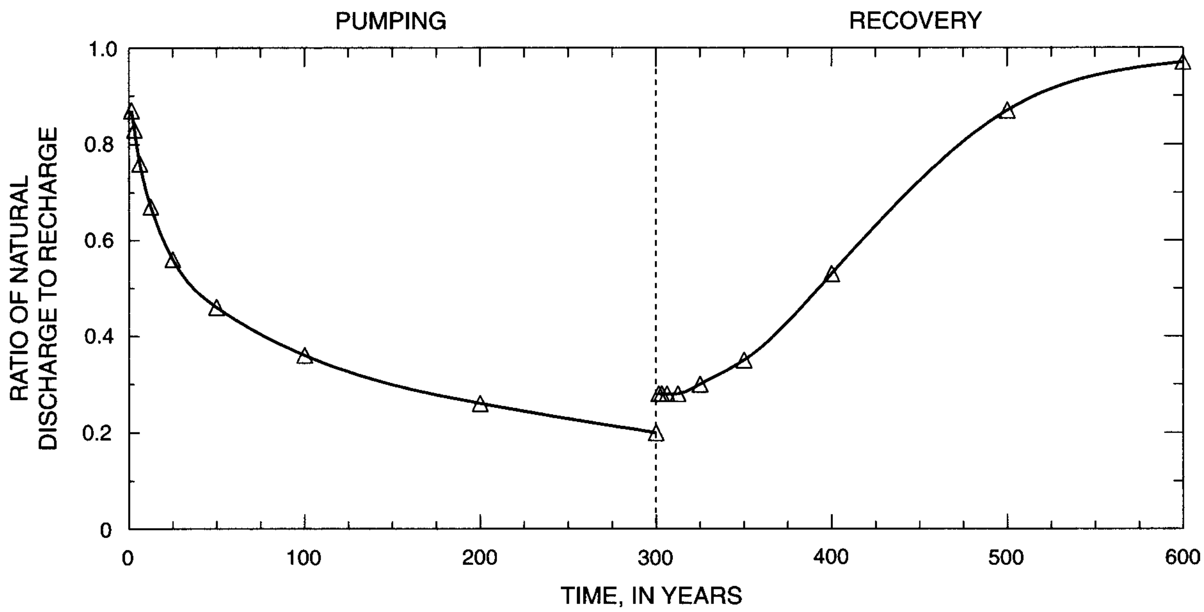


FIGURE 24.—Simulated change in the ratio of natural discharge to recharge during pumping and recovery for development alternative A1.

half of the basin, evapotranspiration remained substantial in the southern one-half. A new equilibrium was not reached, with changes in storage and natural discharge still occurring (figs. 26, 27, 28, 30). Because large quantities of water were removed from storage, over 25 years of recovery were required before substantial increases in natural discharge began to appear.

## DEVELOPMENT ALTERNATIVE A3

In this simulation, there were two centers of concentrated pumping, one in the north and one in south as shown in figure 31. Ground-water withdrawals were split evenly between the two areas and held equal to the estimated annual recharge. A total of 84 cells have simulated withdrawals with 0.552 $ft^3/s$ (400 acre-ft/yr) withdrawn from each cell in the south and 1.104 $ft^3/s$ (799 acre-ft/yr) withdrawn from each cell in the north. The large withdrawals in each cell were evenly divided between the upper two layers.

When ground-water withdrawals were concentrated in two areas, two cones of depression developed during the pumping period (fig. 31). The cone of depression in the north is well defined; whereas the cone of depression in the south is shallower and less well defined. This is the result of much smaller transmissivity values in the north. The maximum water-level decline in the north was more than 160 ft; in the south it was about 60 ft. The average water-level decline at the end of pumping for both areas was almost 76 ft (fig. 32). Unlike the two previous development alternatives, substantial water-level declines were present along the entire eastern boundary (fig. 31). By dividing the withdrawals into two centers, effects at the general-head boundaries were moderated. Basin inflow increased slightly, whereas net basin outflow decreased substantially, but not as much as in development alternative A2 (fig. 33).

Because of the smaller water-level declines, which were distributed over a larger area, water levels recovered more rapidly than in the previous development alternatives. More water initially went into storage (figs. 32 and 34). Like development alternative A2, residual water-level declines after the full recovery period were large—more than 12 ft—in the extreme northeast corner (fig. 35). The entire southern one-half and the central part of the northern one-half of the basin recovered to within 2 ft of the original potentiometric surface. As shown in figure 33, water levels had recovered sufficiently so that the general-head boundaries had essentially returned to near steady-state conditions after 100 years.

This development alternative shows the benefits of distributing rather than concentrating ground-water withdrawals. This development alternative was 86 percent effective in eliminating natural discharge, substantially better than development alternatives A1 and A2. As shown in figures 34 and 36, the rate of change in water removed from storage and natural discharge became small after 100 years as a new equilibrium was approached.

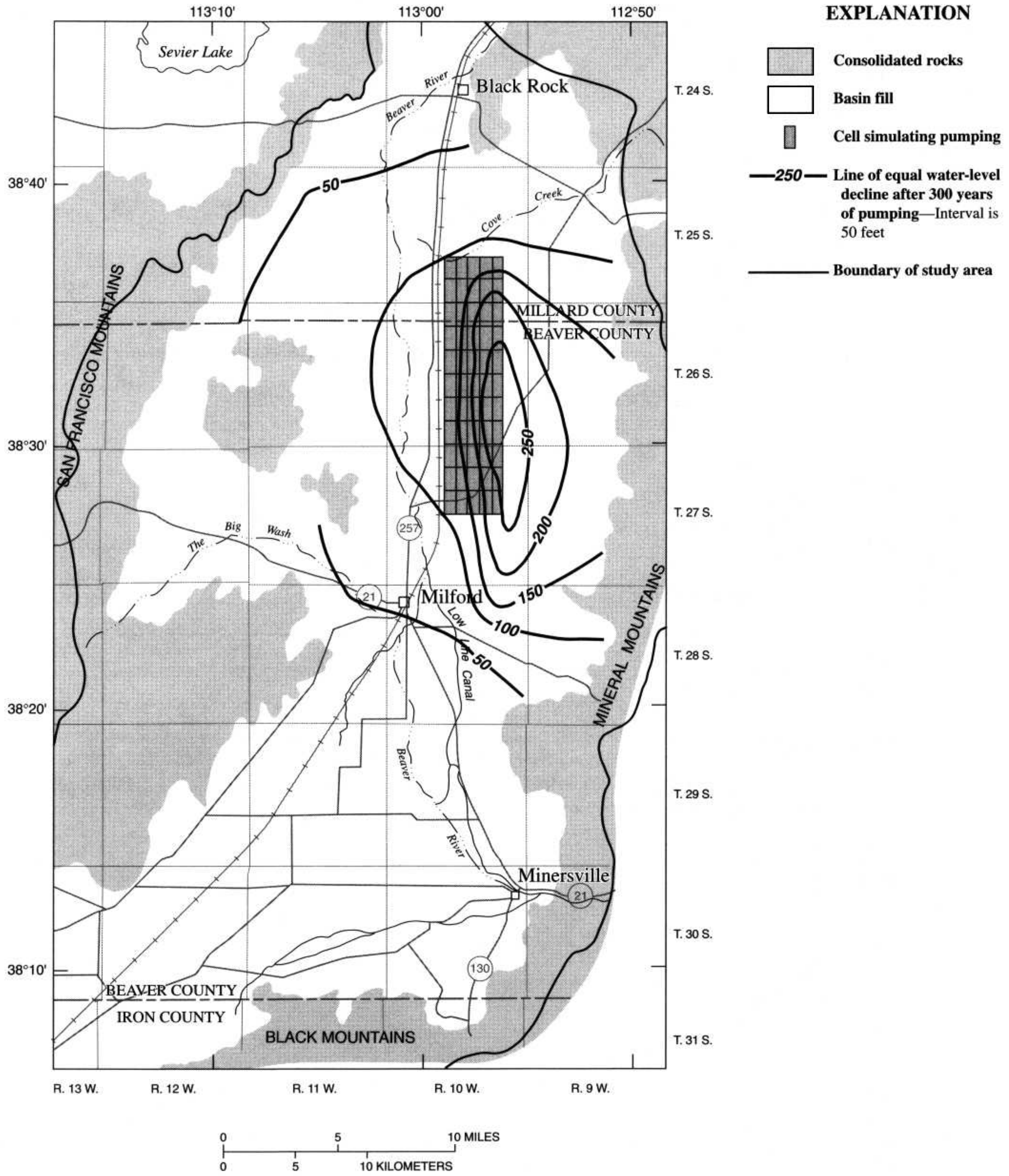


FIGURE 25.—Simulated water-level declines after 300 years of pumping and areal distribution of cells simulating pumping for development alternative A2.

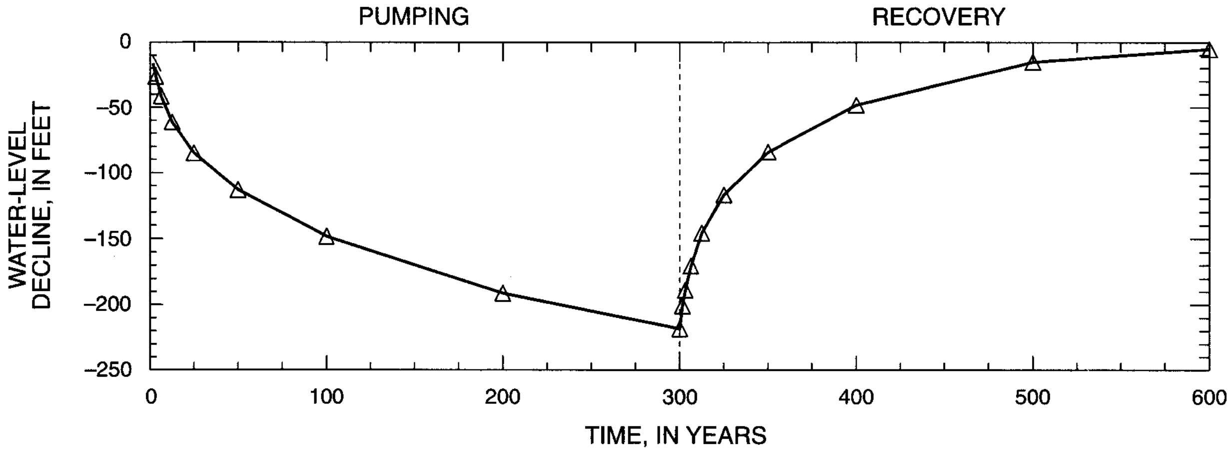


FIGURE 26.—Simulated average water-level decline and recovery in model cells containing pumped wells for development alternative A2.

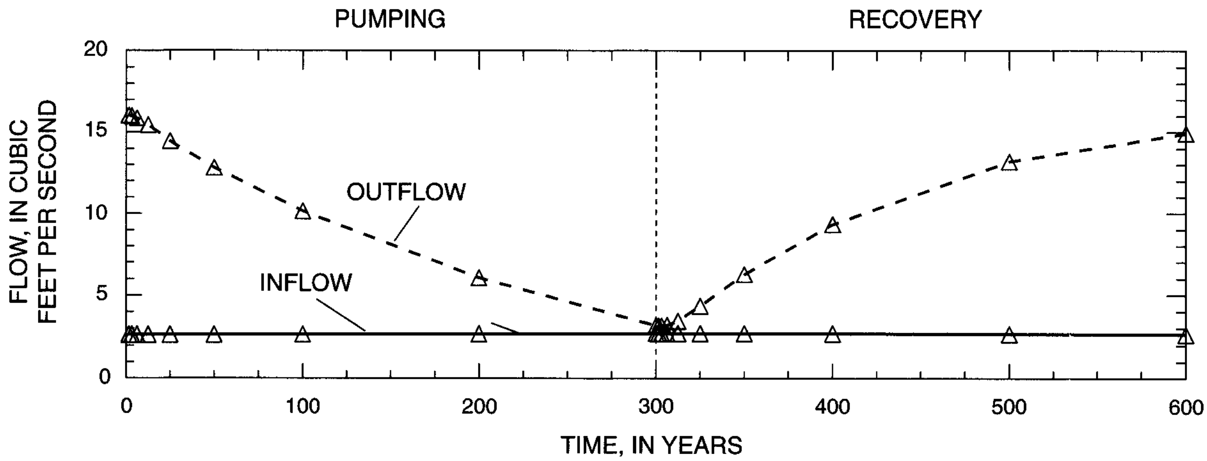


FIGURE 27.—Simulated changes in basin inflow and net outflow at general-head boundaries during pumping and recovery for development alternative A2.

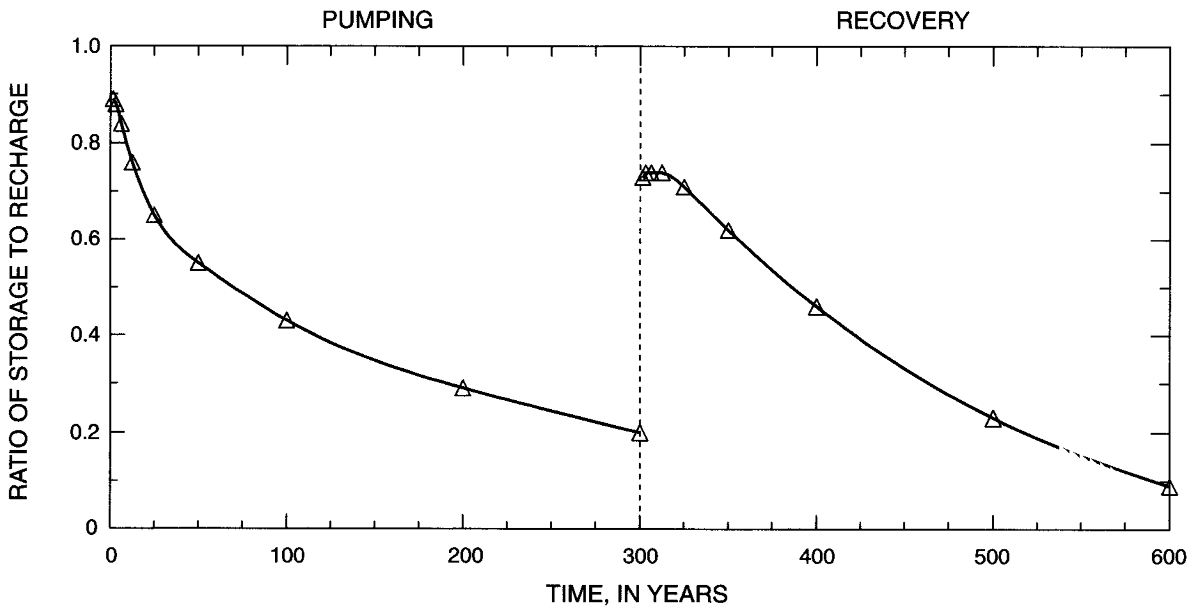


FIGURE 28.—Simulated changes in the ratios of water removed from storage during pumping to recharge and water added to storage during recovery to recharge for development alternative A2.

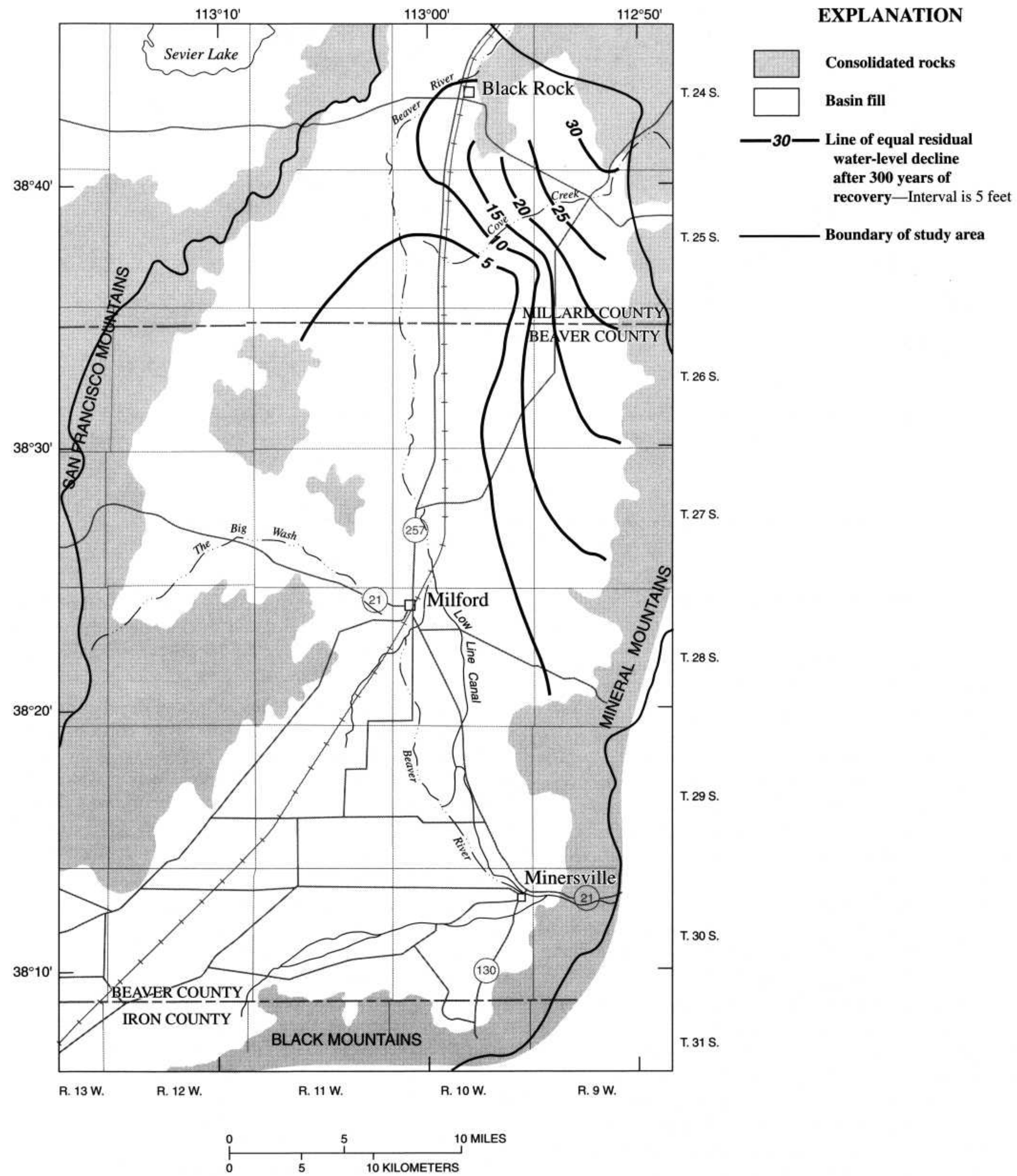


FIGURE 29.—Simulated residual water-level declines after 300 years of recovery for development alternative A2.

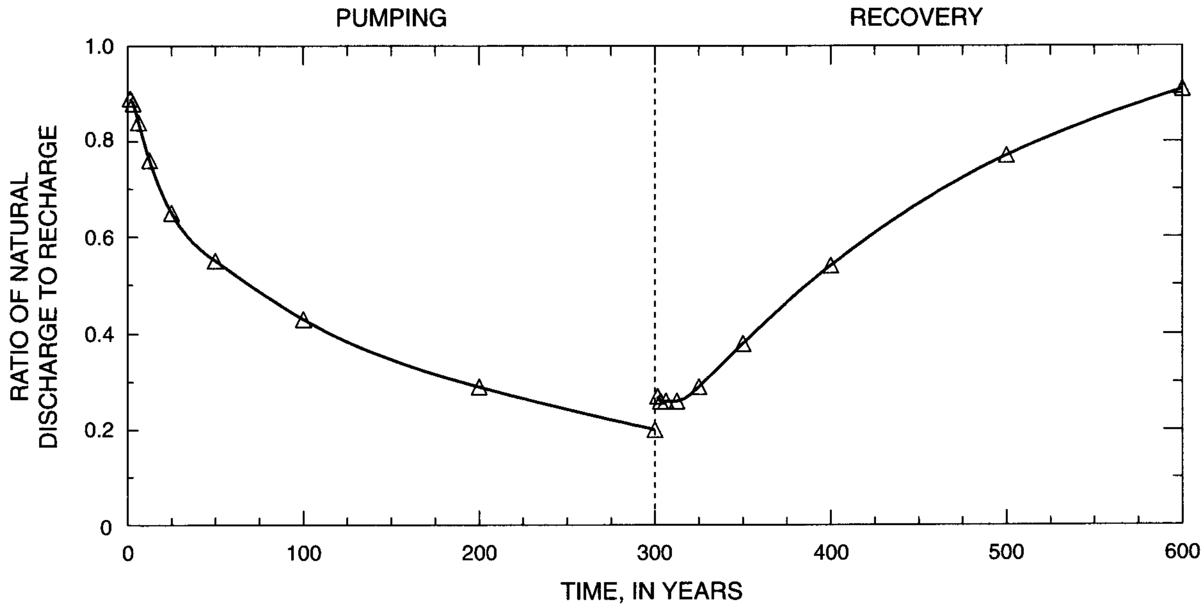


FIGURE 30.—Simulated change in the ratio of natural discharge to recharge during pumping and recovery for development alternative A2.

**DEVELOPMENT ALTERNATIVE B1**

In this development alternative, an entirely different approach was taken for distributing ground-water withdrawals. A trial-and-error method was used to find the pumping distribution most efficient at eliminating natural discharge. Knowledge gained from the previous development alternatives and the fact that evapotranspiration occurs throughout the length of the simulated area provided the basis for the initial distribution of ground-water withdrawals. After each simulation, the distribution of ground-water withdrawals was modified in order to eliminate evapotranspiration and to balance basin outflow with basin inflow at the northwest general-head boundary. The original constraints on ground-water withdrawals were maintained during the process.

The final distribution of ground-water withdrawals, which is one of many possible, used 96 cells distributed along the axis of the basin (fig. 37). This distribution coincides with the area of evapotranspiration as shown on plate 2. As in previous development alternatives, the net ground-water withdrawals equaled the estimated annual recharge. The cells had ground-water withdrawals ranging from 0.552 $ft^3/s$ (400 acre-ft/yr) to 1.104 $ft^3/s$ (799 acre-ft/yr). Ground-water withdrawals from cells near the southwest corner were necessary to eliminate evapotranspiration; and in all simulations using this distribution, the adjacent general-head boundary was affected immediately, thus increasing basin inflow. Ground-water withdrawals were simulated in cells near the northwest general-head boundary for the purpose of balancing basin outflow with inflow.

After 300 years of pumping, cones of depression had developed in the north and the southwest corners of the basin with a discernible trough along the axis of the basin (fig. 38). The maximum water-level decline was more than 60 ft and the average water-level decline was almost 45 ft (fig. 39). The general-head boundaries were affected immediately because of the strategically placed ground-water withdrawals (fig. 40).

Unlike previous development alternatives, strategically placed ground-water withdrawals resulted in distributed water-level declines throughout the basin, thus maximizing the area for potential recharge when pumping ceased. During recovery, more water initially went into storage (fig. 41), thus allowing water levels to rise rapidly and recovery to be more complete; however, like the development alternatives A2 and A3, which have ground-water withdrawals in the north, residual water-level declines are present only in the northern one-half of the basin with maximum residual water-level declines of more than 5 ft in the extreme northeast corner (fig. 42).

This development alternative was efficient at capturing natural discharge with most of the decrease occurring in the first 50 years of pumping (fig. 43). By the end of 300 years of pumping, 89 percent of the natural discharge had

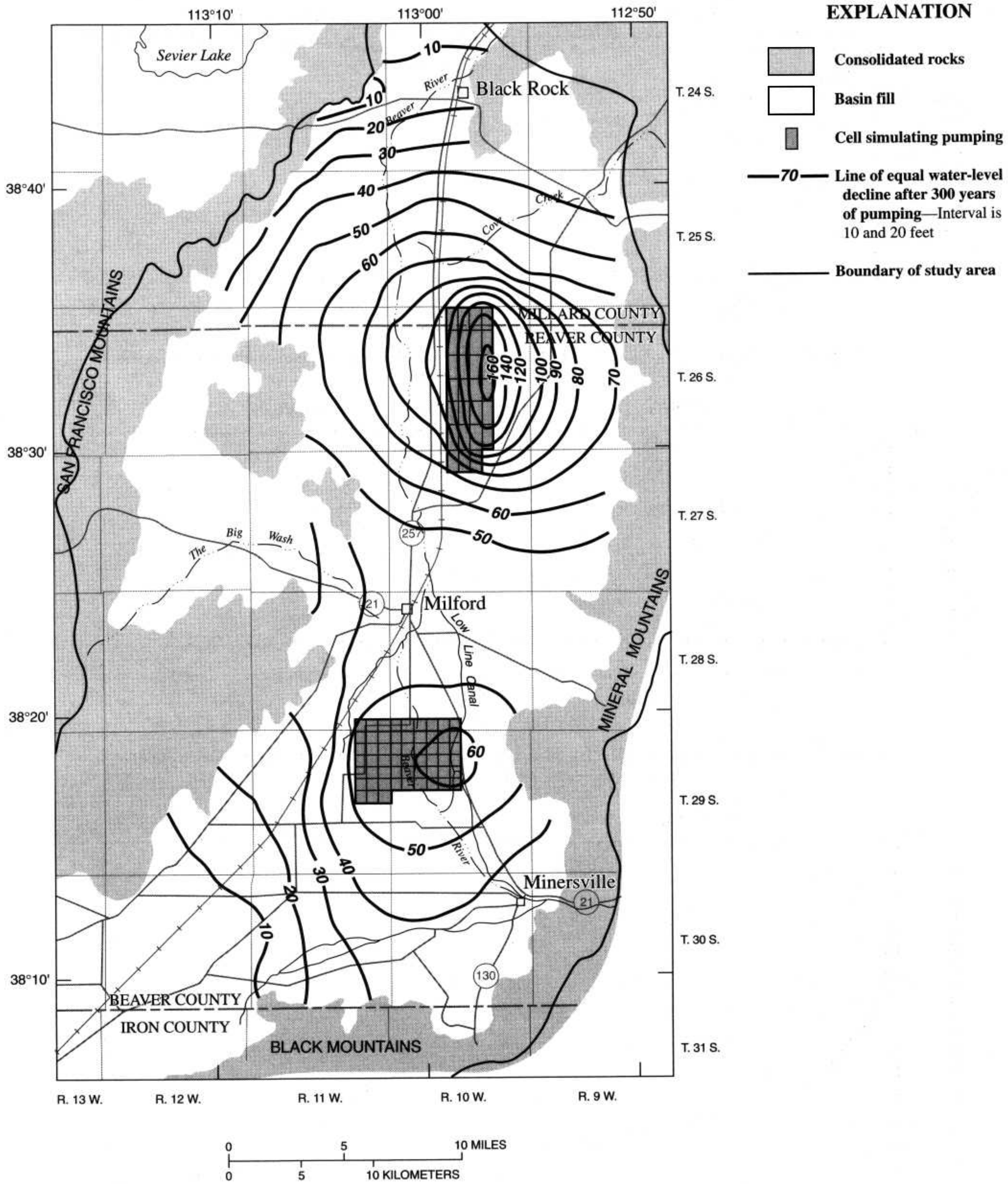


FIGURE 31.—Simulated water-level declines after 300 years of pumping and areal distribution of cells simulating pumping for development alternative A3.

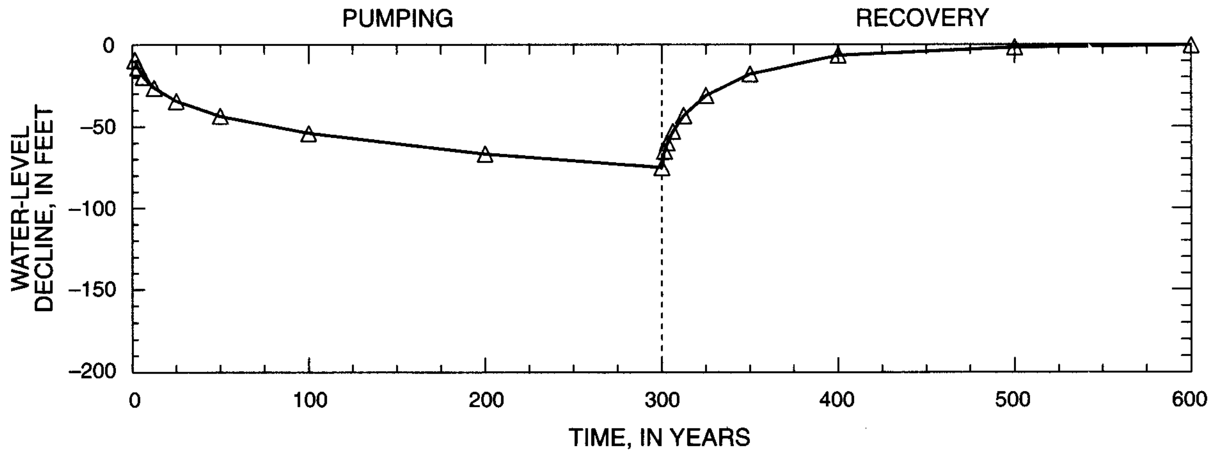


FIGURE 32.—Simulated average water-level decline and recovery in model cells containing pumped wells for development alternative A3.

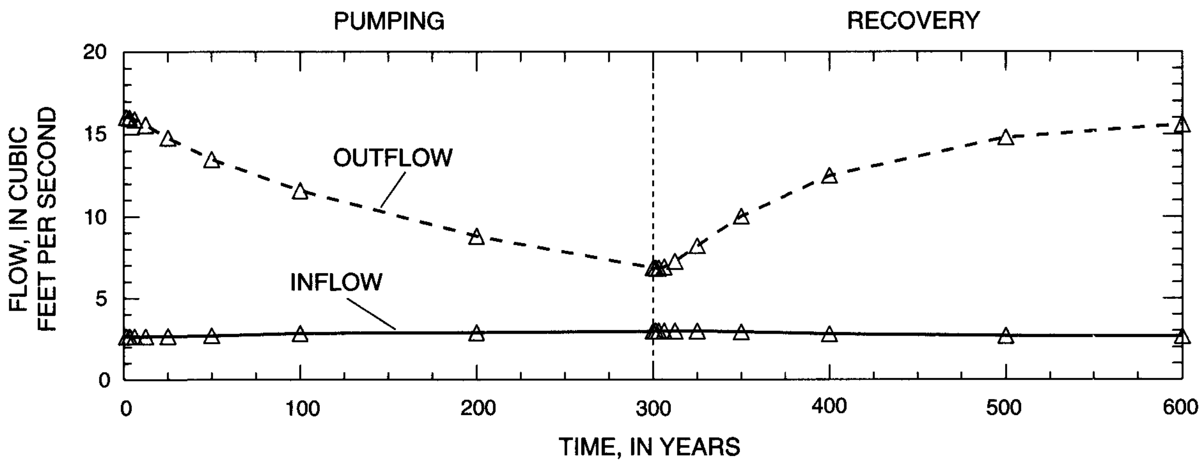


FIGURE 33.—Simulated changes in basin inflow and net outflow at general-head boundaries during pumping and recovery for development alternative A3.

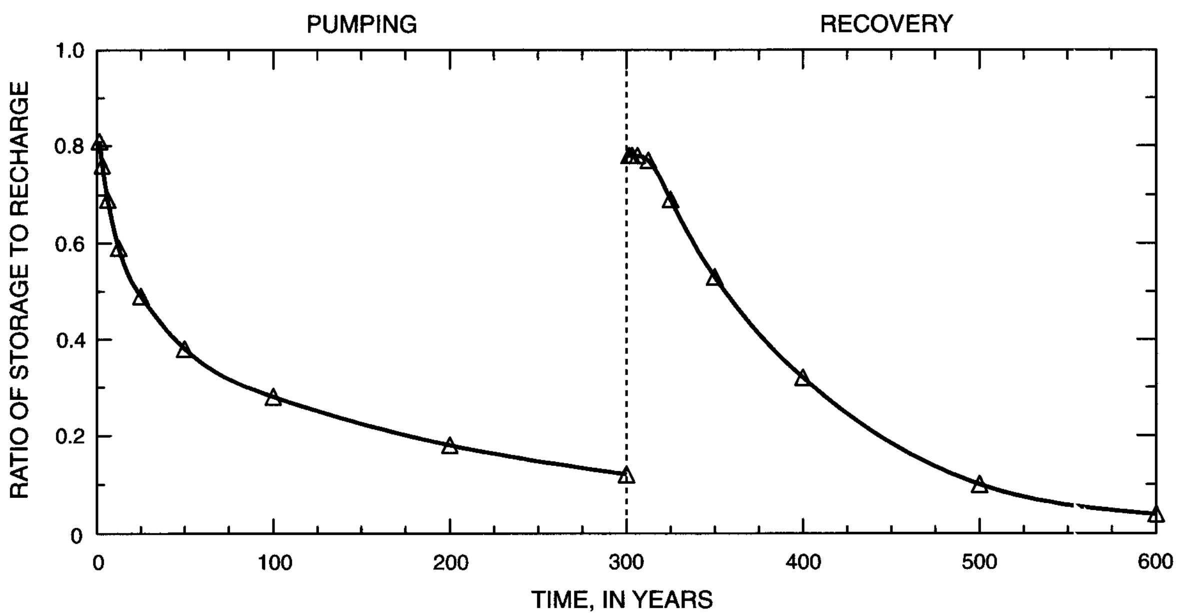


FIGURE 34.—Simulated changes in the ratios of water removed from storage during pumping to recharge and water added to storage during recovery to recharge for development alternative A3.

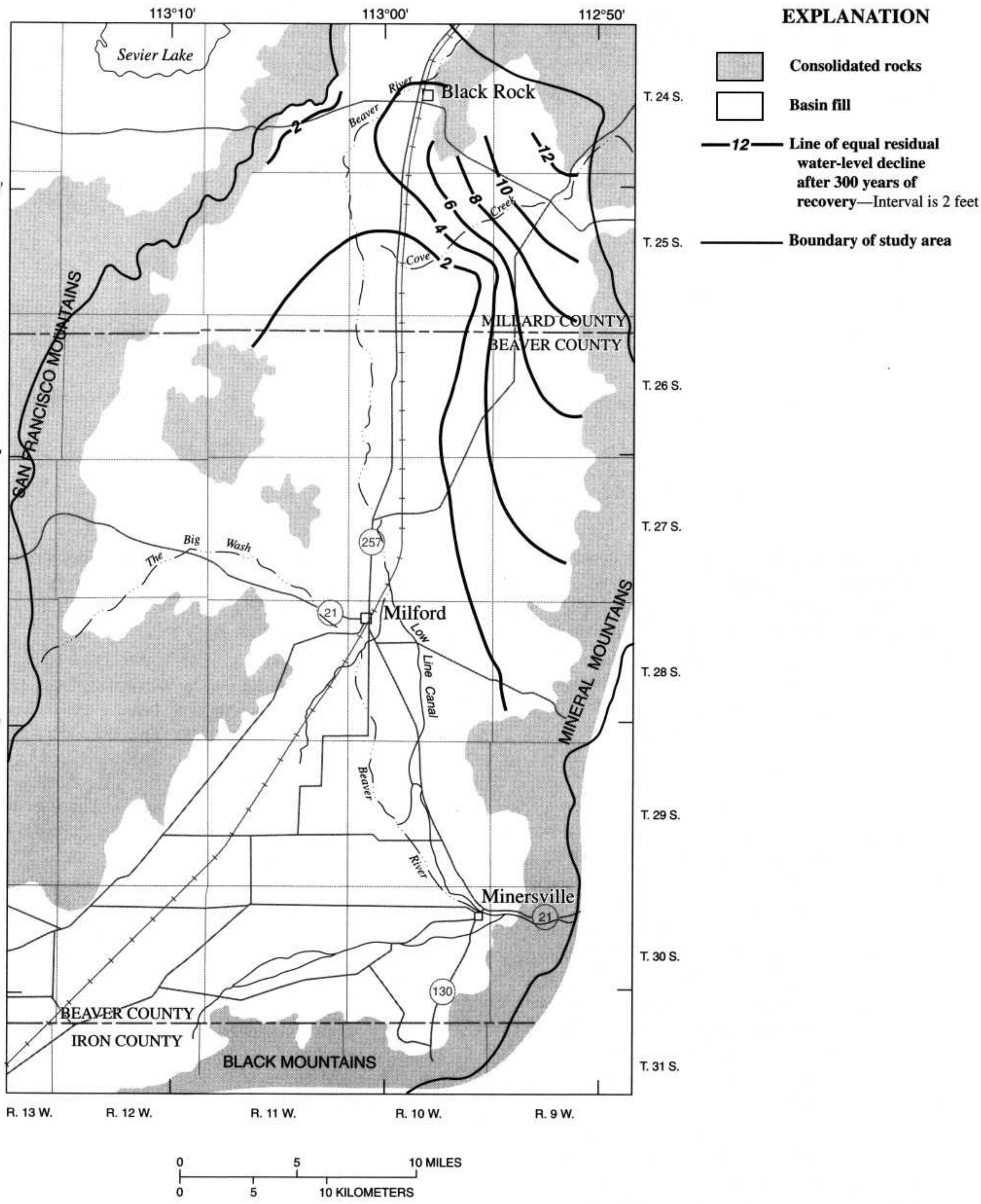


FIGURE 35.—Simulated residual water-level declines after 300 years of recovery for development alternative A3.

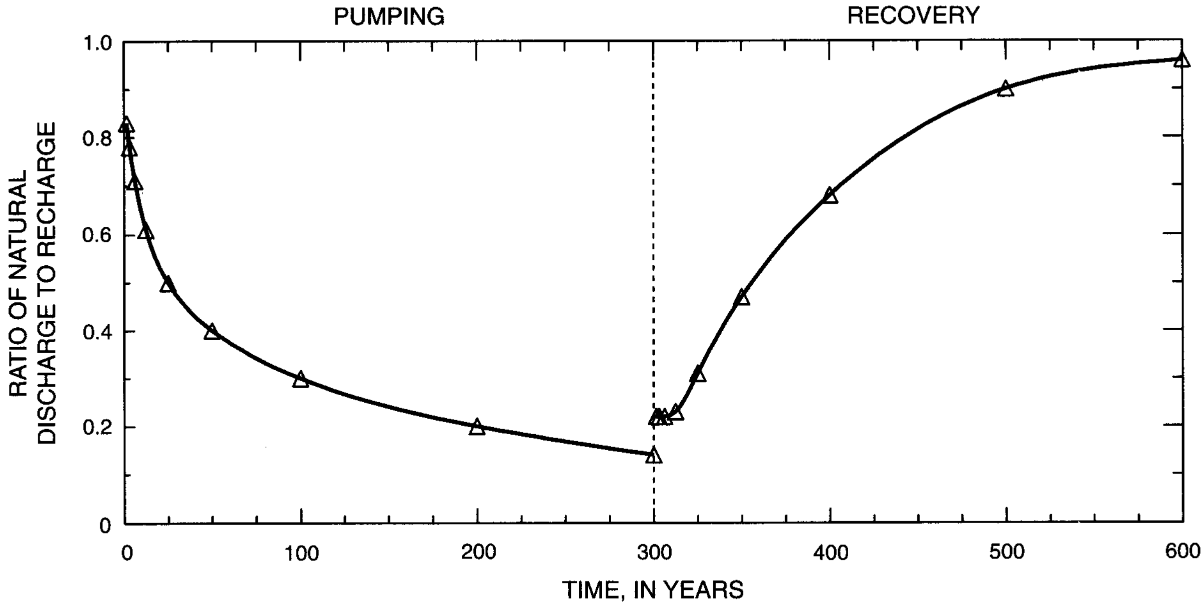


FIGURE 36.—Simulated change in the ratio of natural discharge to recharge during pumping and recovery for development alternative A3.

been eliminated. Evapotranspiration had ceased, thereby leaving net basin outflow as the only form of natural discharge. The ground-water system approached a new equilibrium after 200 years. For the remaining 100 years of pumping, there was no substantial change in the quantity of water removed from storage. Similarly, recovery was rapid with most of it occurring in the first 100 years.

### DEVELOPMENT ALTERNATIVE B2

This development alternative uses the same distribution of withdrawals as development alternative B1 but increases the net ground-water withdrawals by a factor of 1.25. Originally, this simulation used a factor of 1.5; but cells in the upper layer near the northwest general-head boundary began to go dry after 100 years of pumping. After several cells had gone dry, they became inactive for the remainder of the simulation, including the recovery period; therefore, the simulation could not approximate the response of the ground-water system to the hypothetical stress. By using the smaller increase, this problem was not encountered.

As in development alternative B1, a well-defined cone of depression developed in the southwest corner of the basin, with water-level declines of more than 70 ft after 300 years of pumping (fig. 44). A broad trough developed through the center of the area with maximum declines of more than 90 ft in the north and 80 ft in the south. The average water-level decline was more than 80 ft within the entire pumped area (fig. 45). Substantial water-level declines were present at all boundaries The general-head boundaries were affected immediately and changes in the rate of basin inflow and outflow continued throughout the pumping period (fig. 46).

Due to the broad area of water-level declines and large quantities of water removed from storage, almost 50 years of recovery were necessary before substantial quantities of water went into storage (fig. 47). After 300 years of recovery, residual water-level declines were less than 2 ft throughout most of the area (fig. 48). As in previous development alternatives that pumped from the north part of the basin, substantial residual water-level declines were present in the northeast corner.

The ratio of storage versus recharge declined drastically during the first 50 years of pumping (fig. 47). During the remaining 250 years, this ratio continued to decline, but at a much slower rate. Eighty-six percent of the natural discharge was eliminated after 100 years with most of the remaining 14 percent eliminated in the last 200 years of pumping (fig. 49). By comparing the ratios of storage and natural discharge to recharge, it is apparent that as natural discharge was eliminated, less water was removed from storage.

### DEVELOPMENT ALTERNATIVE B3

In the final development alternative, ground-water withdrawals were varied during the pumping phase. For the first 50 years, the applied stress was 1.75 times the estimated annual recharge, and was held equal to re-

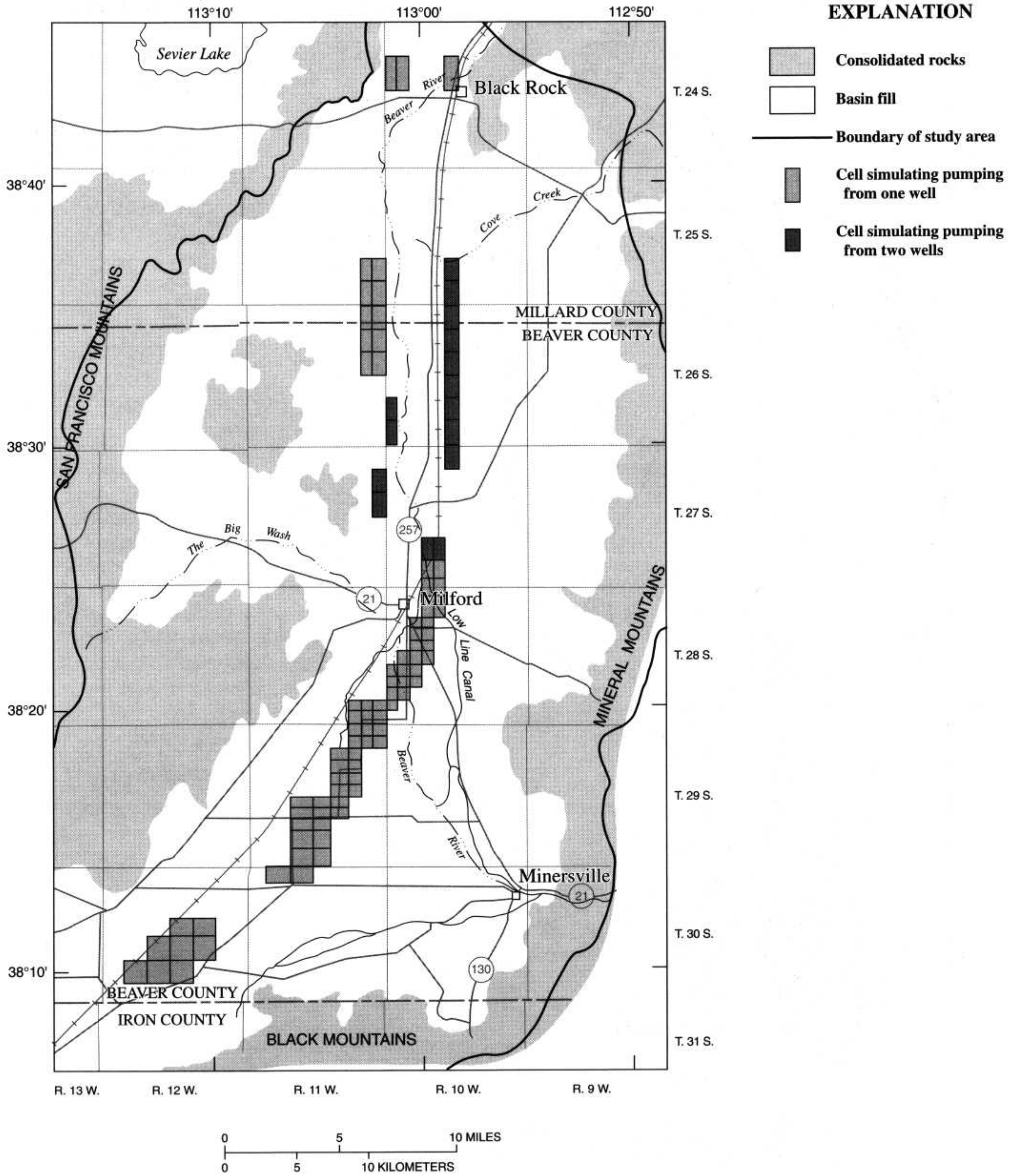


FIGURE 37.—Areal distribution of cells simulating pumping for development alternatives B1, B2, and B3.

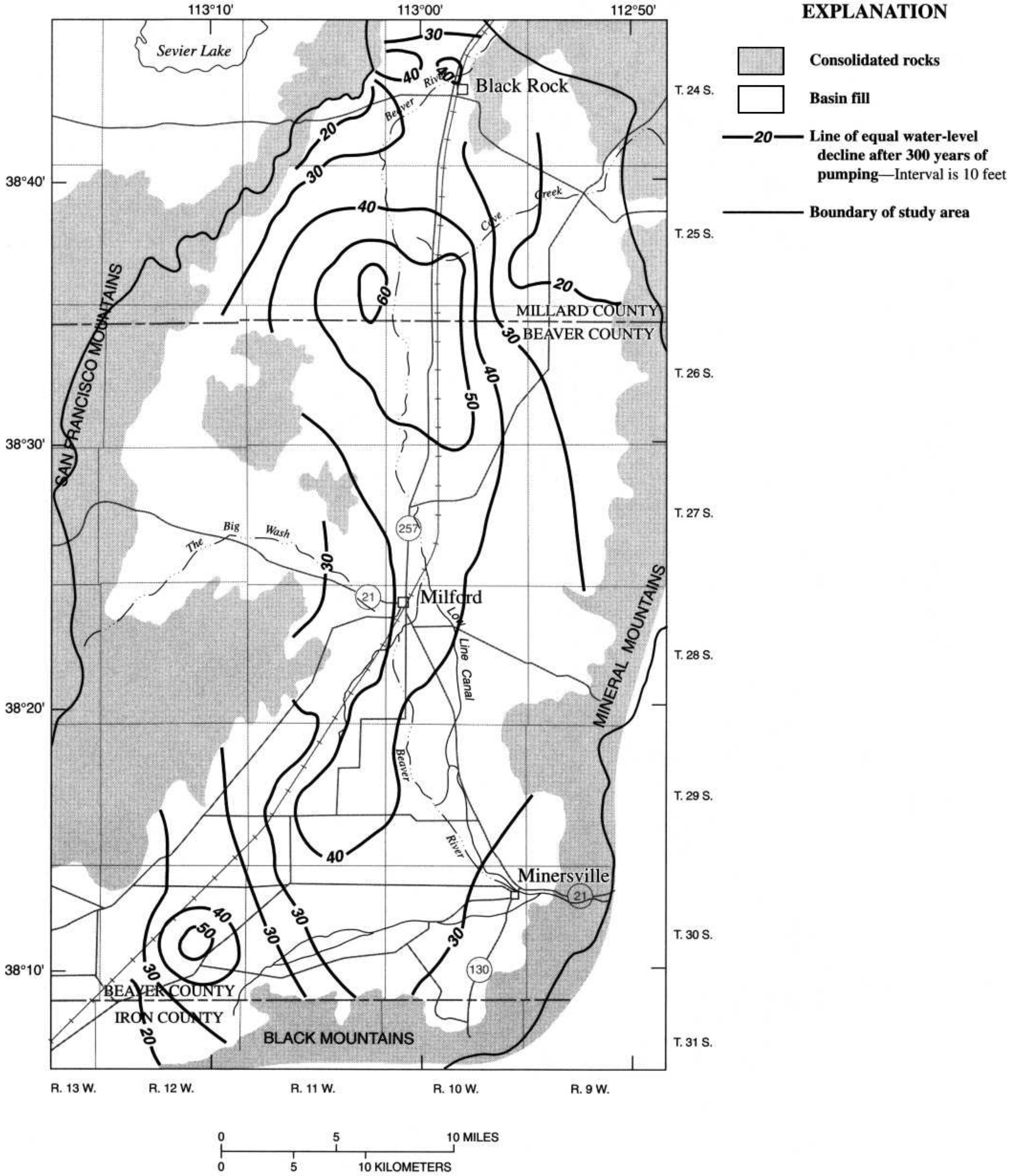


FIGURE 38.—Simulated water-level declines after 300 years of pumping for development alternative B1.

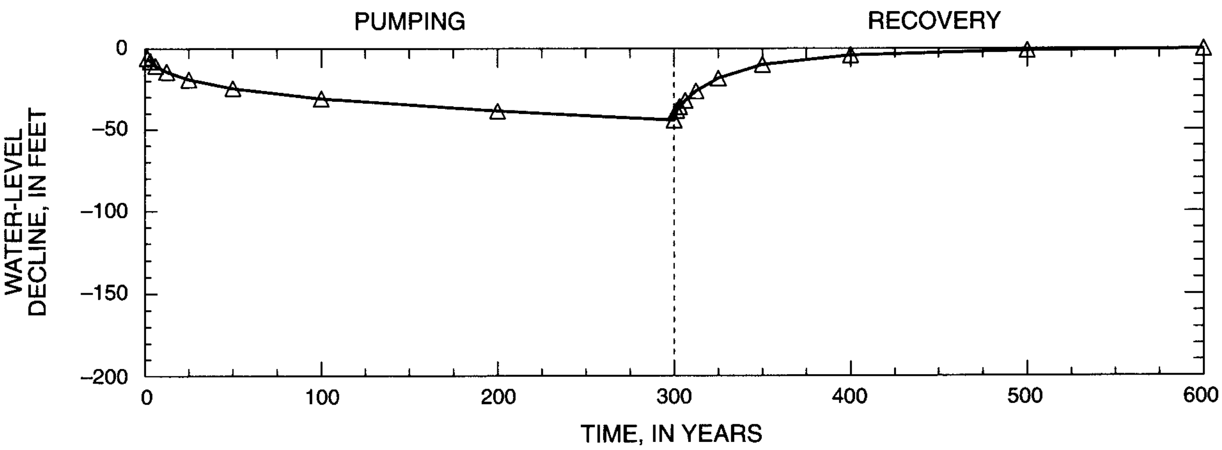


FIGURE 39.—Simulated average water-level decline and recovery in model cells containing pumped wells for development alternative B1.

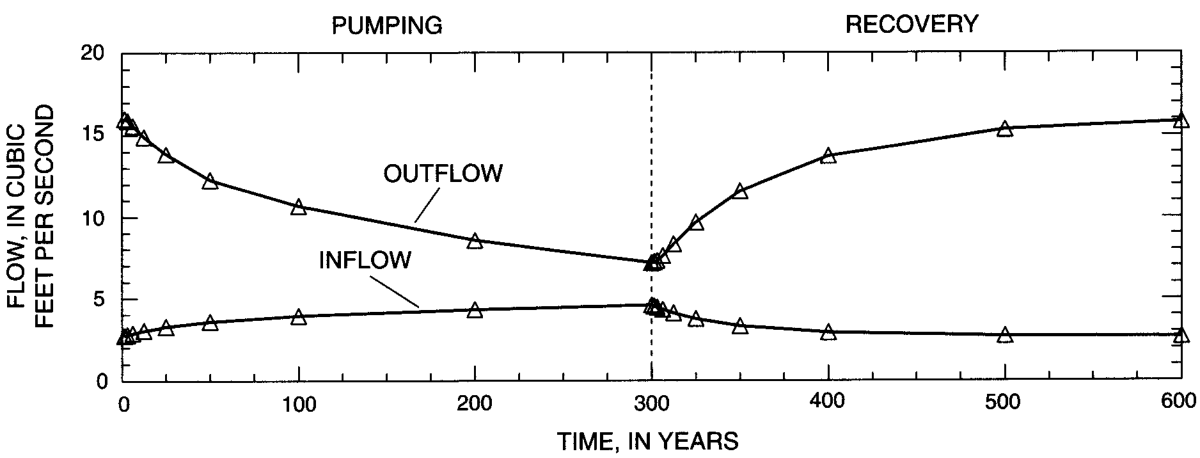


FIGURE 40.—Simulated changes in basin inflow and net outflow at general-head boundaries during pumping and recovery for development alternative B1.

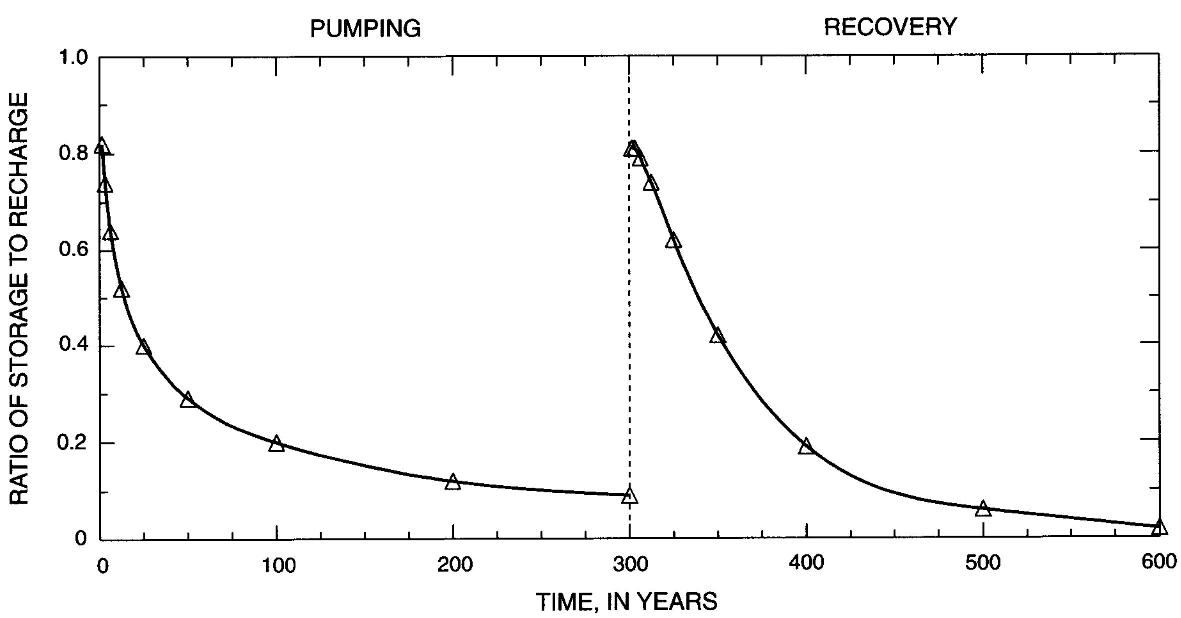


FIGURE 41.—Simulated changes in the ratios of water removed from storage during pumping to recharge and water added to storage during recovery to recharge for development alternative B1.

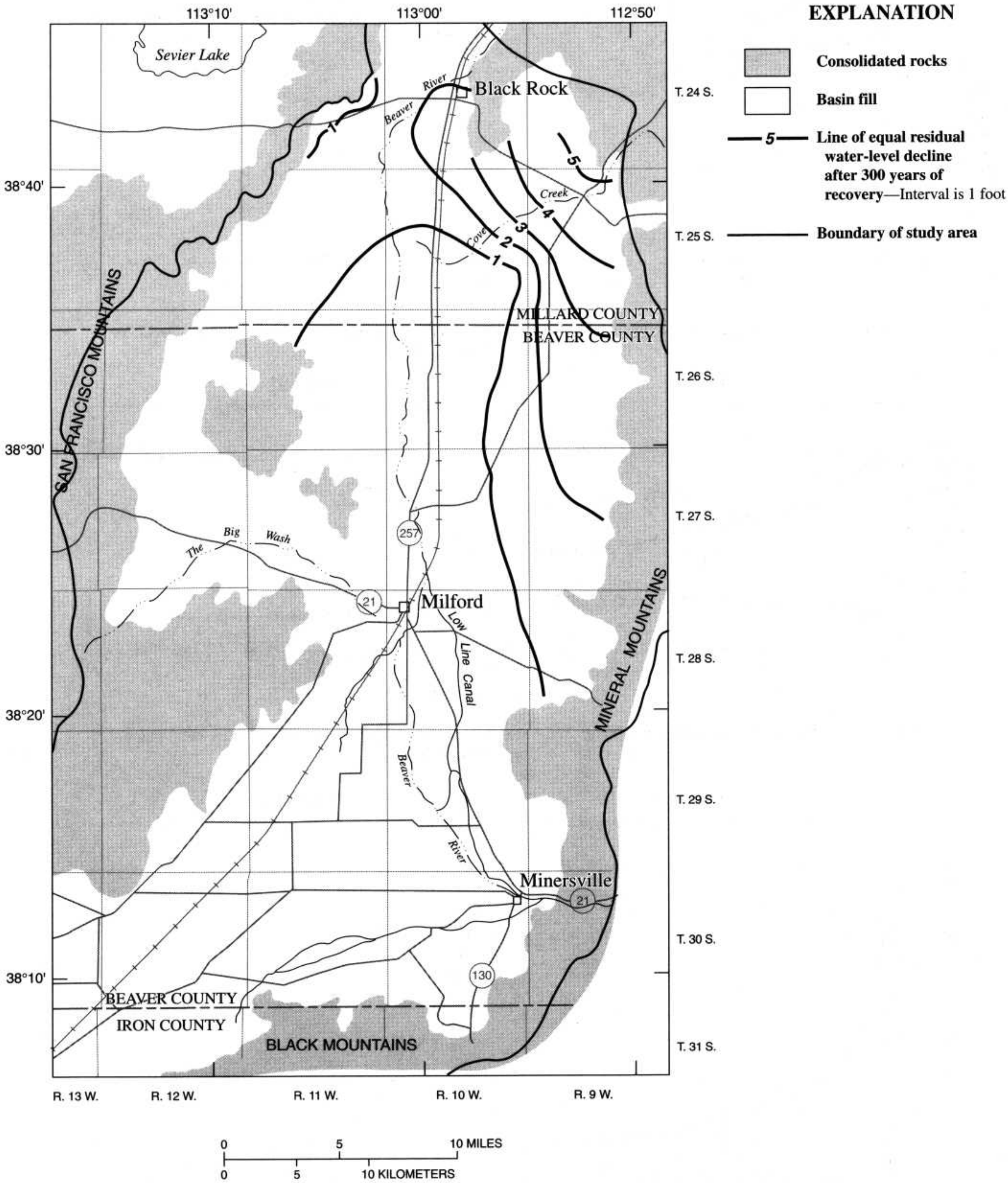


FIGURE 42.—Simulated residual water-level declines after 300 years of recovery for development alternative B1.

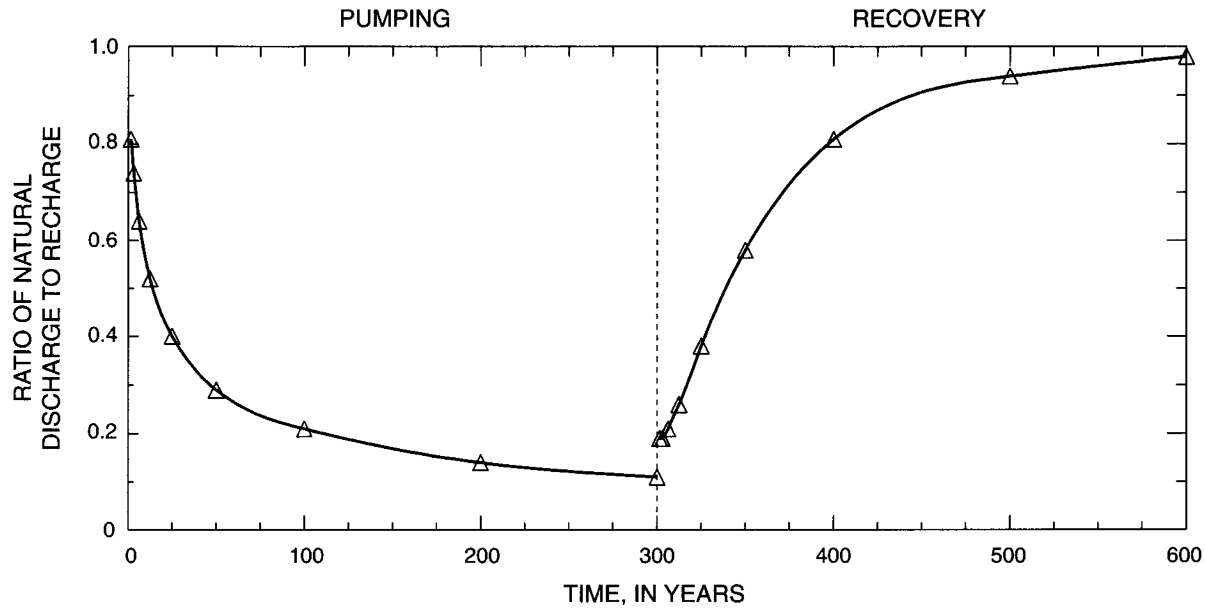


FIGURE 43.—Simulated change in the ratio of natural discharge to recharge during pumping and recovery for development alternative B1.

charge for the remaining 250 years. The same distribution of ground-water withdrawals derived for development alternative B1 was used. The response of the ground-water system to this hypothetical stress was quite different compared to the previous development alternatives.

As in development alternatives B1 and B2, a well-defined cone of depression, with water-level declines of more than 50 ft, developed in the southwest corner of the area. In this case, however, the cone of depression developed after only 50 years of pumping (fig. 50). An elongate trough of water-level declines developed along the axis of the basin with maximum declines of more than 60 ft in three separate areas. Water-level declines developed along all basin boundaries. A small trough of water-level declines developed in the extreme north end of the basin near Black Rock. Under actual conditions, water-level declines in that area probably would be less because the basalt near Black Rock could provide more water than the constant flux allowed in these simulations.

When the net ground-water withdrawals were reduced, the average water level rose in the pumped cells for the next 50 years and then stabilized for the remaining 200 years (fig. 51). Similarly, effects at both general-head boundaries stabilized after the first 50 years (fig. 52). After the full 300 years of pumping, the computed water-level declines (fig. 53) are different from the computed water-level declines after 50 years of pumping. Although water levels rose in the southern one-half of the basin, the cone of depression in the southwest corner remained well defined. Similarly, water-level declines at the southern boundaries were reduced. In contrast, water levels continued to decline throughout the northern one-half of the basin. Although the maximum water-level decline did not decrease substantially, the effects of continued pumping at the reduced rate can be seen by the increased water-level declines at the northern basin boundaries. The continued water-level declines are due to smaller transmissivity values and less recharge compared to the southern one-half of the basin.

Initially, the quantity of water removed from storage was large; but, after 25 years, it began to stabilize. When the net ground-water withdrawals were reduced for the remaining 250 years, the quantity of water removed from storage decreased drastically with the net change in storage approaching zero (fig. 54). With partial recovery in the last 250 years of pumping, water levels were able to recover more rapidly after pumping ceased. As shown in figure 55, most of the area recovered to within 1 ft of the original water levels. Residual water-level declines of more than 6 ft are found in the extreme northeast corner of the basin.

In the first 50 years of the simulation, natural discharge was captured efficiently, eliminating 86 percent. For the remainder of the pumping period, only another 5 percent of the natural discharge was eliminated (fig. 56). After 200 years, all evapotranspiration had ceased, thus natural discharge for the remaining 100 years was composed entirely of net basin outflow. After 50 years, with natural discharge mostly captured and ground-water withdrawals reduced to a quantity equal to recharge,

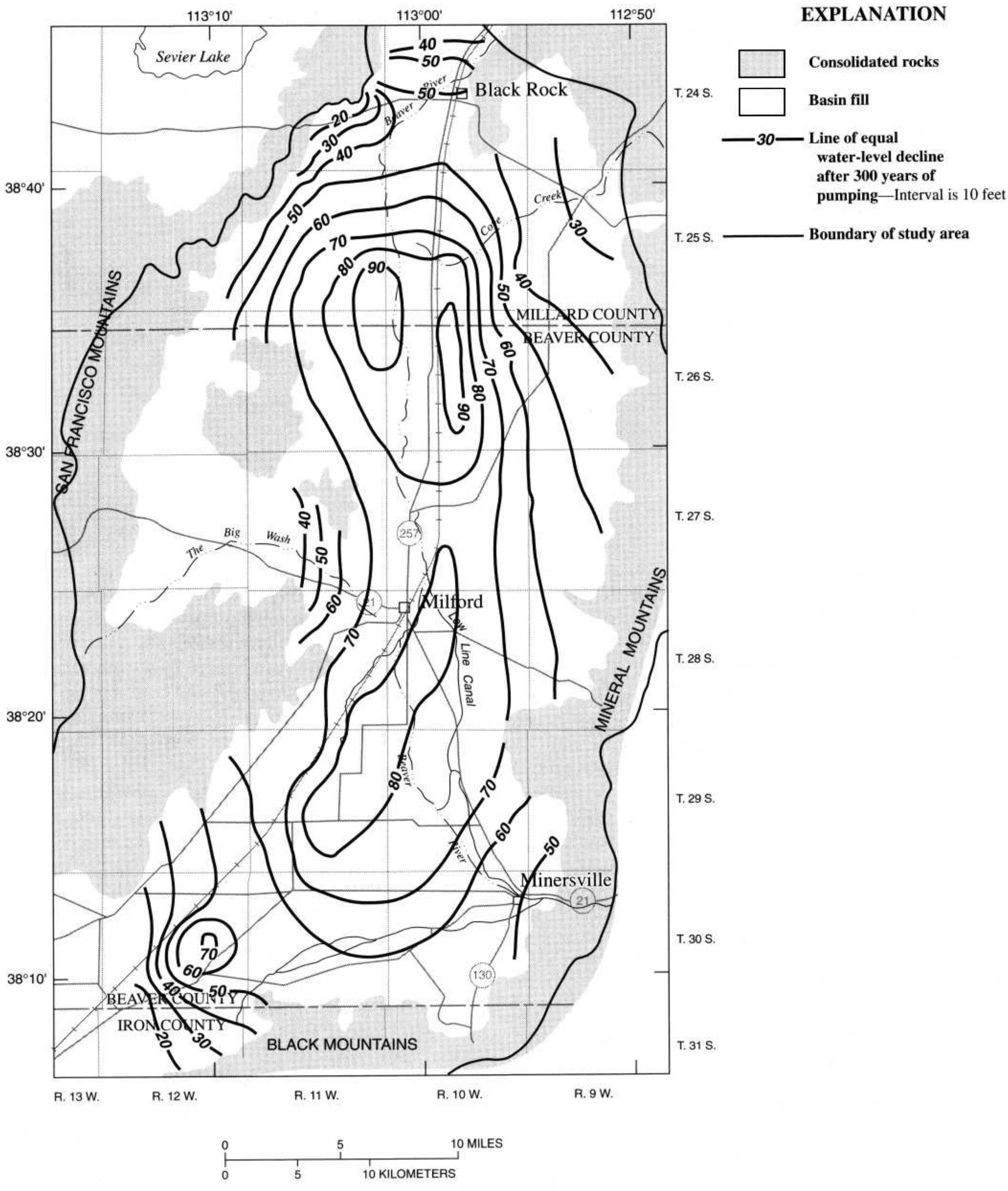


FIGURE 44.—Simulated water-level declines after 300 years of pumping for development alternative B2.

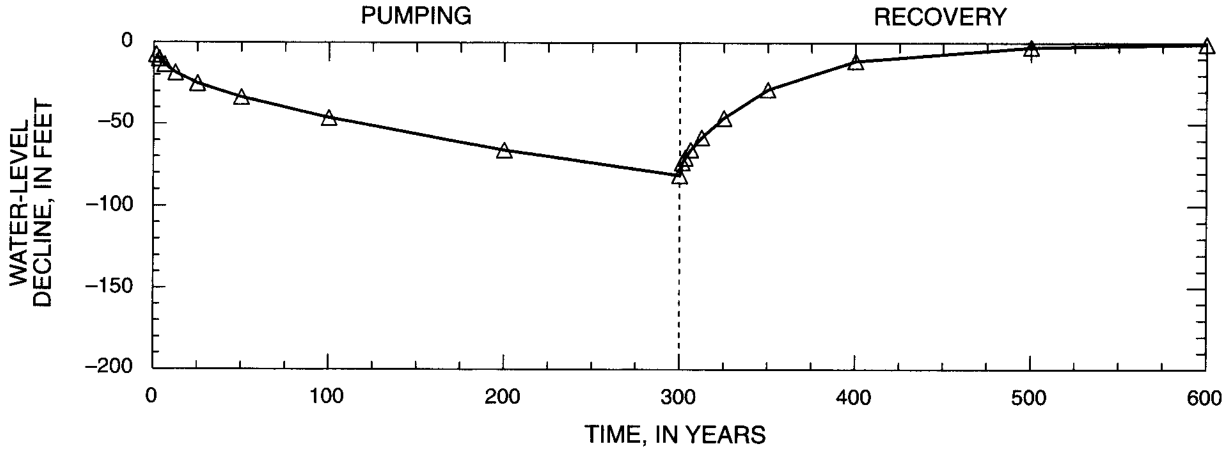


FIGURE 45.—Simulated average water-level decline and recovery in model cells containing pumped wells for development alternative B2.

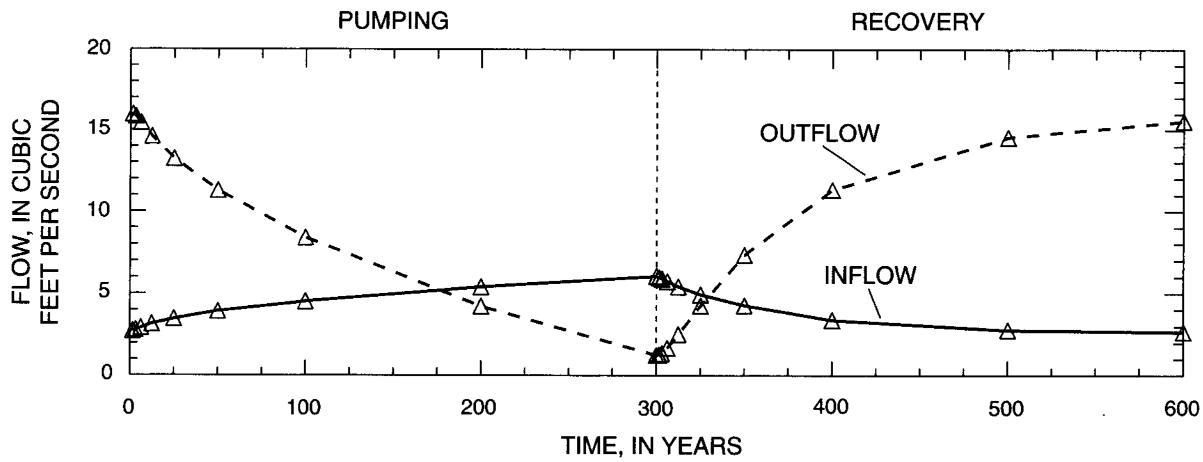


FIGURE 46.—Simulated changes in basin inflow and net outflow at general-head boundaries during pumping and recovery for development alternative B2.

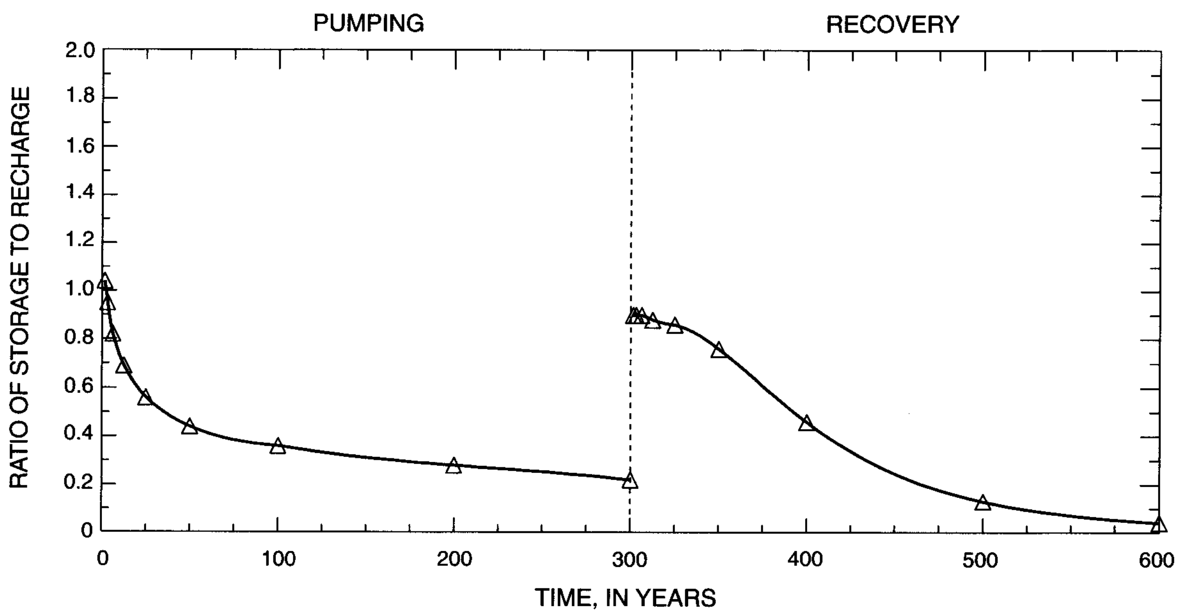


FIGURE 47.—Simulated changes in the ratios of water removed from storage during pumping to recharge and water added to storage during recovery to recharge for development alternative B2.

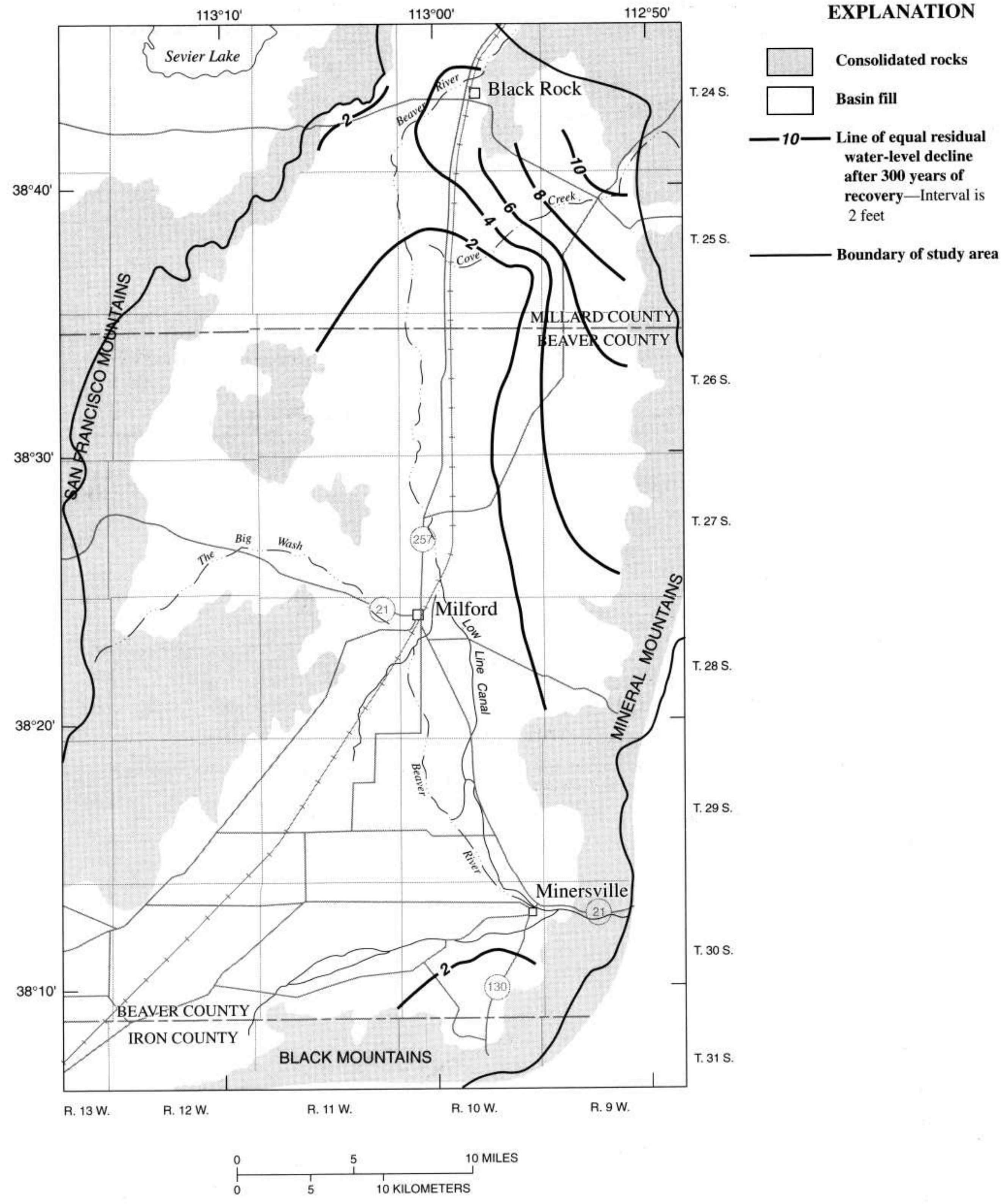


FIGURE 48.—Simulated residual water-level declines after 300 years of recovery for development alternative B2.

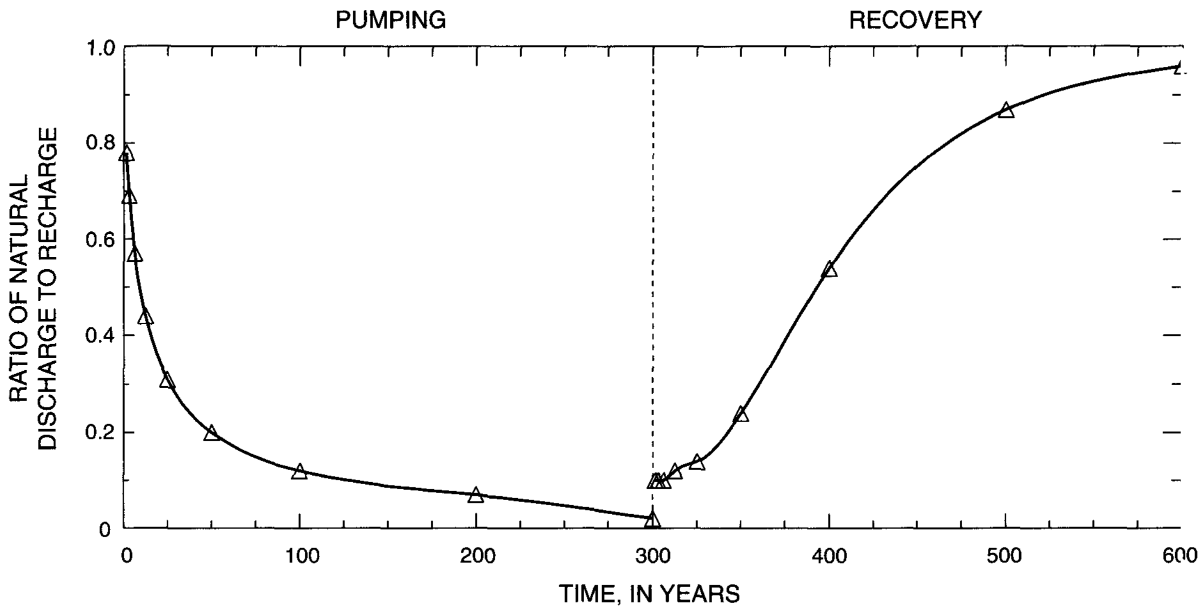


FIGURE 49.—Simulated change in the ratio of natural discharge to recharge during pumping and recovery for development alternative B2.

water removed from storage was about equal to the quantity of water exiting the basin through the general-head boundary.

### EVALUATION OF DEVELOPMENT ALTERNATIVES

Four different distributions of ground-water withdrawals were used in "sustained"-yield simulations to determine (1) their efficiency in reducing or eliminating natural discharge, (2) their effect on water-level declines, and (3) their residual effects on water-level recoveries and resumption of natural discharge after pumping ceased. Two additional simulations tested the effects of ground-water withdrawals greater than the average annual recharge.

All development alternatives resulted in declining water levels and reduced natural discharge during pumping; but in most cases, water levels and natural discharge recovered to near pre-pumping conditions after pumping had ceased. The extent of water-level declines and the rate of reduction of natural discharge was most dependent on the areal distribution of withdrawals. Because increased pumping above average annual recharge goes beyond the concept of "sustained" yield, variations in the rate of pumping were not tested for development alternatives that have concentrated pumping centers. Increasing the rate of pumping for these development alternatives would have formed deeper cones of depression and would not have decreased natural discharge substantially.

During the 300-year recovery phase, the rates at which water levels recovered and natural discharge increased were dependent on (1) the areal distribution of ground-water withdrawals relative to recharge boundaries, (2) the areal distribution of transmissivity, and (3) the quantity of water removed from storage.

"Sustained"-yield simulations involving concentrated pumping centers (development alternatives A1, A2, and A3) were least effective in reducing natural discharge, and formed well-defined cones of depression with large water-level declines. Development alternatives A1 and A2 had the largest water-level declines and the largest amount of water removed from storage (table 5). Development alternative A1, with its concentrated pumping center in the southern one-half of the basin area, had the advantage of larger transmissivity values in the pumped area and closer proximity to the main sources of recharge than alternative A2 with its pumping center in the north; therefore, water-level declines were less and recovery was faster for development alternative A1. Because natural discharge occurs throughout the basin area, neither development alternative A1 or A2 were completely effective in reducing natural discharge. Development alternative A3, which equally divided pumping between two centers, began to approach the optimum development pattern by more effectively reducing natural discharge, coupled with smaller water-level declines and less water removed from storage. These conditions allowed for faster recovery after pumping ceased.

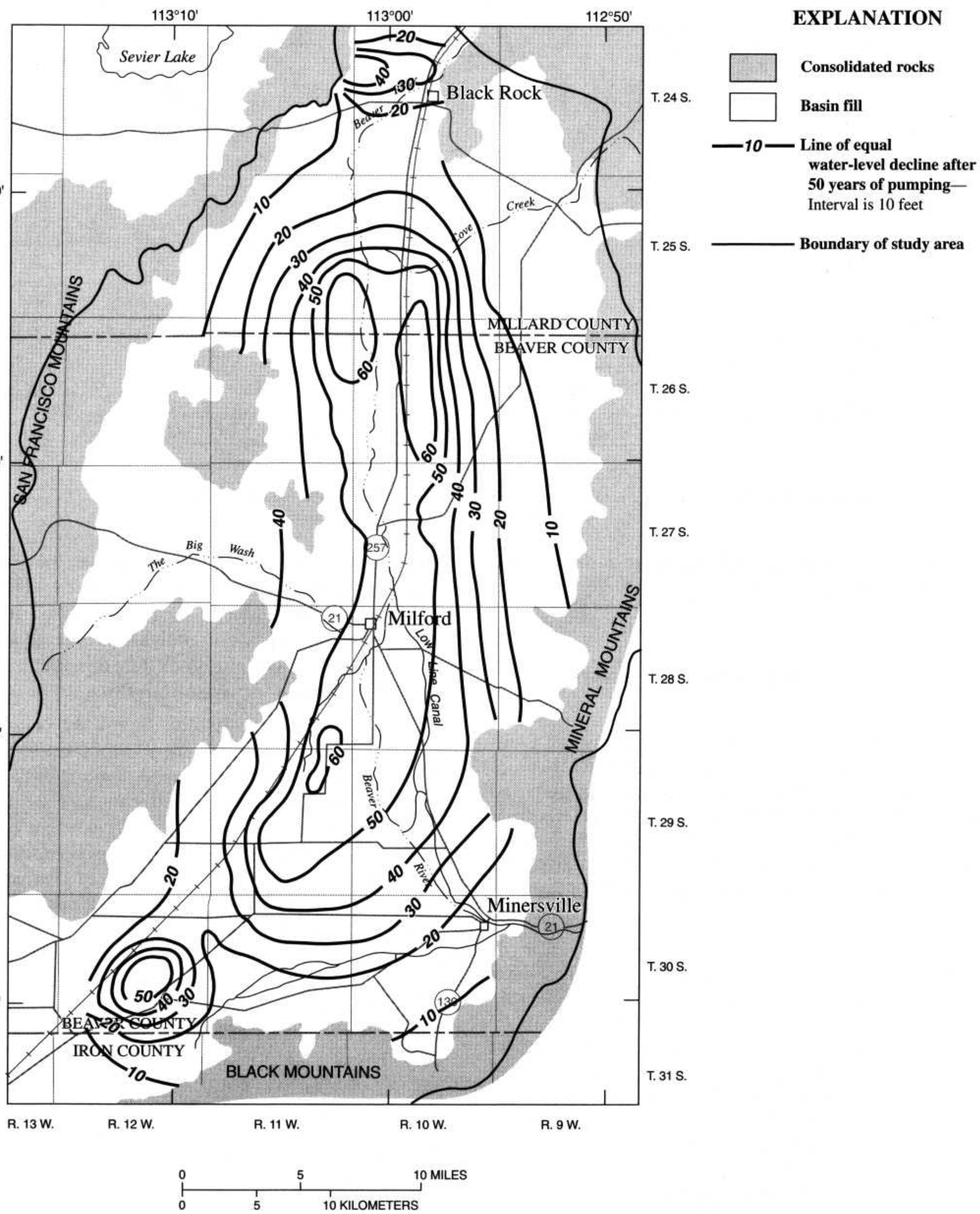


FIGURE 50.—Simulated water-level declines after 50 years of pumping for development alternative B3.

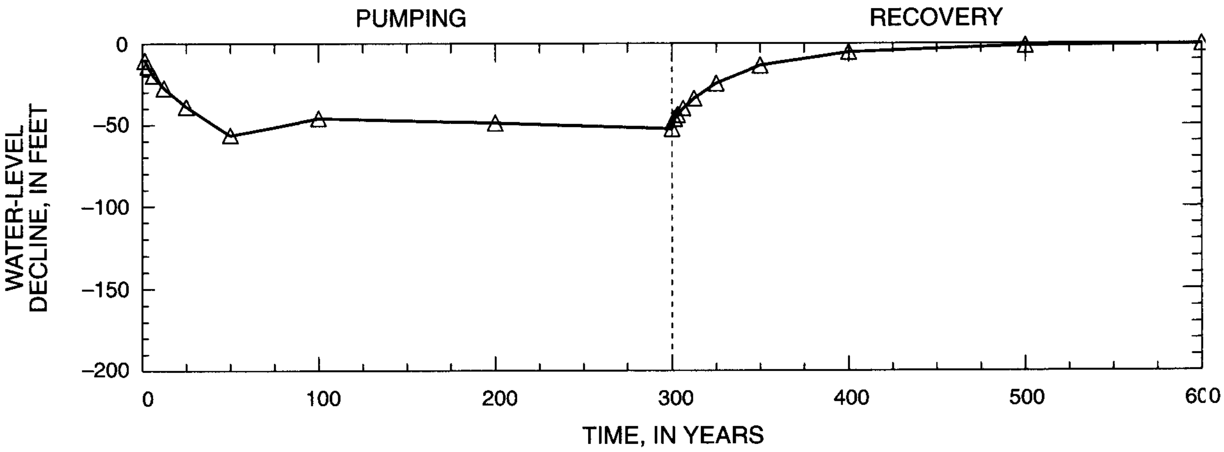


FIGURE 51.—Simulated average water-level decline and recovery in model cells containing pumped wells for development alternative B3.

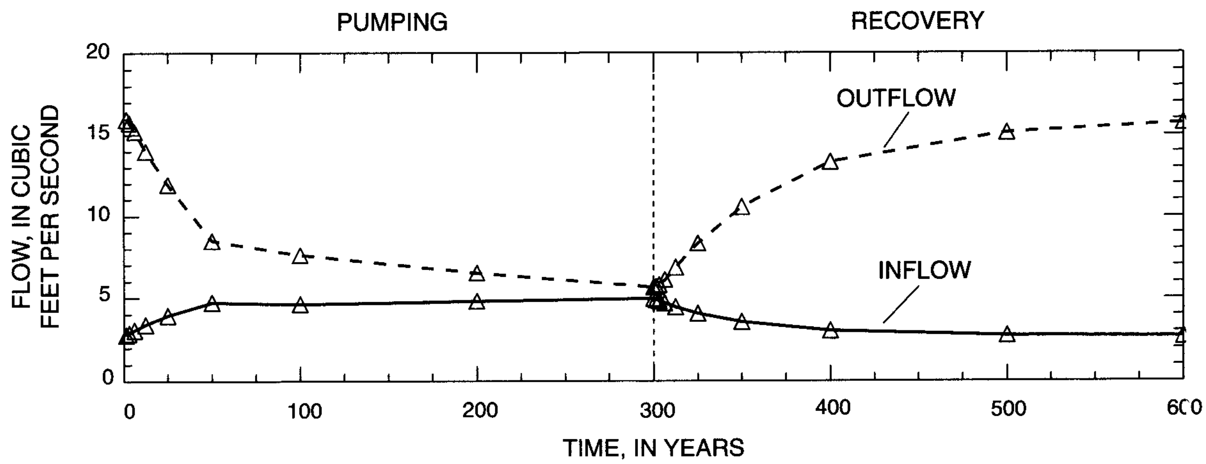


FIGURE 52.—Simulated changes in basin inflow and net outflow at general-head boundaries during pumping and recovery for development alternative B3.

A development alternative with withdrawals strategically distributed, such as development alternative B1, proved to be the most effective in reducing natural discharge, eliminating 89 percent of the total evapotranspiration and basin outflow as the ground-water system approached a new equilibrium. This was accomplished with minimal water-level declines throughout the basin and the least amount of water removed from storage (table 5). By removing ground water normally lost to evapotranspiration and basin outflow, the ground-water system was not substantially depleted, thus allowing for rapid recovery.

Development alternatives B2 and B3 provided some insight into the effects of ground-water mining by withdrawing more ground water than the average annual recharge. Net ground-water withdrawals for development alternative B2 were 1.25 times larger than the estimated average annual recharge for the basin. This development alternative almost eliminated natural discharge after 200 years of pumping, but it also produced water-level declines throughout the basin, especially in the north. Pumping at a large rate for the first 50 years, such as development alternative B3, proved to be effective in eliminating natural discharge in a short time. When the pumping rate was reduced to the estimated average annual recharge for the remaining 250 years of pumping, water levels partially recovered and then stabilized. This development alternative had two additional advantages: (1) it removed virtually no water from storage after the first 100 years of pumping, and (2) it produced the second smallest water-level declines after the full 300 years of pumping. Along with development alternative B1, this alternative could be another viable development option for the beneficial use of ground water before it is consumed by evapotranspiration or is lost by flowing out of the basin, despite the initial disadvantage of large water-level declines that might promote the compaction of sediments and land subsidence.

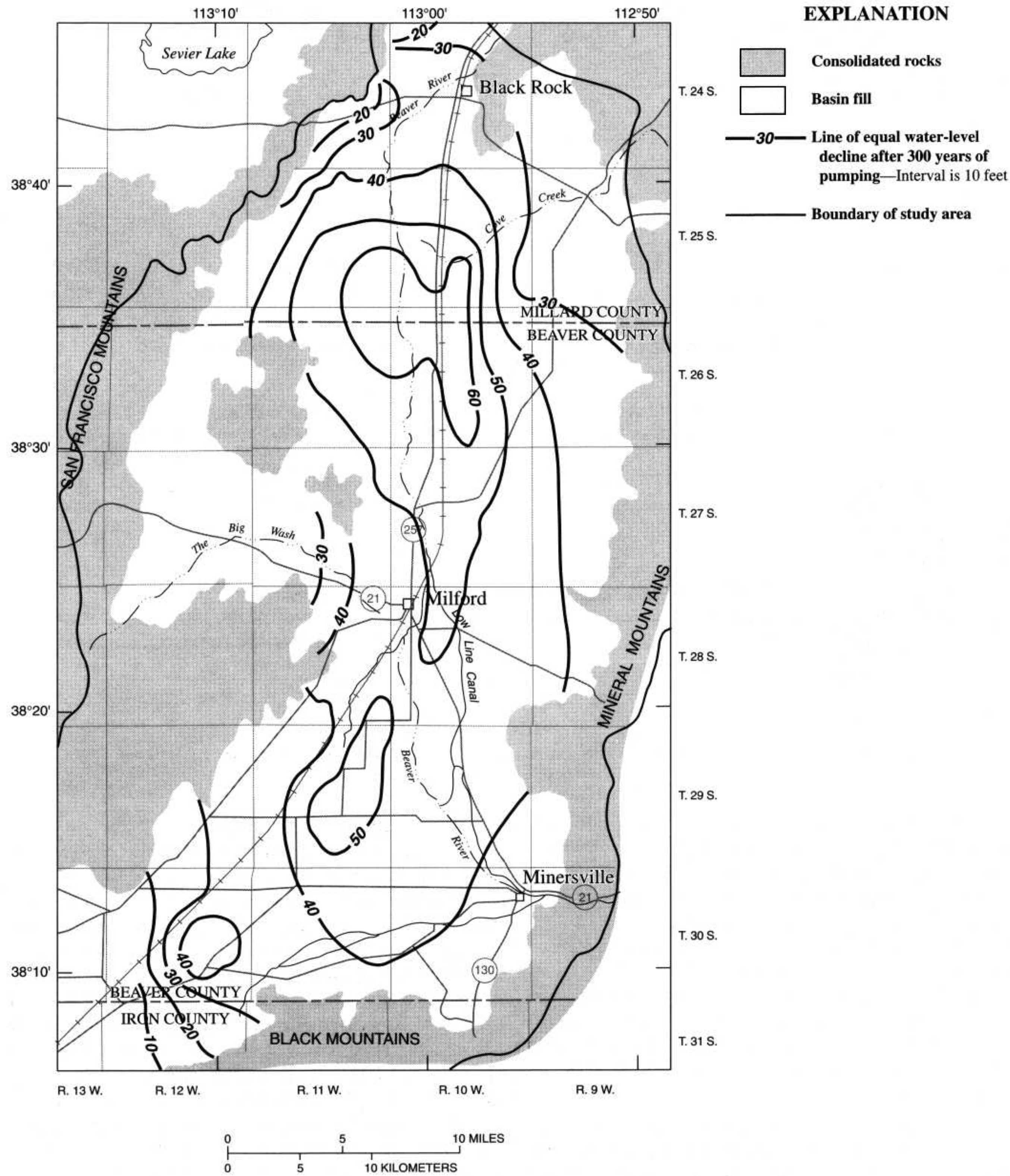


FIGURE 53.—Simulated water-level declines after 300 years of pumping for development alternative B3.

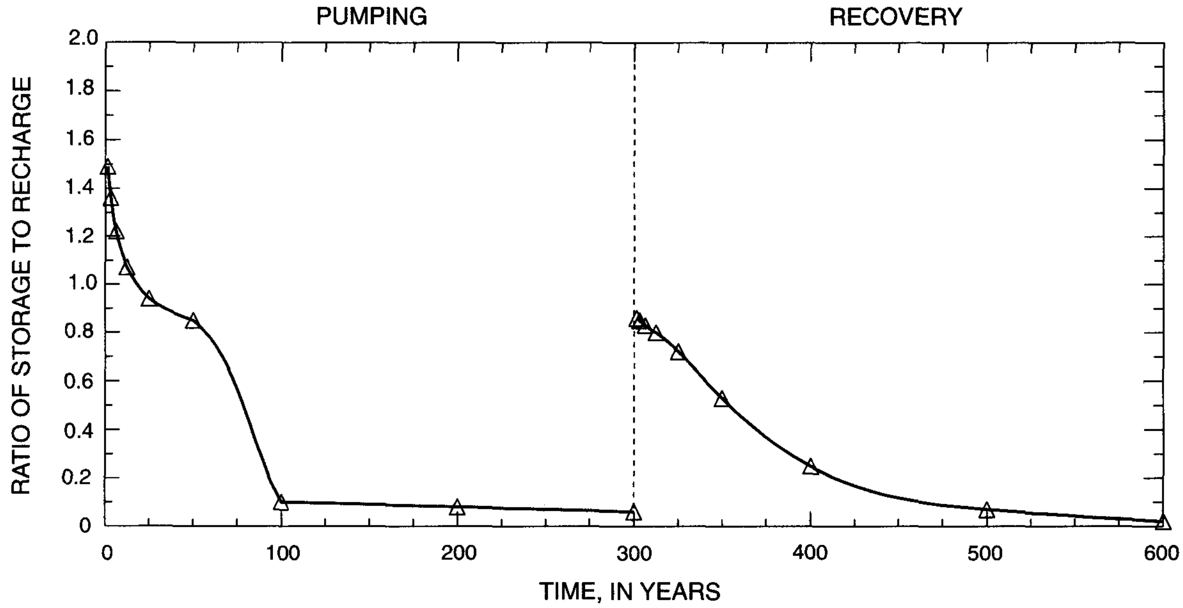


FIGURE 54.—Simulated changes in the ratios of water removed from storage during pumping to recharge and water added to storage during recovery to recharge for development alternative B3.

TABLE 5.—*Cumulative total of simulated water removed from storage after pumping and recovery for each development alternative in the Milford area, Utah*

[Data are in cubic feet; acre-feet shown in parentheses]

| Development alternative | Following pumping | Following recovery |
|---|---|---|
| A1 | $1.88 \times 10^{11}$ | $4.53 \times 10^{9}$ |
| | (4,320,000) | (104,000) |
| A2 | $2.20 \times 10^{11}$ | $1.73 \times 10^{10}$ |
| | (5,050,000) | (397,000) |
| A3 | $1.53 \times 10^{11}$ | $6.85 \times 10^{9}$ |
| | (3,510,000) | (157,000) |
| B1 | $1.11 \times 10^{11}$ | $3.08 \times 10^{9}$ |
| | (2,550,000) | (70,700) |
| B2 | $2.06 \times 10^{11}$ | $7.21 \times 10^{9}$ |
| | (4,730,000) | (166,000) |
| B3 | $1.39 \times 10^{11}$ | $4.23 \times 10^{9}$ |
| | (3,190,000) | (97,100) |

## NEED FOR FUTURE STUDIES

Transient simulations produced water-level declines at the basin fill-consolidated rock interface that might not occur if the consolidated rocks are able to yield and transmit water readily to the basin fill. In this study, the flux entering the ground-water system from consolidated rocks at the margin of the basin was determined initially by using constant-head cells along this boundary. Because of the lack of data, the estimated water levels at these cells may lead to uncertainty in the estimated flux. Additional well data and, if possible, aquifer-test data would help define the hydraulic properties of the basin fill at these boundaries and permit a better estimate for this uncertain component of the water budget.

This study redefined the flow direction in the northern one-half of the study area, using limited test-hole data. Additional data might better define the extent and quantity of basin outflow along the northwest boundary.

The vertical head gradient within the area of present ground-water development had to be estimated because water-level data solely from the confined aquifer were lacking. Data from newer wells completed only in the confined aquifer, without multiple perforated zones, might permit a refined conceptualization of the ground-water system. Aquifer tests using wells with limited perforated zones might permit better estimates of vertical hydraulic conductivity and vertical hydraulic gradient. With this information, transient simulations could project effects of future ground-water withdrawals within the developed area with greater accuracy.

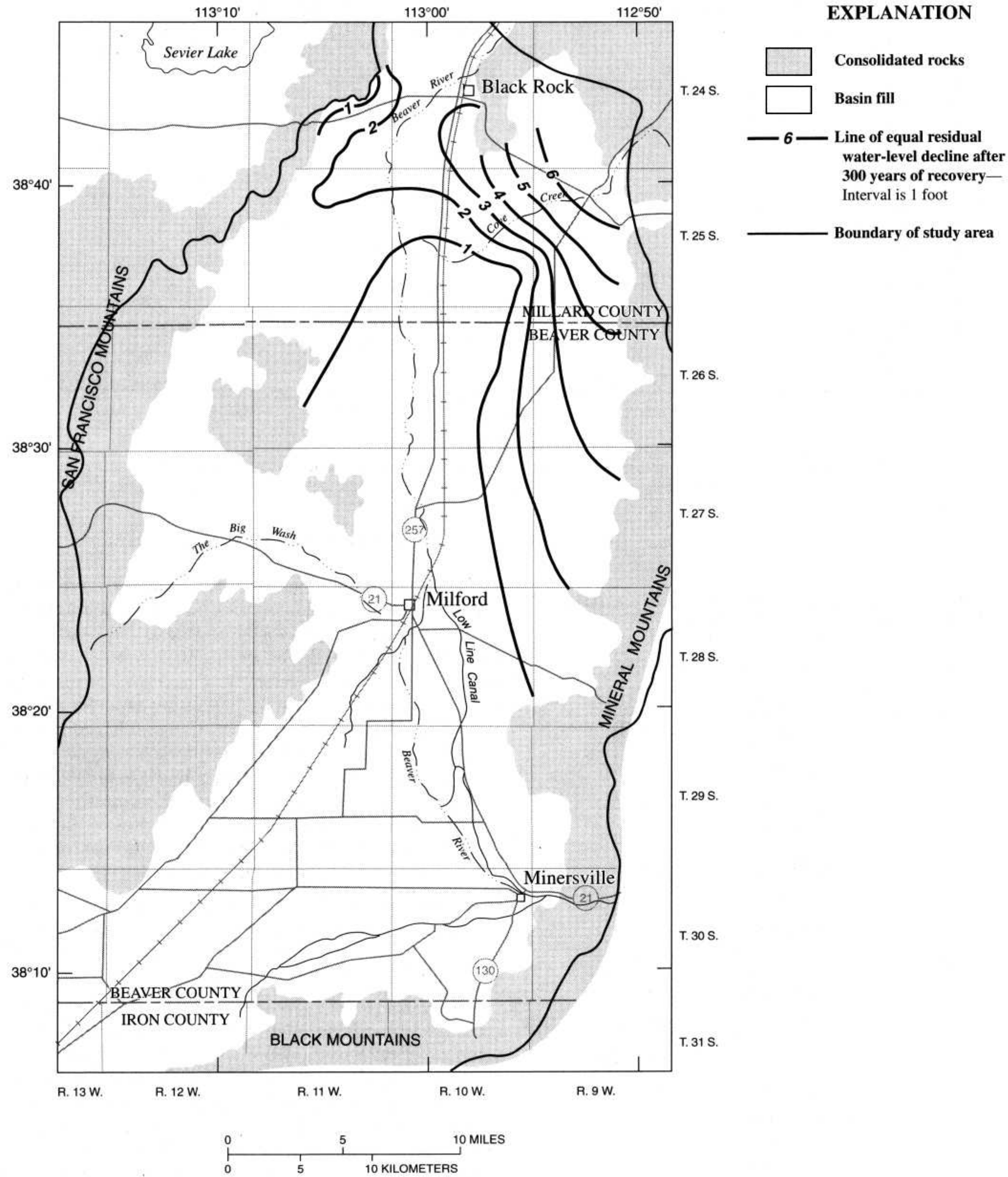


FIGURE 55.—Simulated residual water-level declines after 300 years of recovery for development alternative B3.

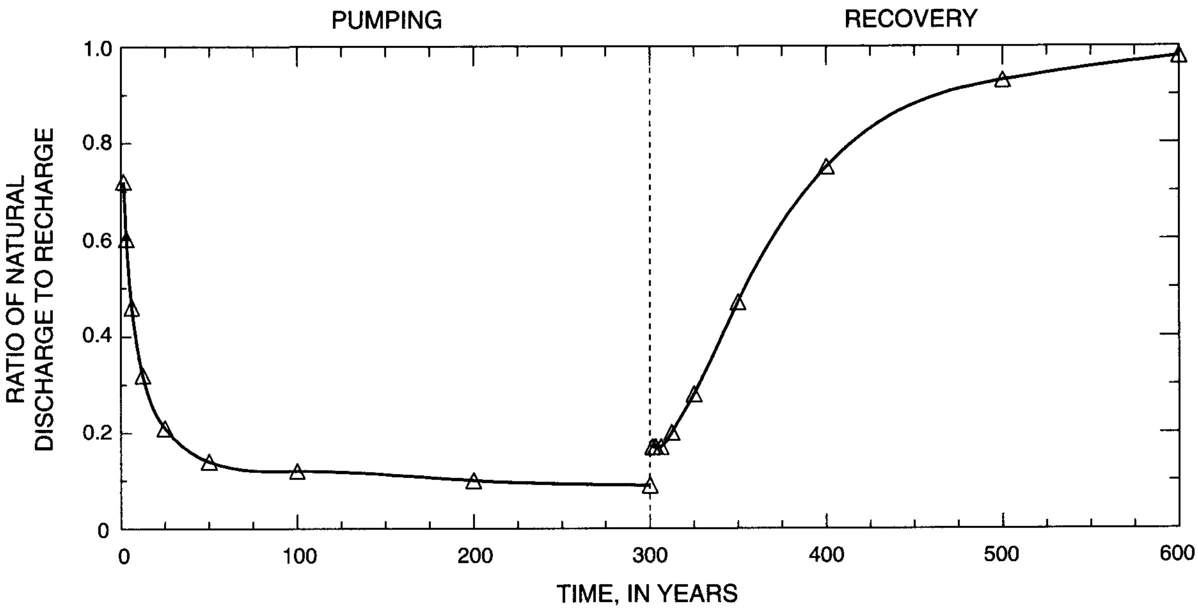


FIGURE 56.—Simulated change in the ratio of natural discharge to recharge during pumping and recovery for development alternative B3.

## SUMMARY

As part of the Great Basin Regional Aquifer-System Analysis program, a three-dimensional, finite-difference model was constructed to simulate the ground-water system in the Milford area of southwestern Utah. The calibrated model was used to make short-term predictive simulations to estimate water-level declines using the current (1984) pumping distribution, and hypothetical long-term simulations using several different pumping distributions.

Ground-water movement in the basin-fill aquifer generally is from south to north with a prominent east-west component of flow from the eastern recharge boundary along the Mineral Mountains toward the center of the basin. Recharge from the western boundary appears to be inconsequential; therefore, the flow direction along the western margin basically parallels the main flow direction in the center of the basin. Measured and inferred water levels from new test holes in the northwest part of the basin indicate that ground water exits the basin in a northwesterly direction through the north end of the San Francisco Mountains rather than as underflow following the Beaver River drainage to the north.

The basin-fill aquifer was simulated by using three layers to represent the three-dimensional system. After the model was calibrated, simulations were able to approximate steady-state conditions for 1927 and transient conditions from 1950-82. Through steady-state calibration, subsurface inflow from consolidated rocks along the Mineral Mountains was computed to be almost 24,000 acre-ft/yr. Basin outflow to the northwest was computed to be more than 11,000 acre-ft/yr and evapotranspiration was computed to be almost 27,000 acre-ft/yr. Two transient simulations using constant and varying recharge from surface water for each stress period were made to test the effects of these conditions on the ground-water system. With the present model-grid configuration, substantial differences in computed water-level changes between the two methods of simulating recharge are indicated in the vicinity of the Beaver River in the southeast part of the area; but, for most of the simulated area, minimal or no differences in water levels were indicated.

Sensitivity analysis showed that the largest changes in the computed-head distributions were caused by changes in recharge at the eastern boundary, evapotranspiration rates, and evapotranspiration extinction depths. Similarly, the largest changes in ground-water flow at head-dependent boundaries, such as the general-head boundaries and the area of evapotranspiration, were caused by changes in recharge at the eastern boundary, evapotranspiration rates and extinction depths, and transmissivity values.

The calibrated ground-water flow model was used to make short-term predictive simulations over a 37-year period from 1983 to 2020. Three simulations were made using rates of ground-water withdrawal equal to 1, 1.5, and 2 times the 1979-82 average rate. Water-level declines of about 6 to 12 ft were projected using the average rate for 1979-82. The declines are minimal primarily because the average rate of withdrawal for 1979-82 is virtually equal to the estimated average annual recharge. At 1.5 times the 1979-82 average rate, projected maximum water-level declines increased to more than 35 ft. Although this rate of withdrawal was reached only once (1974) in the Milford area, future long-term average withdrawals could conceivably approach this level. As a worst-case simulation, maximum water-level declines of more than 70 ft were projected using withdrawals equal to twice the 1979-82 average rate.

In order to test the concepts of "sustained" yield, ground-water mining, and the capture of natural discharge, several 600-year simulations were made using hypothetical distributions of ground-water withdrawals. Simulations using concentrated pumping centers were the least efficient at eliminating natural discharge and approaching new equilibrium conditions, and produced the largest water-level declines. Simulations using a distribution with ground-water withdrawals strategically placed in discharge areas were the most efficient at eliminating natural discharge, and in some cases approached a new equilibrium condition.

## REFERENCES CITED


Appel, C.L., and others, 1983, Ground-water conditions in Utah, spring of 1983: Utah Division of Water Resources Cooperative Investigations Report No. 23, 97 p.

Armstrong, R.L., 1970, Geochronology of Tertiary igneous rocks, eastern Basin and Range Province, western Utah, eastern Nevada, and vicinity, U.S.A.: Geochimica et Cosmochimica Acta, v. 34, p. 203-232.

Arnow, Ted, and Mattick, R.E., 1968, Thickness of valley fill in the Jordan Valley east of Great Salt Lake, Utah: U.S. Geological Survey Professional Paper 600-B, p. B79-B82.

Avery, C.F., and others, 1984, Ground-water conditions in Utah, spring of 1984: Utah Division of Water Resources Cooperative Investigations Report No. 24, 79 p.

Bowman, J.R., and Rohrs, D.T., 1981, Light stable isotope studies of spring and thermal waters from the Roosevelt Hot Springs and Cove Fort/Sulphurdale thermal areas and of clay minerals from the Roosevelt Hot Springs thermal area: U.S. Department of Energy Report No. ID/12079-44, Department of Geology and Geophysics, University of Utah, 36 p.

Brumbaugh, W.D., and Cook, K.L., 1977, Gravity survey of the Cove Fort-Sulphurdale KGRA and the north Mineral Mountains area, Millard and Beaver Counties, Utah: U.S. Department of Energy Technical Report v. 77-4, contract EY-76-S-07-1601, Department of Geology and Geophysics, University of Utah, 130 p.

Carter, J.A., and Cook, K.L., 1978, Regional gravity and aeromagnetic surveys of the Mineral Mountains and vicinity, Millard and Beaver Counties, Utah: U.S. Department of Energy Final Report v. 77-11, contract EY-76-S-07-1601, Department of Geology and Geophysics, University of Utah, 179 p.

Condie, K.C., and Barsky, C.K., 1972, Origin of Quaternary basalts from the Black Rock Desert region, Utah: Geological Society of America Bulletin, v. 83, no. 2, p. 333-352.

Crebs, T.J., and Cook, K.L., 1976, Gravity and ground magnetic surveys of the central Mineral Mountains, Utah: Final Report v. 6, National Science Foundation Grant GI-43741, Department of Geology and Geophysics, University of Utah, 129 p.

Criddle, W.D., 1958, Consumptive use and irrigation water requirements of Milford Valley: U.S. Department of Agriculture, Agriculture Research Service, 41-14, 45 p.

Dennis, P.E., 1942, Shorelines of the Escalante Bay of Lake Bonneville: Utah Academy of Science, Arts, and Letters Proceedings, v. 19, p. 121-124.

Fenneman, N.M., 1931, Physiography of the western United States: New York, McGraw-Hill, 534 p.

Gertson, R.C., and Smith, R.B., 1979, Interpretation of a seismic refraction profile across the Roosevelt Hot Springs, Utah and vicinity: U.S. Department of Energy Report No. ADO/78-1701.a.3, Department of Geology and Geophysics, University of Utah, 120 p.

Harrill, J.R., Welch, A.H., Prudic, D.E., Thomas J.M., Carman, R.L., Plume, R.W., Gates, J.S., and Mason, J.L., 1983, Aquifer systems in the Great Basin region of Nevada, Utah, and adjacent states: A study plan: U.S. Geological Survey Open-File Report 82-445, 49 p.

Hintze, L.F., 1973, Geologic history of Utah: Brigham Young University Geology Studies, v. 20, part 3, 181 p.

———1980, Geologic map of Utah: Utah Geological and Mineral Survey, 1 sheet, scale 1:500,000.

Keys, W.S., and MacCary, L.M., 1971, Applications of borehole geophysics to water-resources investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 2, chap. E1, 126 p.

Lemmon, D.M., and Morris, H.T., 1983, Preliminary geologic map of the Beaver Lake Mountains quadrangle, Beaver and Millard Counties, Utah: U.S. Geological Survey Open-File Report 83-181, 14 p.

Lohman, S.W., 1972, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

Maxey, G.B., and Eakin, T.E., 1949, Ground water in White River Valley, White Pine, Nye, and Lincoln Counties, Nevada: Nevada State Engineer Water-Resources Bulletin No. 8, 59 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, various pagination.

Moore, D.O., 1968, Estimating mean runoff in ungaged semiarid areas: Nevada Department of Conservation and Natural Resources Water-Resources Bulletin 36, p. 29-39.

Mower, R.W., 1982, Hydrology of the Beryl-Enterprise area, Escalante Desert, Utah, with emphasis on ground water: Utah Department of Natural Resources Technical Publication No. 73, 66 p.

Mower, R.W., and Cordova, R.M., 1974, Water resources of the Milford Area, Utah, with emphasis on ground water: Utah Department of Natural Resources Technical Publication No. 43, 106 p.

Mower, R.W., and Feltis, R.D., 1968, Ground-water hydrology of the Sevier Desert, Utah: U.S. Geological Survey Water-Supply Paper 1854, 75 p.

Nelson, W.B., 1950, Ground water in the Milford District *in* Fix, P.F., Nelson, W.B., Lofgren, B.E., and Butler, R G., Ground water in the Escalante Valley, Beaver, Iron, and Washington Counties, Utah: Utah State Engineer Technical Publication No. 6 (Utah State Engineer 27th Biennial Report), p. 180-210.

———1954, Status of ground-water development in four irrigation districts in southwestern Utah, *in* Progress report on selected ground-water basins in Utah: Utah State Engineer Technical Publication No. 9, p. 5-93.

Nelson, W.B., and Thomas, H.E., 1952, Milford district of Escalante Valley, Beaver County, *in* Thomas, H.E., Nelson, W.B., Lofgren, B.E., and Butler, R.G., Status of development of selected ground-water basins in Utah: Utah State Engineer Technical Publication No. 7, p. 49-56.

Rohrs, D.T., and Bowman, J.R., 1980, A light stable isotope study of the Roosevelt Hot Springs area, southwestern Utah: U.S. Department of Energy Report No. IDO/78-1701.a.1.5, Department of Geology and Geophysics, University of Utah, 88 p.

Sandberg, G.W., 1962, Ground-water conditions in the Milford and Beryl-Enterprise districts and in Cedar City and Parowan Valleys, Utah, 1954-60: U.S. Geological Survey Open-File Report, 84 p.

———1966, Ground-water resources of selected basins in southwestern Utah: Utah State Engineer Technical Publication No. 13, 46 p.

Seiler, R.L., and others, 1985, Ground-water conditions in Utah, spring of 1985: Utah Division of Water Resources, Cooperative Investigations Report No. 25, 84 p.

Smith, J.L., 1980, A model study of the regional hydrogeologic regime, Roosevelt Hot Springs, Utah: U.S. Department of Energy Report IDO/78-28392.a.10, Department of Geology and Geophysics, University of Utah, 30 p.

Thangsuphanich, I., 1976, Regional gravity survey over the southern Mineral Mountains, Beaver County, Utah: unpublished M.S. thesis, University of Utah, 37 p.

U.S. Weather Bureau, [1963], Normal annual and May-September precipitation (1931-60) for the State of Utah: Map of Utah, 2 sheets, scale 1:500,000.

Ward, S.H., Parry, W.T., Nash, W.P., Sill, W.R., Cook, K.L., Smith, R.B., Chapman, D.S., Brown, F.H., Whelan, J.A., and Bowman, J.R., 1978, A summary of the geology, geochemistry, and geophysics of the Roosevelt Hot Springs Thermal area, Utah: Geophysics, v. 43, p. 1515-1542.

White, W.N., 1932, A method of estimating ground-water supplies based on discharge by plants and evaporation from soil--results of investigations in Escalante Valley, Utah: U.S. Geological Survey Water-Supply Paper 659-A, p. 1-105.

Willardson, L.S., and Bishop, A.A., 1967, Analysis of surface irrigation application efficiency: American Society of Civil Engineers Proceedings, Journal of Irrigation and Drainage Division, v. 93, no. IR2, Paper 5267, p. 21-36.