Results of Hypothetical Ground-Water Pumping in Carson Valley, a River-Dominated Basin in Douglas County, Nevada, and Alpine County, California

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 95-4174

A product of the Regional Aquifer-System Analysis of the Great Basin—Nevada, Utah, and adjacent states

U.S. DEPARTMENT OF THE INTERIOR
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Carson City, Nevada
1995

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
acre-foot (acre-ft)	1,234	cubic meter
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
foot (ft)	0.3048	meter
foot per second (ft/s)	0.3048	meter per second
inch (in.)	2.540	centimeter
inch per year (in/yr)	2.540	centimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	2.59	square kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot per year (ft/yr)	0.0008351	meter per day

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929, formerly called "Sea-Level Datum of 1929"), which is derived from a general adjustment of the first-order leveling networks of the United States and Canada.

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ABSTRACT

Five scenarios of hypothetical ground-water pumping were simulated using a ground-water flow model for the basin-fill aquifer in Carson Valley, Nevada-California, as part of the Great Basin Regional Aquifer-System Analysis project in Nevada, Utah, and adjacent states. The purpose of the simulations is to compare changes in ground-water flow resulting from different distributions of pumping in and between selected basins having different hydrologic and physical characteristics. Carson Valley was chosen for the simulations because it is representative of basins where the aquifer is in direct hydraulic connection with a river.

Ground water is generally unconfined near land surface and confined at depth where finer grained sediments in the basin-fill aquifer impede vertical flow. Confined ground-water levels are generally 5 to 20 feet above land surface on the valley floor. Ground-water flow within the aquifer is generally from the edges of the basin to the center of the valley, then northward. Recharge is from precipitation that falls within the Carson Valley drainage area, which includes the adjacent mountains. Some of the precipitation that falls on the adjacent mountains recharges the aquifer along the margins as subsurface flow or as leakage from perennial and ephemeral streams that carry runoff from the mountains into the valley and from irrigation ditches. Discharge from the aquifer consists primarily of evapotranspiration on the valley floor and seepage to the Carson River and ditches.

Each of the five hypothetical scenarios simulated a pumpage of 100,000 acre-feet per year. This quantity approximately equals the simulated steady-state recharge excluding leakage from the Carson River and ditches. To simplify the model simulation, secondary recharge of pumped water or redistribution of a percentage of the pumped water into the Carson River is not considered. Some of the pumped water usually returns as secondary recharge or flows into streams or ditches. Thus, the simulations represent maximum drawdown and changes in recharge and discharge compared with what actually may occur.

Pumpage was divided among model cells in the upper, unconfined layer and the lower, confined layer. Each hypothetical scenario is simulated for 600 years—300 years of pumping followed by 300 years of recovery—to allow the aquifer to reach equilibrium during pumping and to return to initial conditions after pumping ceases. The same pumping and recovery periods are used for simulation of hypothetical scenarios in other selected basins in the Great Basin study area for comparison purposes.

Results from all five hypothetical scenarios indicate that leakage from the Carson River and associated ditches and ground-water seepage to the river and ditches would respond rapidly to pumping anywhere in the valley. Overall, pumping in all five scenarios reduces surface-water outflow from the valley, by 76,000 to 86,000 acre-feet per year (26 to 29 percent of the average annual outflow), depending on the location of pumping. The reduction in surface-water outflow accounts

for 76 to 86 percent of the simulated pumpage. Evapotranspiration decreases between 15,000 and 24,000 acre-feet per year (10 to 16 percent of average annual evapotranspiration). When pumping is stopped, the aquifer returns to near-initial conditions within 100 years. In conclusion, pumping ground water from basin-fill aquifers that are hydraulically connected to rivers within the Great Basin study area likely will reduce surface-water outflow from the basins before capturing evapotranspiration. Consequently, the quantity of pumping may depend on how much reduction in surface-water outflow can be tolerated.

INTRODUCTION

Scenarios of hypothetical ground-water pumping have been simulated using a ground-water flow model of Carson Valley, Douglas County, Nev., and Alpine County, Calif. (fig. 1). The simulations, which are discussed herein, were done as part of the Great Basin Regional Aquifer–System Analyses (RASA) study of Nevada, Utah, and adjacent states. The Great Basin RASA study is part of a National program to provide information on the geohydrology and geochemistry of regional aquifer systems in the United States, which can be used for regional assessment of ground-water resources (Bennett, 1979; Weeks and Sun, 1987, p. 1).

The Great Basin RASA study area is characterized by north to northeast-trending basins and mountains. The basins are partly filled with sedimentary deposits eroded from the adjacent mountains. These deposits are the principal aquifers in the basins and are referred to as basin-fill aquifers. The basin-fill aquifers are considered a regional aquifer system because individual basins typically share common characteristics (Harrill and others, 1983, p. 3). Generally, the basins are interconnected by permeable sedimentary deposits or consolidated rock, or are joined by a through-flowing river and its associated alluvium, or are isolated hydrologic systems.

A total of 240 areas that include the basin (or valley) and the drainage areas of the adjacent mountains are recognized within the Great Basin study area (referred to as hydrographic areas by Harrill and others, 1983, p. 24). Scenarios of hypothetical ground-water pumping were simulated for five basins. The purpose of the simulations is to compare changes in ground-water flow resulting from different distributions of pumping in and between basins having different hydrologic and physical characteristics. Such comparisons are important to better understanding the general response of basin-fill aquifers to pumping. The general concept that pumping ground-water from an aquifer must be balanced by an increase in recharge, by a decrease in discharge from the aquifer elsewhere, by a loss of storage in the aquifer, or by a combination of these factors was addressed many years ago by Theis (1940, p. 277). However, differences in the timing and distribution of these responses to pumping from aquifers in the Great Basin study area commonly are not included in managing the ground-water resources. In many basins, the magnitude of pumping may depend on the hydrologic effects that can be tolerated (Bredehoeft and others, 1982, p. 56).

Carson Valley was chosen for study because it is representative of basins where the basin-fill aquifer is hydraulically connected to a river, and because a ground-water flow model exists (Maurer, 1986, 1992) that can simulate the effects of pumping on ground-water flow and flow in the Carson River. The Carson River joins several basins, including Carson Valley, to form a river-connected aquifer system. Streams entering Carson Valley are diverted into a complicated flow-routing system for irrigation of alfalfa and native grass. The irrigation system uses natural channels and hundreds of ditches to distribute surface water over the valley floor (Maurer, 1986, p. 13). Throughout much of the valley floor, surface water is directly connected to the basin-fill aquifer.

The ground-water flow model was developed as part of a cooperative study with the Douglas County Department of Public Works, in response to increased demand for ground water (Maurer, 1986, p. 3). The basin-fill aquifer in Carson Valley is a major source of potable ground water in the Carson River drainage area (Glancy and Katzer, 1975, p. 15). The aquifer is the sole source of water for a rapidly expanding urban population. Consequently, pumping of ground water is increasing.

Purpose and Scope

This report describes five scenarios of hypothetical ground-water pumping simulated using the ground-water flow model of the basin-fill aquifer. The report has three purposes. First, it briefly describes the basin-fill aquifer and ground-water flow model; a detailed description of the aquifer and model is given by Maurer (1986). Second, it describes the five scenarios of hypothetical pumping. And third, it summarizes the results of the model simulations.

Each scenario is simulated for an arbitrary period of 600 years—300 years of pumping followed by 300 years of no pumping. Similar scenarios were simulated for the other basins chosen for analysis by the RASA study. The 300-year pumping period was chosen to allow sufficient time for the basin-fill aquifer to reach a new equilibrium (steady-state condition), enabling a comparison among the aquifers. Likewise, the 300-year recovery period was chosen to allow sufficient time for each aquifer to return to its initial condition.

Physical Setting

Carson Valley is a north-trending alluvial basin that encompasses about 360 mi^2, mainly in Douglas County, Nev., and extending southwestward into Alpine County, Calif. (fig. 1). The valley is bounded on the west by the Carson Range of the Sierra Nevada, and on the east by the Pine Nut Mountains. The valley floor slopes from an altitude of about 5,000 ft above sea level in the south to about 4,600 ft in the north where the Carson River exits the valley.

Climate

Although somewhat more lush than most valleys in the Great Basin RASA study area, the climate is characteristic of the region. Most of the precipitation results from Pacific storm systems, which are common from November through March. About 70 percent of the average annual precipitation falls during this period. Average monthly precipitation is greatest in January and least in July, when precipitation is typically from summer thunderstorms. The valley floor receives less than 10 in. of precipitation in an average year. Average annual precipitation in the highest parts of the Carson Range and Pine Nut Mountains, however, is as much as 46 and 26 in., respectively (Maurer, 1986, p. 7).

Carson River

The East and West Forks of the Carson River enter Carson Valley from the south and join to form the Carson River north of Minden, Nev. (fig. 1). Average annual flow of the East Fork where it enters Carson Valley is 278,000 acre-ft, based on a 64-year period of record (Bostic and others, 1991, p. 131). Average annual flow of the West Fork where it enters the valley is about 80,000 acre-ft/yr, based on a 59-year period of record (Bostic and others, 1991, p. 137). Average annual flow of the Carson River where it exits Carson Valley is about 295,000 acre-ft, based on a 51-year period of record (Bostic and others, 1991, p. 143). Clear Creek discharges into the Carson River just upstream from where the Carson River exits Carson Valley (fig. 1); however, the estimated average annual discharge is 1,100 acre-ft (Arteaga and Durbin, 1979, p. 24), only 0.04 percent of the average annual flow of the river.

BASIN-FILL AQUIFER

The basin-fill deposits form the principal aquifer in Carson Valley. Thus, the aquifer is referred to as the basin-fill aquifer. It underlies 150 mi^2 of the 360-mi^2 valley, as shown in figure 1. The aquifer does not extend to the Pine Nut Mountains because the basin fill in this area is not saturated, or is saturated in only the bottommost interval, or contains thin intervals of perched ground water not connected directly to the principal aquifer.

Composition

The basin-fill aquifer is composed of younger (Quaternary) and older (Tertiary) basin-fill deposits (Maurer, 1986, p. 11-12). Younger deposits principally consist of flood-plain and alluvial-fan sediments. Flood-plain sediments are composed of well-sorted, medium to fine sand and silt with lenses of gravel and clay. These deposits are coarser at the south end where the East and West Forks of the Carson River enter the valley (fig. 1), and become finer toward the north end. On the west side, alluvial-fan sediments flank the Carson Range, and are composed of poorly sorted mixtures of clay, silt, sand, and gravel, associated with debris flows. On the east side, alluvial-fan sediments

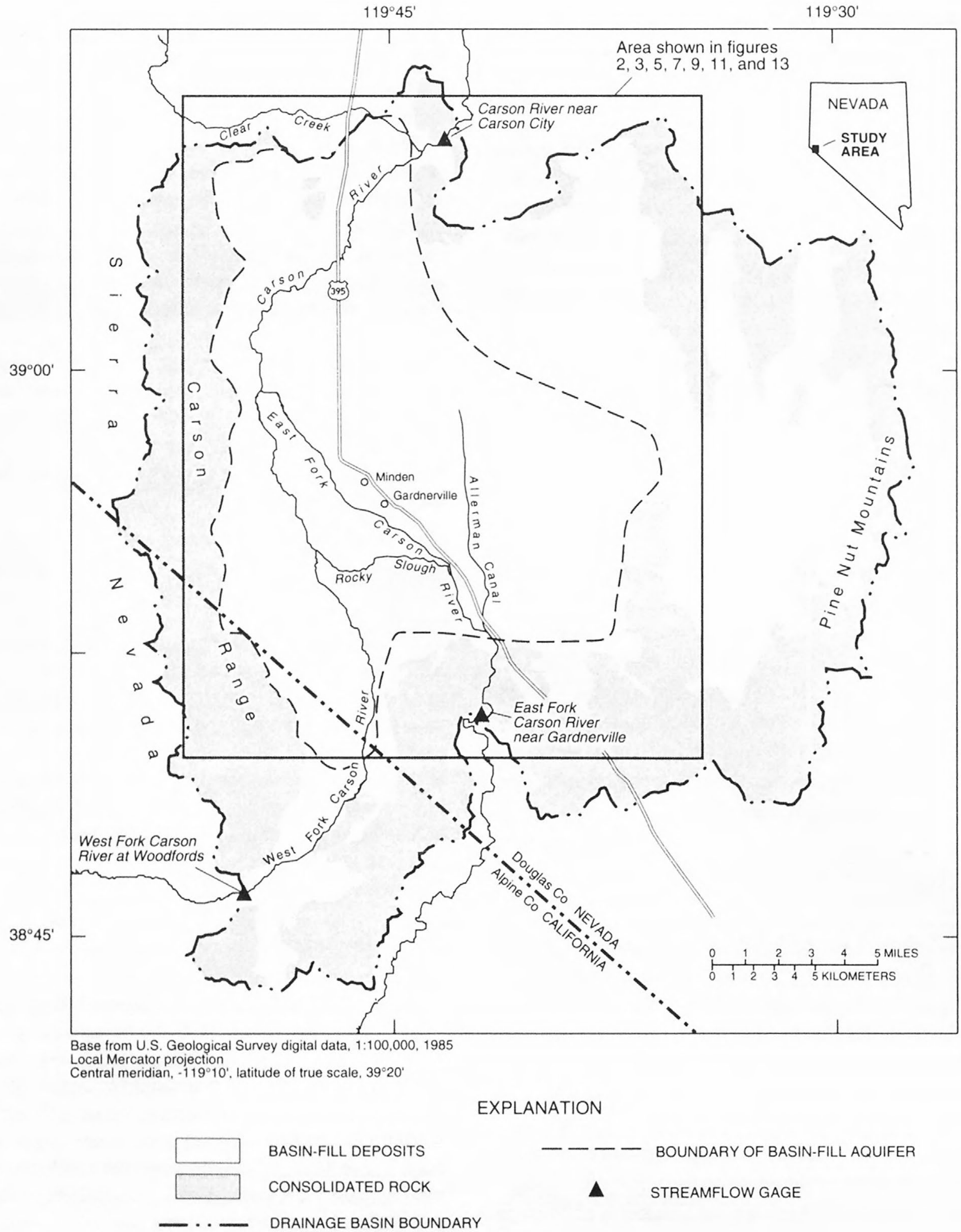


Figure 1. Location and general features of Carson Valley and extent of basin-fill aquifer (modified from Maurer, 1986, fig. 1).

are less prevalent. Older deposits included as part of the basin-fill aquifer (Maurer, 1986, p. 12) are typically finer grained than the younger deposits. The older deposits are exposed on the east side of the valley and are presumed to underlie the younger deposits on the west side.

Ground-Water Flow

Ground water flows from the edges of the aquifer on the west and east sides toward the Carson River, and then northward, parallel to the river. Ground water is present under unconfined (water table) and confined conditions (Maurer, 1986, p. 17). Confined ground-water levels are generally 5 to 20 ft above land surface on the valley floor in areas where finer grained sediment impede vertical flow, whereas unconfined levels range from about 5 ft below the valley floor to more than 100 ft below land surface along the margins of the valley.

Recharge and Discharge

Recharge to the basin-fill aquifer is from precipitation in the valley, subsurface flow from the adjacent mountains, and leakage from streams that enter the basin (Maurer, 1986, p. 45-46). Subsurface flow from the adjacent mountains is through weathered and fractured consolidated rock in the mountains or, on the east side, through a thin saturated interval of basin-fill deposits not included as part of the basin-fill aquifer (see fig. 1). Simulated steady-state recharge, excluding leakage from the Carson River and irrigation ditches, is about 102,000 acre-ft/yr, and was determined from summing values in figure 13 of Maurer (1986, p. 53). This recharge includes about 47,000 acre-ft/yr from precipitation on the valley floor. Because the water table is near land surface on the valley floor and because most of the precipitation falls during the winter months, most of the precipitation on the valley floor is assumed to recharge ground water during the winter only to be discharged as evapotranspiration during the summer (Maurer, 1986, p. 46, 52).

The combined annual flow of the East and West Forks of the Carson River averages 358,000 acre-ft and greatly exceeds the other components of recharge to the aquifer (Maurer, 1986, p. 42). The elaborate ditch system developed to spread surface water for irrigation has resulted in a more diffuse and greater area of recharge than was present prior to settlement in the valley. In places, the quantity of leakage from the Carson River and irrigation ditches changes depending on the relation between the ground-water table and the stage in the river and ditches.

Discharge from the basin-fill aquifer is primarily from evapotranspiration on the valley floor. Evapotranspiration from areas of irrigated crops (mostly alfalfa and native grass) is the largest component of ground-water discharge (Maurer, 1986, p. 39). However, nonirrigated stands of native vegetation (mainly rabbitbrush) also may consume ground water where the water table is less than 30 to 40 ft below the land surface (Maurer, 1986, p. 54). At the north end of the valley, ground water also discharges as seepage to the Carson River and drainage ditches.

GROUND-WATER FLOW MODEL

A ground-water flow model of the basin-fill aquifer in Carson Valley, developed by Maurer (1986), was used in this study to determine the effects of selected hypothetical pumping scenarios. The model uses a computer program written by McDonald and Harbaugh (1988) in which solution of the ground-water flow equation for three dimensions is approximated by finite-difference techniques. Development, calibration, and limitations of the model are described by Maurer (1986, p. 46-96). Computer data files used for the calibrated model of Carson Valley are described and model input values are provided by Maurer (1992).

The basin-fill aquifer is divided into a uniform grid of finite-difference cells, as shown in figure 2. Dimensions of the grid cells are 1 mi on each side. In the simulations, pumpage, leakage from the Carson River and ditches, ground-water seepage to the Carson River and ditches, and evapotranspiration are averaged over each grid cell.

Two layers in the model simulate flow in the basin-fill aquifer (fig. 2). Layer one (the upper layer) represents the unconfined part of the aquifer, and ranges in thickness from less than 100 ft near the west side of the valley to more than 200 ft in the central part (Maurer, 1986, p. 49). Deposits beneath layer one and extending downward to consolidated rock constitute layer two and represent a confined aquifer. This layer is at most 5,000 ft thick along the west side of the valley floor but is not as areally extensive as the upper layer (fig. 2); it only extends eastward to model row 6.

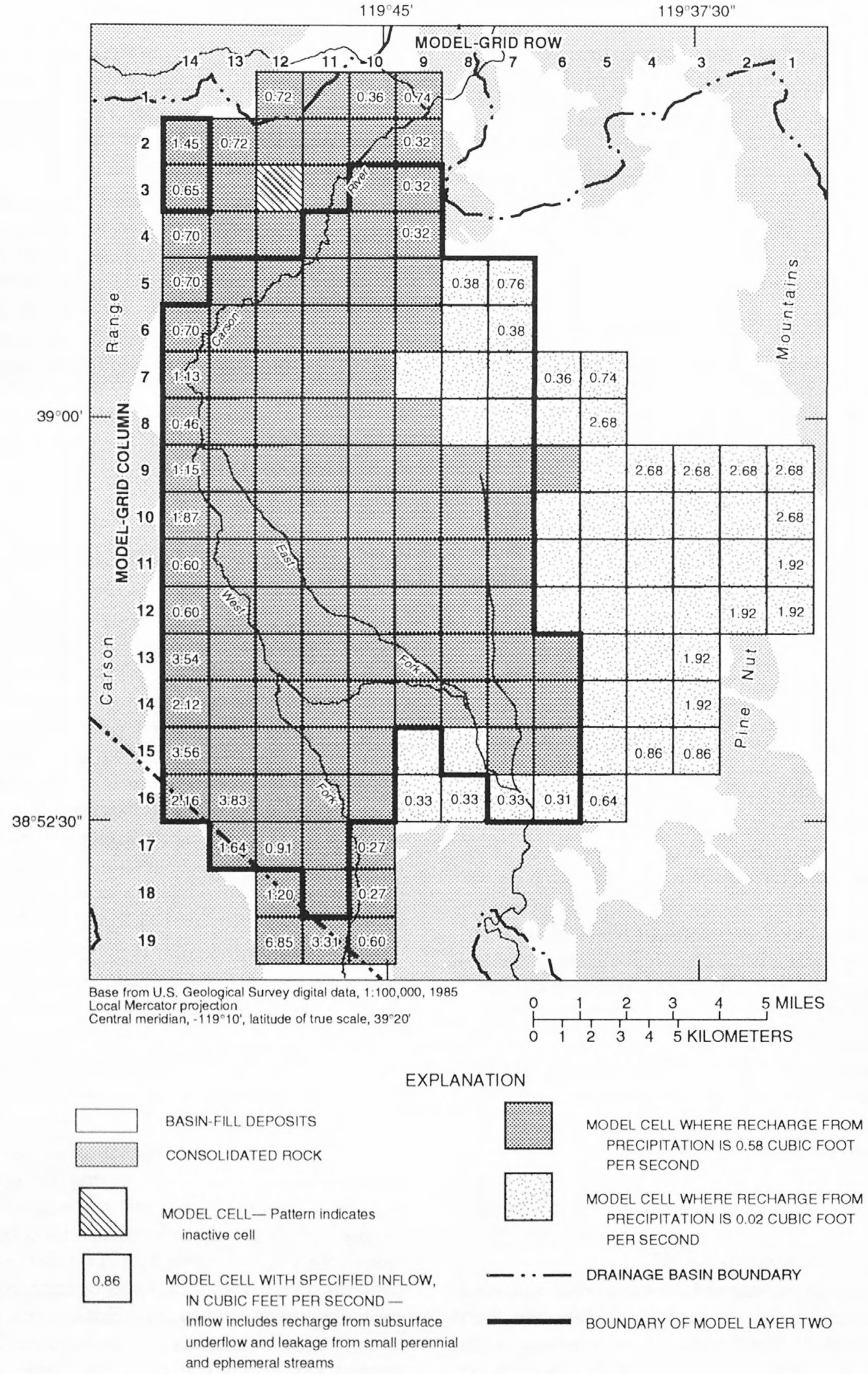


Figure 2. Finite-difference grid network used in ground-water flow model of basin-fill aquifer (modified from Maurer, 1986, figs. 12 and 13).

Hydraulic properties of the basin-fill aquifer were adjusted during model calibration (Maurer, 1986, p. 51). Estimated hydraulic conductivity for layer one ranges from 10^{-4} to 10^{-3} ft/s on the valley floor and is 10^{-5} ft/s on the east side and extreme northwest and southwest corners (Maurer, 1986, p. 30). The hydraulic conductivity for layer two is about 10^{-4} ft/s, values in the model range from $9x10^{-5}$ to $1.35x10^{-4}$ ft/s. Ground-water flow between layers is represented by a confining unit that is thin compared to the thickness of the aquifer. A leakance value is assigned between model layers where both layers have active cells. The leakance value is the vertical hydraulic conductivity divided by the estimated thickness of fine-grained deposits. Vertical hydraulic conductivity ranges from 10^{-8} to 10^{-10} ft/s (Maurer, 1986, p. 31).

The calibrated steady-state ground-water budget for the basin-fill aquifer in Carson Valley is listed in table 1. The model-simulated components of ground-water recharge and discharge are presented by Maurer (1986, p. 58-60). Recharge to the basin-fill aquifer includes precipitation, subsurface underflow and leakage from small perennial and ephemeral streams not specifically simulated as streams, and simulated leakage from the Carson River and principal irrigation ditches. Discharge includes simulated evapotranspiration and seepage to the Carson River and irrigation ditches.

Average long-term recharge to the basin-fill aquifer as subsurface flow from the adjacent Carson Range and Pine Nut Mountains and as leakage from small perennial and ephemeral streams that begin in the mountains is simulated as a constant rate in cells at the periphery of model layer one (fig. 2). These values differ from those presented by Maurer (1986, fig. 13) because recharge from precipitation is not included in the values shown in figure 2. This recharge totals 75.7 ft^3/s (about 55,000 acre-ft/yr, table 1). Recharge from precipitation on the valley floor also is simulated as a constant rate. For model cells representing land that is irrigated or land covered with phreatophytes (fig. 2), all annual precipitation (8 in.) is assumed to recharge cells in the upper model layer (Maurer, 1986, p. 52). Recharge in these cells totals 63.2 ft^3/s (about 46,000 acre-ft/yr, table 1). For model cells representing land covered with xerophytic vegetation along the east side of the valley (fig. 2), only 3 percent of the estimated precipitation is assumed to recharge the basin-fill aquifer. Recharge in these cells totals 1.2 ft^3/s (about 900 acre-ft/yr, table 1). This value is slightly less than the 1,000 acre-ft/yr reported by Maurer (1986, p. 41).

Evapotranspiration from the basin-fill aquifer is simulated as a head-dependent flow boundary in model cells where rabbitbrush, native grass, or alfalfa is present (fig. 3; and Maurer, 1986, p. 54). The quantity of evapotranspiration simulated in the model varies as a function of depth to ground water in the upper model layer. Evapotranspiration is at a maximum when ground water is at land surface, decreasing to zero when the water level is at or below a depth of 35 ft (Maurer, 1986, p. 54). The maximum rate of evapotranspiration assigned to model cells ranges from 0.4 ft/yr in areas of sparse rabbitbrush to 4.0 ft/yr in areas of irrigated grass and alfalfa. Simulated evapotranspiration in the calibrated steady-state model is 205 ft^3/s (about 149,000 acre-ft/yr, table 1). This value is slightly more than the 148,000 acre-ft/yr reported by Maurer (1986, p. 59).

Both forks of the Carson River and the larger irrigation ditches are simulated as head-dependent flow boundaries that allow recharge as leakage from, and discharge as seepage to, the river and ditches. Recharge from stream leakage is limited by the amount of average annual flow in the East and West Forks where the streams enter Carson Valley. Flow in both forks of the Carson River and ditches was simulated using the stream package (Prudic, 1988). The distribution of model cells representing a river or ditch reach is similar to the distribution of cells used to simulate evapotranspiration (fig. 3).

The rate of flow between surface water and the basin-fill aquifer depends on the difference in head between the aquifer and river or ditch, and on the conductance term, which is the ability of the streambed deposits to transmit water (Prudic, 1988, p. 7). An explanation as to how each term was estimated is presented by Maurer (1986, p. 54-57). Only the conductance term was adjusted during model calibration. Model-calibrated conductances are 2.0 ft^2/s except for reaches in rows 7 and 8 (fig. 3). Conductances for these reaches are 1.2 ft^2/s (Maurer, 1986, p. 59).

Simulated leakage from the Carson River and ditches is 145 ft^3/s (about 105,000 acre-ft/yr, table 1), whereas simulated ground-water seepage to the Carson River and ditches is 80 ft^3/s (about 58,000 acre-ft/yr, table 1). These results suggest that the Carson River and the irrigation ditches are major sources of ground-water recharge and major destinations of discharge from the basin-fill aquifer.

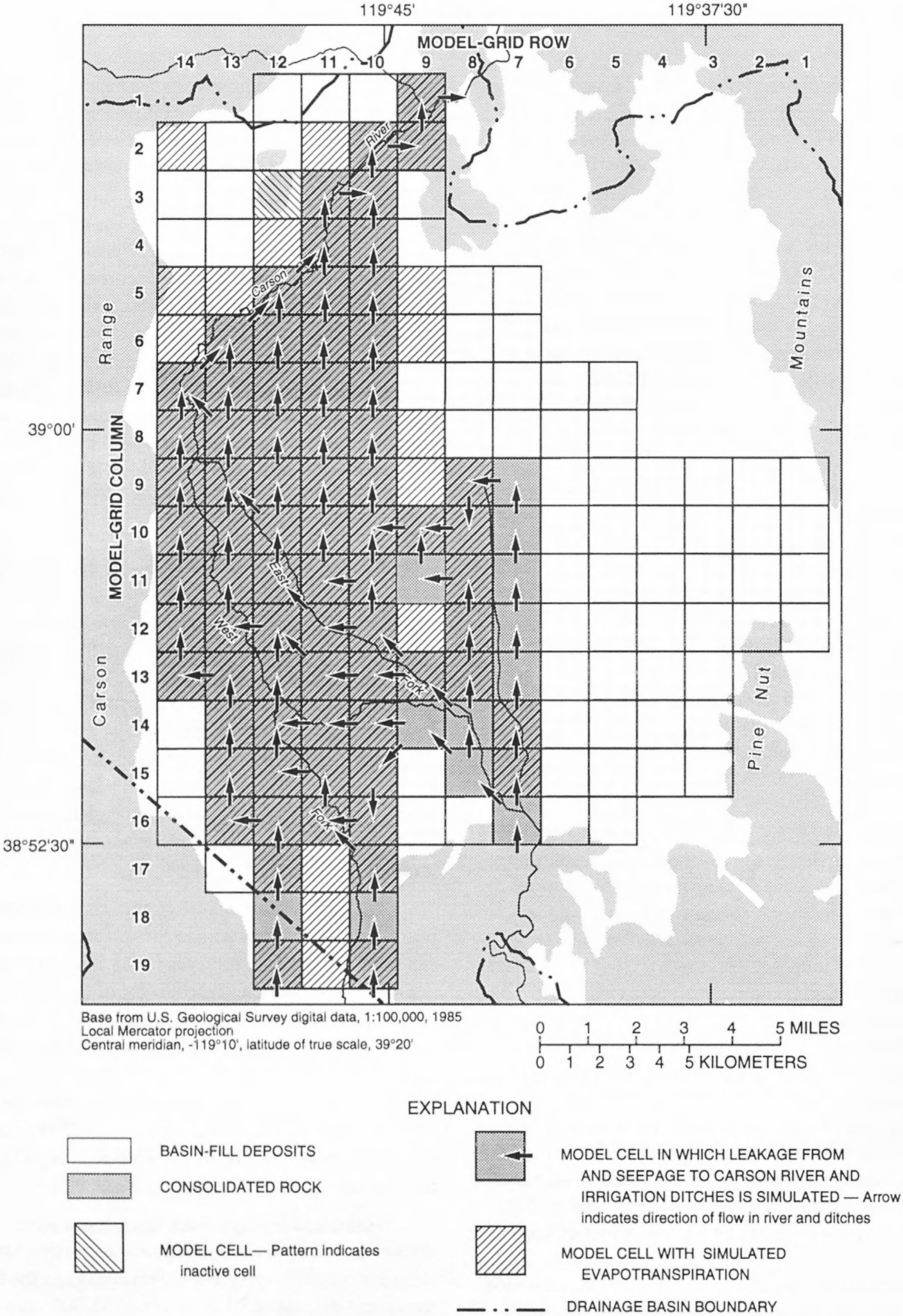


Figure 3. Distribution of model cells used to simulate leakage from and seepage to Carson River and irrigation ditches, and cells with simulated evapotranspiration (modified from Maurer, 1986, figs. 14 and 15).

Table 1. Estimated average annual ground-water recharge and discharge for basin-fill aquifer in Carson Valley on basis of best-fit steady-state simulation[1]

Water-budget component		Estimated quantity (acre-feet per year)
RECHARGE[2]		
Recharge from precipitation in areas of irrigated crops or phreatophytes		46,000
Recharge from precipitation in areas of xerophytes		900
Subsurface underflow and leakage from small perennial and ephemeral streams[3]		55,000
Leakage from Carson River and ditches		105,000
	Total (rounded)	207,000
DISCHARGE		
Evapotranspiration		149,000
Seepage to Carson River and ditches		58,000
	Total	207,000

[1] Model-computed difference between total recharge and discharge is 4 acre-feet per year, or less than 0.01 percent.
[2] Recharge from precipitation, subsurface underflow, and leakage from small perennial and ephemeral streams is 102,000 acre-feet per year.
[3] Includes recharge from streams not specifically simulated in model.

Results from the steady-state model (Maurer, 1986, p. 51-59) are used as initial conditions for the hypothetical simulations. Changes in the these initial conditions may produce different results from those presented herein. No pumping was simulated in the steady-state model, thus the model represents a period when surface water had been diverted for irrigation and ground water was neither pumped for irrigation or public supply.

GROUND-WATER PUMPING SCENARIOS

Five hypothetical pumping scenarios were selected for the basin-fill aquifer in Carson Valley on the basis of geography and hydrologic characteristics of the aquifer. Economic considerations (for example, pumping costs or the cost of distributing the water) were not used to select the distribution of pumpage. Four of the hypothetical scenarios concentrate pumping in specific areas—at the south and north ends of the valley, and on the east and west sides—and the fifth has pumping dispersed over the entire valley floor.

Simulated pumpage for each scenario is set at a rate of 100,000 acre-ft/yr, approximately equal to simulated steady-state recharge excluding leakage from the Carson River and ditches. The rate was chosen for consistency with hypothetical simulations of other basins simulated as part of the Great Basin RASA study, and because allocation of ground-water rights in Nevada and Utah, states encompassing much of the Great Basin RASA study area, generally is limited to not exceed the average annual recharge in each basin to minimize long-term drawdown by capturing natural discharge. However, pumping ground water at a rate equal to the average annual recharge does not insure minimal drawdown in a basin or efficient capture of natural discharge. For example, concentrating pumpage in areas distant from natural discharge could produce excessive drawdown in the pumped area while failing to capture natural discharge. In contrast, concentrating pumpage in areas near a river or lake could produce minimal drawdown, and fail to capture natural ground-water discharge by instead inducing leakage and reducing surface-water supplies. The scenarios chosen, in a general way, simulate the effects of different pumping distributions in Carson Valley on drawdown, on capturing natural discharge, and on inducing leakage from surface-water supplies.

Pumpage is distributed among active cells in both model layers within each assigned area. All pumpage is assumed to be consumed. The simulations also do not allow any of the pumped water to flow back to the Carson River. Secondary recharge of pumped water or redistribution of a percentage of the pumped water into streams or ditches was not considered because of a multitude of options and percentages that could be used. Thus, the hypothetical scenarios represent conditions for maximum drawdown, and maximum decreases in storage and in surface-water outflow from the modeled area compared with what actually may occur. Finally, neither legal nor economic issues were considered in the model simulations.

Four periods were simulated for each scenario—two for pumping and two for recovery. The first period simulated pumping from 0 to 200 years in 26 time steps. The first step was 94 seconds; each successive step increased by a factor of two. The length of each time step was computed by the model for 200 years using the number of time steps (26) and the ratio of the length of each time step to that of the preceding time step (2). The second period was a continuation of the first and simulated pumping from 200 to 300 years in only one step. The reason for dividing 300 years of pumping into two simulation periods was to provide results at the end of specified times of 1.5, 12.5, 25, 50, 100, and 200 years (at end of steps 19, 22, 23, 24, 25, and 26 in the first period), and 300 years (at the end of the second period). The 300-year recovery period that followed the pumping was divided into the same two periods and used the same time-step intervals.

The strongly implicit procedure (McDonald and Harbaugh, 1988, p. 12-1 through 12-59) was used to solve the ground-water flow equation for each model cell during each time step. A solution was assumed when the calculated heads in all model cells changed less than 0.1 ft between successive iterations within a time step.

SIMULATION RESULTS

Results of the scenarios of hypothetical pumping are discussed in terms of changes in the amount of recharge to, and discharge from, and storage in the basin-fill aquifer relative to long-term equilibrium conditions presented by Maurer (1986, p. 60). The modeling intent is not to predict changes from actual ground-water development in the valley; rather the intent is to show general trends in aquifer response to pumping in different areas of the valley. Prior to pumping in the valley, ground-water levels and storage in the aquifer are in a state of approximate dynamic equilibrium—declining during periods of high rates of evapotranspiration and low precipitation and streamflow, and rising during periods of low rates of evapotranspiration and high precipitation and streamflow. Over long periods, however, changes in water levels, storage, and flow through the aquifer system are near zero.

Conceptual diagrams of ground-water flow prior to any pumping are shown in figure 4A for the south and north ends of the valley. In the south end, water recharges the aquifer as percolation of precipitation, subsurface flow from adjacent mountains, and leakage from perennial streams and ditches. The water table beneath some of the ditches may not be in contact with the ditch but may be separated by a thin unsaturated zone. Discharge in both the south and north ends is by evapotranspiration on the valley floor. In addition, some ground water also discharges at the north end as seepage to the Carson River and ditches (fig. 4A).

When water initially is pumped from wells, water levels decline in the aquifer and water is removed from storage. As pumping continues, water levels continue to decline in the aquifer and the area of drawdown expands until pumpage is balanced by an equal reduction in natural discharge, by an increase in recharge to the aquifer, or by a combination of these.

In the model simulations, recharge from percolation of precipitation, or as subsurface flow from the adjacent mountains, is constant. Also, no additional recharge is simulated as leakage from streams or ditches where the bottom of the stream or ditch is separated from the aquifer by an unsaturated zone. Thus, pumping ground water in the south end (fig. 4B) results in a reduction of natural evapotranspiration, an increase in leakage from the river in areas where the ground water is in direct hydraulic connection with surface water (no intervening unsaturated zone), and a decrease in northward ground-water flow.

Pumping of ground water in an area where ground water seeps to a river or ditch may result in reduced seepage or in leakage from the river or ditch to the aquifer, as shown for pumping at the north end of Carson Valley (fig. 4B). In some instances, ground water may seep to the river (illustrated with the ditch in fig. 4B) on one side, and water from the river may leak to the aquifer on the other, as discussed by Cohen and others (1965, p. 70). Although actually possible, such a condition could not be simulated with the model because only net leakage from the river or seepage from the aquifer can be simulated for each model cell.

The areas of pumping for each hypothetical scenario, the number of model cells with pumpage in layers one and two, the pumping rate for each cell, and the figures associated with each simulation are summarized in table 2. Hydrologic response of the basin-fill aquifer to the five hypothetical scenarios after 1.5, 25, 100, and 300 years of pumping and after 1.5, 25, 100 and 300 years of recovery is summarized in table 3. Results of each scenario also are depicted on maps and graphs.

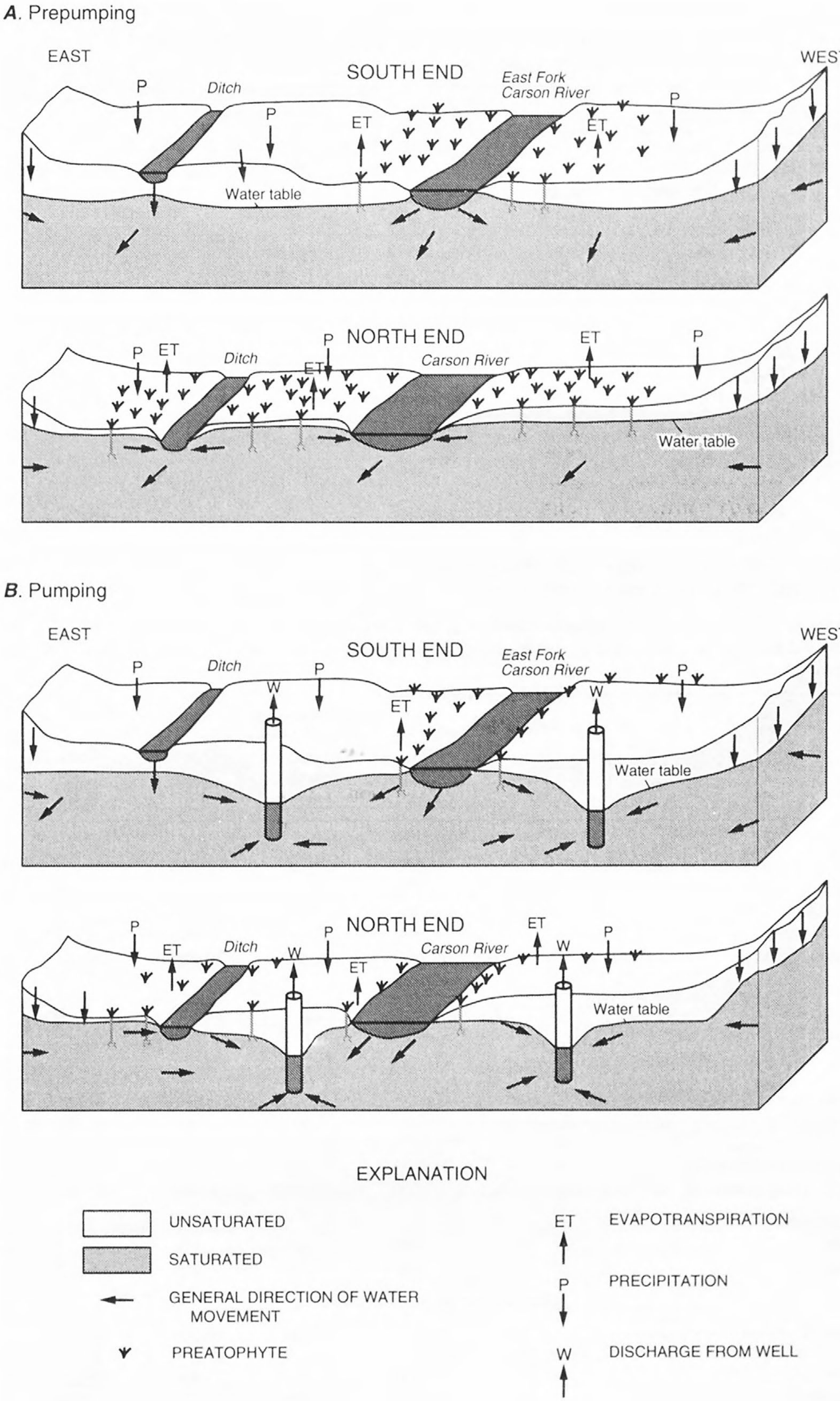


Figure 4. Schematic block diagrams, viewed from north, of south and north ends of Carson Valley showing generalized changes in distribution of recharge, discharge, and ground-water flow as a result of pumping.

Table 2. Description of simulations for scenarios of hypothetical ground-water pumping in Carson Valley

Development scenario	Area of pumping[1]	Number of cells with pumpage: Layer one	Number of cells with pumpage: Layer two	Pumping rate for each cell (cubic feet per second)	Figures summarizing simulation results
One	South	16	15	4.46	5,6
Two	North	23	15	3.64	7,8
Three	East	18	18	3.88	9,10
Four	West	18	18	3.88	11,12
Five	Valley Floor	105	91	.71	13,14

[1] Geographical designations refer to location of pumping in valley. Pumping in scenario five is dispersed throughout valley floor. Total pumpage for each simulation is 100,000 acre-feet per year for 300 years (followed by no pumpage for 300 years).

Table 3. Summary of hydrologic response from scenarios of hypothetical ground-water pumping in Carson Valley after 1.5, 25, 100, and 300 years of pumping and 1.5, 25, 100, and 300 years of recovery

[Budget values are rounded to two significant figures for values greater than 1,000 and to nearest 100 for values less than 1,000; positive values indicate increases and negative values indicate decreases; drawdown is rounded to nearest foot. Abbreviations: acre-ft, acre-feet; acre-ft/yr, acre-feet per year; ft, feet.]

	Ground-water development scenarios				
	One (south end)	Two (north end)	Three (east end)	Four (west end)	Five (valley floor)
Change after 1.5 years of pumping					
Leakage from river and ditches (acre-ft/yr)	32,000	46,000	12,000	38,000	29,000
Ground-water seepage to river and ditches (acre-ft/yr)	-22,000	-18,000	-11,000	-27,000	-38,000
River outflow (acre-ft/yr)	-54,000	-64,000	-23,000	-65,000	-67,000
Evapotranspiration (acre-ft/yr)	-6,900	-8,300	-9,900	-11,000	-8,700
Ground-water storage (acre-ft)	-74,000	-56,000	-120,000	-51,000	-54,000
Maximum drawdown (ft):					
Layer one	52	78	50	41	22
Layer two	77	177	52	73	36
Change after 25 years of pumping					
Leakage from river and ditches (acre-ft/yr)	47,000	59,000	46,000	46,000	42,000
Ground-water seepage to river and ditches (acre-ft/yr)	-29,000	-21,000	-23,000	-34,000	-43,000
River outflow (acre-ft/yr)	-76,000	-80,000	-69,000	-80,000	-85,000
Evapotranspiration (acre-ft/yr)	-18,000	-18,000	-23,000	-18,000	-14,000
Ground-water storage (acre-ft)	-330,000	-180,000	-520,000	-140,000	-140,000
Maximum drawdown (ft):					
Layer one	199	147	124	145	45
Layer two	198	221	125	122	44
Change after 100 years of pumping					
Leakage from river and ditches (acre-ft/yr)	49,000	59,000	50,000	47,000	43,000
Ground-water seepage to river and ditches (acre-ft/yr)	-31,000	-21,000	-25,000	-35,000	-43,000
River outflow (acre-ft/yr)	-80,000	-80,000	-75,000	-82,000	-86,000
Evapotranspiration (acre-ft/yr)	-20,000	-19,000	-24,000	-19,000	-14,000
Ground-water storage (acre-ft)	-400,000	-200,000	-640,000	-150,000	-160,000
Maximum drawdown (ft):					
Layer one	229	159	137	151	45
Layer two	227	226	140	126	44

Table 3. Summary of hydrologic response from scenarios of hypothetical ground-water pumping in Carson Valley after 1.5, 25, 100, and 300 years of pumping and 1.5, 25, 100, and 300 years of recovery—Continued

	Ground-water development scenarios				
	One (south end)	Two (north end)	Three (east end)	Four (west end)	Five (valley floor)
Change after 300 years of pumping					
Leakage from river and ditches (acre-ft/yr)	49,000	59,000	50,000	47,000	43,000
Ground-water seepage to river and ditches (acre-ft/yr)	-31,000	-21,000	-26,000	-35,000	-43,000
River outflow (acre-ft/yr)	-80,000	-80,000	-76,000	-82,000	-86,000
Evapotranspiration (acre-ft/yr)	-20,000	-19,000	-24,000	-19,000	-15,000
Ground-water storage (acre-ft)	-420,000	-200,000	-670,000	-150,000	-160,000
Maximum drawdown (ft):					
Layer one	232	160	139	151	45
Layer two	230	226	142	126	44
Net change after 300 years of pumping and 1.5 years of recovery					
Leakage from river and ditches (acre-ft/yr)	19,000	20,000	41,000	13,000	7,700
Ground-water seepage to river and ditches (acre-ft/yr)	-20,000	-15,000	-20,000	-16,000	-11,000
River outflow (acre-ft/yr)	-39,000	-35,000	-61,000	-29,000	-19,000
Evapotranspiration (acre-ft/yr)	-12,000	-6,900	-20,000	-3,400	-6,000
Ground-water storage (acre-ft)	-320,000	-120,000	-530,000	-74,000	-100,000
Maximum drawdown (ft)					
Layer one	170	82	109	109	23
Layer two	165	43	101	71	71
Net change after 300 years of pumping and 25 years of recovery					
Leakage from river and ditches (acre-ft/yr)	1,400	200	2,000	400	400
Ground-water seepage to river and ditches (acre-ft/yr)	-1,600	-600	-3,100	-500	-600
River outflow (acre-ft/yr)	-3,000	-800	-5,100	-900	-1,000
Evapotranspiration (acre-ft/yr)	-1,400	-300	-2,100	-100	-300
Ground-water storage (acre-ft)	-57,000	-11,000	-110,000	-4,900	-18,000
Maximum drawdown (ft):					
Layer one	32	12	41	5	2
Layer two	18	2	13	3	1
Net change after 300 years of pumping and 100 years of recovery					
Leakage from river and ditches (acre-ft/yr)	100	0	200	0	0
Ground-water seepage to river and ditches (acre-ft/yr)	-100	0	-200	0	0
River outflow (acre-ft/yr)	-200	0	-400	0	0
Evapotranspiration (acre-ft/yr)	-100	0	-200	0	0
Ground-water storage (acre-ft)	-6,800	-1,000	-14,000	-500	-2,400
Maximum drawdown (ft):					
Layer one	3	1	6	1	0
Layer two	1	0	2	0	1
Net change after 300 years of pumping and 300 years of recovery					
Leakage from river and ditches (acre-ft/yr)	0	0	0	0	0
Ground-water seepage to river and ditches (acre-ft/yr)	0	0	0	0	0
River outflow (acre-ft/yr)	0	0	0	0	0
Evapotranspiration (acre-ft/yr)	0	0	0	0	0
Ground-water storage (acre-ft) [1]	-400	-100	-600	-200	-400
Maximum drawdown (ft):					
Layer one	1	0	1	0	0
Layer two	0	0	0	0	0

[1] Storage values are less than mass-balance error in model simulation at end of 600-year period.

Pumping Concentrated at South End of Valley

Hypothetical scenario one simulates pumping concentrated at the south end of Carson Valley. A pumping rate of 4.46 ft^3/s (3,230 acre-ft/yr) is assigned to each of 16 model cells in layer one and 15 cells in layer two (table 2). Distribution of cells assigned a pumping rate is shown in figure 5.

Pumping from the south end of Carson Valley results in a drawdown of about 200 ft in both model layers (fig. 5). The 200-ft drawdown in layer one is limited to two cells at the east end of the pumped area. The drawdown in these cells approaches the bottom of the cells. Drawdown is less than 5 ft throughout most of the north end of Carson Valley in both model layers. Drawdown in layer one also is less than 5 ft along most of the West Fork of the Carson River, although pumping is assigned to cells throughout the area. The 200-ft drawdown in layer two also is limited to two cells. Drawdown in layer two is more than 5 ft throughout most of the valley.

Average drawdown in the pumped area increases rapidly in both model layers during the first 25 years and continues to increase slowly for another 75 years before stabilizing during the remaining 200 years of the 300-year pumping period (fig. 6). Average drawdown in cells after 300 years of pumping is slightly more than 100 ft in layer two and slightly less than 75 ft in layer one.

Pumping from the south end of Carson Valley results in an almost immediate increase in leakage from the Carson River and ditches, as well as a rapid decrease in the ground-water seepage to the river and ditches and in the evapotranspiration (fig. 6). The cumulative volume of water removed from storage also increases rapidly during the first 25 years, but after 100 years of pumping, it increases slowly from about 400,000 acre-ft to 420,000 acre-ft at the end of the 300-year pumping period.

Results after 1.5 years indicate that about 39 percent of the pumpage is water removed from storage. Increased leakage from the Carson River and ditches accounts for 32 percent of the pumpage and decreased ground-water seepage to the river and ditches accounts for another 22 percent (fig. 6, table 3). After 25 years, storage accounts for only about 6 percent of the pumpage; increased leakage from and decreased ground-water seepage to the river and ditches accounts for about 76 percent, and decreased evapotranspiration accounts for about 18 percent. After 100 years, the basin-fill aquifer, in effect, reaches equilibrium because little water is removed from storage. The net result of pumping 100,000 acre-ft/yr at the south end of the valley is to reduce surface-water outflow from the valley by about 80,000 acre-ft/yr and evapotranspiration by 20,000 acre-ft/yr (table 3).

Streamflows and ground-water levels recover rapidly when pumping stops (fig. 6). Within 25 years, evapotranspiration is 1,400 acre-ft/yr less than the initial rate and surface-water outflow from the valley is 3,000 acre-ft/yr less (table 3). The volume of water in storage increases about 360,000 acre-ft after 25 years of recovery—57,000 acre-ft less than initial volume. Storage is about 6,800 acre-ft less than the initial volume after 100 years of recovery and only 400 acre-ft less after 300 years. Drawdown of about 1 ft is simulated in cells distant from points of recharge after 300 years of recovery.

Pumping Concentrated at North End of Valley

Hypothetical scenario two simulates pumpage concentrated at the north end of Carson Valley. A pumping rate of 3.64 ft^3/s (2,640 acre-ft/yr) is assigned to each of 23 cells in layer one and 15 cells in layer two (table 2). Distribution of cells assigned a pumping rate is shown in figure 7.

Pumping from the north end of Carson Valley results in a drawdown of more than 120 ft in layer one and 200 ft in layer two. Drawdown exceeding 120 ft in layer one is limited to three cells assigned a pumping rate, whereas drawdown exceeding 200 ft in layer two is in one cell. Drawdown of less than 5 ft in layer one and less than 40 ft in layer two is simulated south of the pumped area (fig. 7).

Average drawdown in the pumped area increases rapidly during the first 25 years of pumping but does not change significantly during the remaining 275 years (fig. 8). Average drawdown in cells with pumping in layer two is about 100 ft after 300 years, whereas the average drawdown in layer one is less than 50 ft. The greater drawdown in layer two results from the smaller storage coefficient and from dependence on leakage across a confining bed to maintain water levels. Average drawdown is less than that simulated in the south end (scenario one). This could be due to the slightly lower pumping rate assigned to more model cells in scenario two.

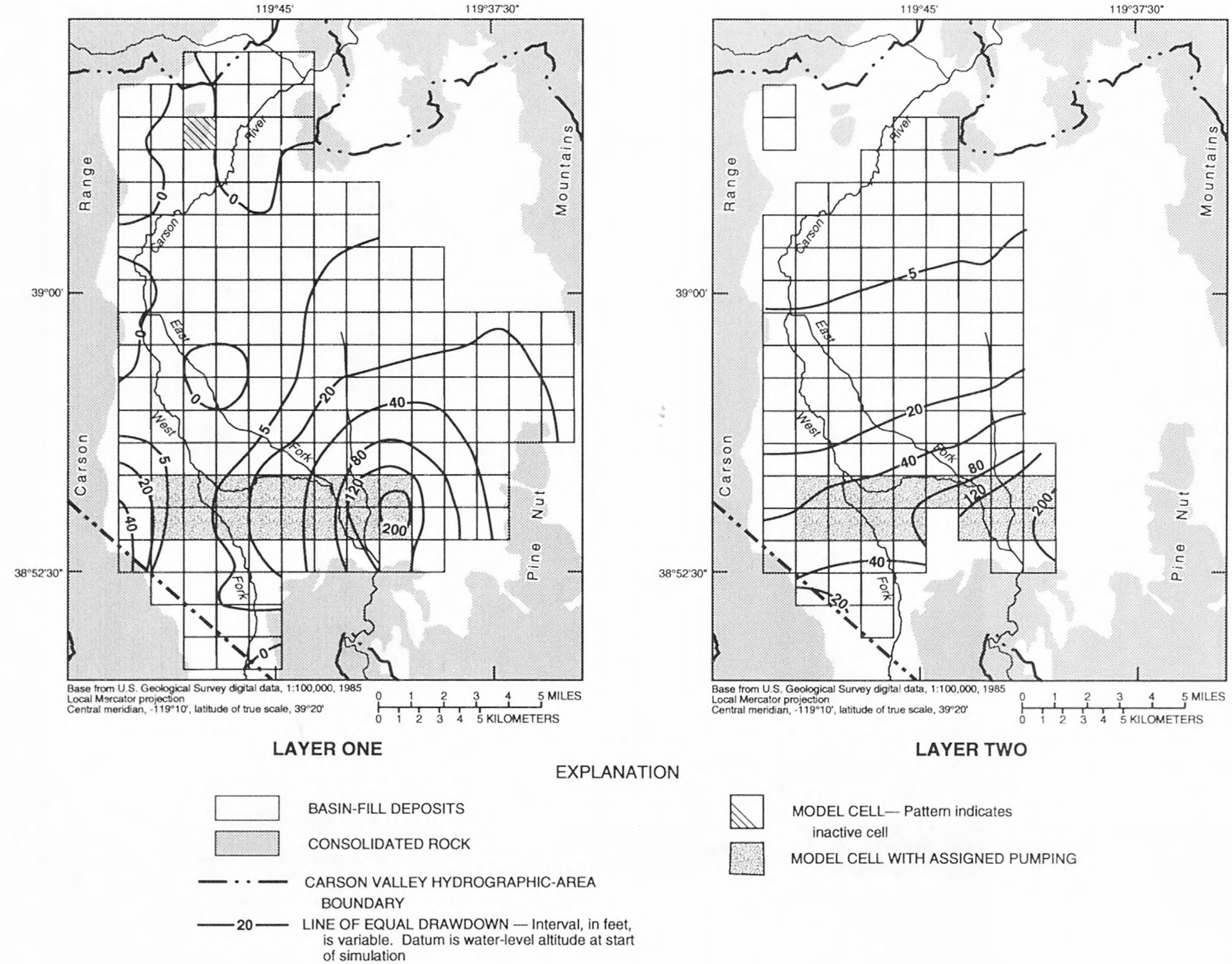


Figure 5. Location of model cells with pumping, and distribution of drawdown in layers one and two after 300 years of pumping for scenario one (hypothetical pumping concentrated at south end of Carson Valley).

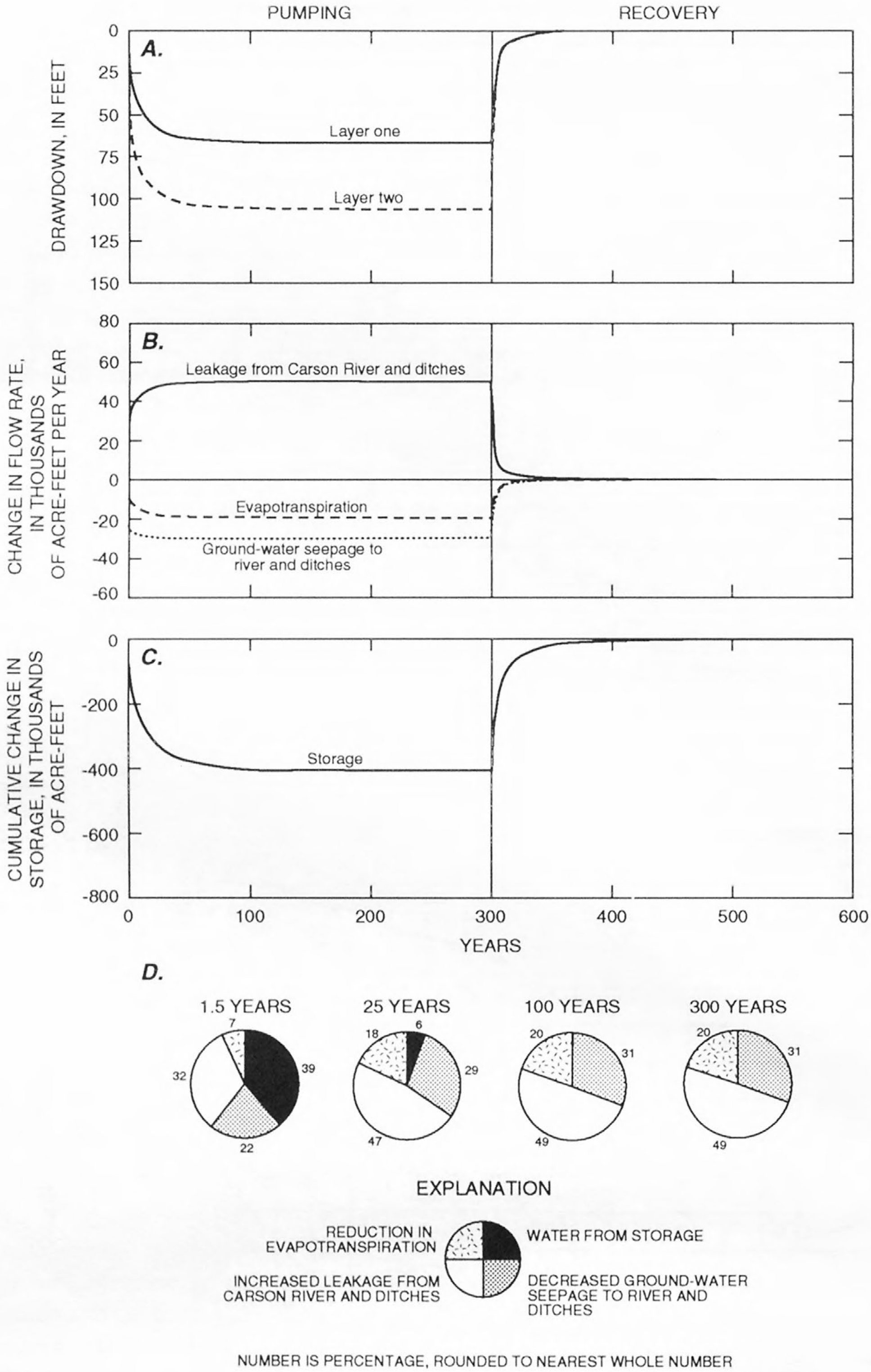
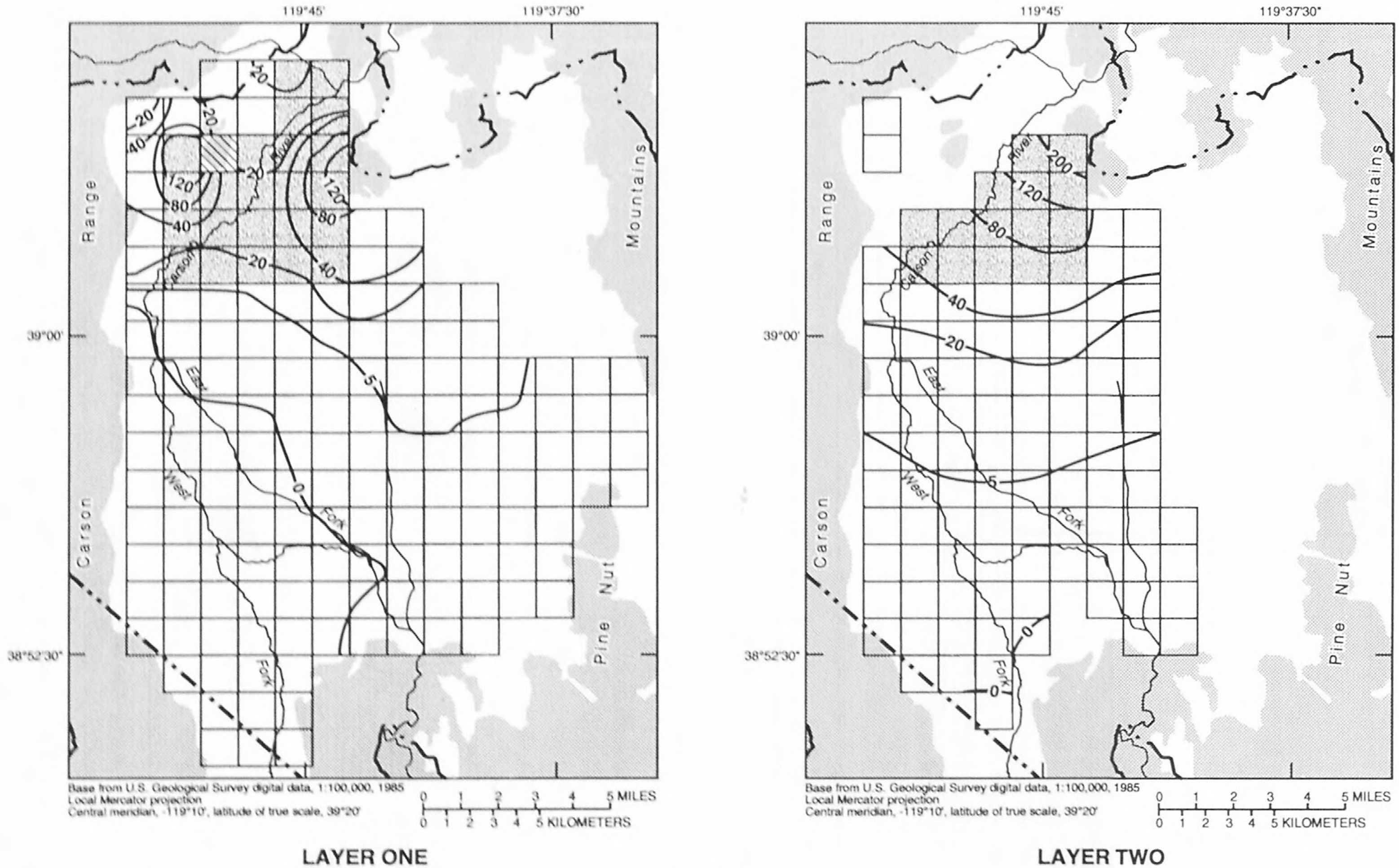


Figure 6. Simulated changes for scenario one (hypothetical pumping concentrated at south end of Carson Valley): *A*, average drawdown in model cells with pumping; *B*, changes in flow rates of leakage from Carson River and ditches, ground-water seepage to river and ditches, and evapotranspiration; *C*, cumulative change in storage; and *D*, sources of pumpage.



EXPLANATION

BASIN-FILL DEPOSITS

CONSOLIDATED ROCK

CARSON VALLEY HYDROGRAPHIC-AREA BOUNDARY

—20— LINE OF EQUAL DRAWDOWN — Interval, in feet, is variable. Datum is water-level altitude at start of simulation

MODEL CELL — Pattern indicates inactive cell

MODEL CELL WITH ASSIGNED PUMPING

Figure 7. Location of model cells with pumping, and distribution of drawdown in layers one and two after 300 years of pumping for scenario two (hypothetical pumping concentrated at north end of Carson Valley).

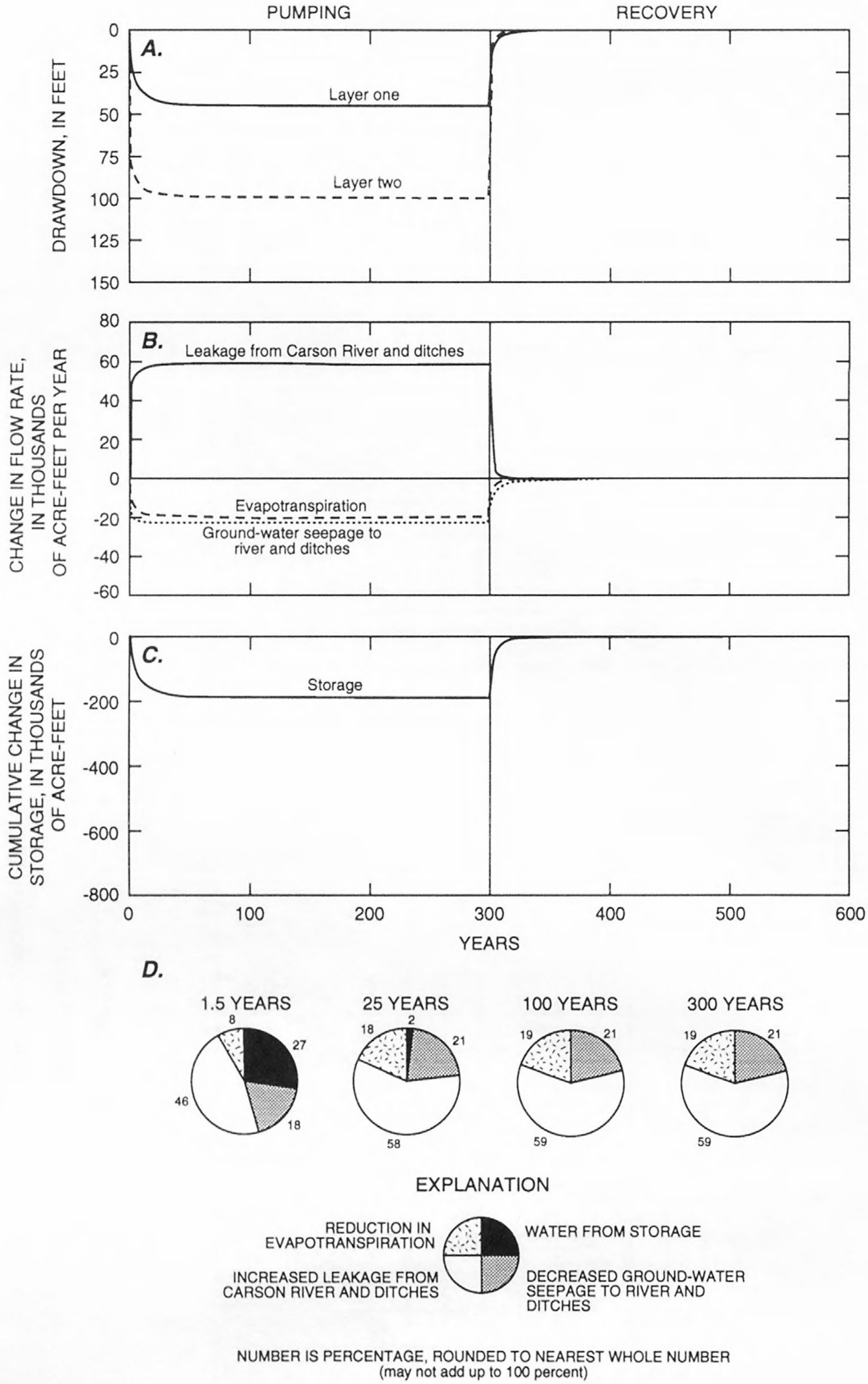


Figure 8. Simulated changes for scenario two (hypothetical pumping concentrated at north end of Carson Valley): *A*, average drawdown in model cells with pumping; *B*, changes in flow rates of leakage from Carson River and ditches, ground-water seepage to river and ditches, and evapotranspiration; *C*, cumulative change in storage; and *D*, sources of pumpage.

Leakage from the Carson River and ditches, ground-water seepage to the river and ditches, and evapotranspiration change rapidly during the first 25 years of simulation, but then remain nearly constant for the remainder of the 300-year pumping period (fig. 8). Similarly, the cumulative volume of water removed from storage increases rapidly during the first 25 years, but then remains nearly constant—at about 200,000 acre-ft—until the end of the 300-year pumping period. This response is similar to that simulated for pumping concentrated at the south end after 100 years except leakage from the Carson River and ditches is 10,000 acre-ft/yr more (59,000 acre-ft/yr compared with 49,000 acre-ft/yr; table 3), and ground-water seepage to the river and ditches is 10,000 acre-ft/yr less (21,000 acre-ft/yr compared with 31,000 acre-ft/yr; table 3). Leakage from the Carson River and ditches increases more with pumping at the north end of the valley than any other scenario.

Results after 1.5 years indicate that about 27 percent of the pumpage is water removed from storage. Increased leakage from the Carson River and ditches accounts for 46 percent of the pumpage, and decreased ground-water seepage to the river and ditches accounts for 18 percent (fig. 8). After 25 years, storage accounts for 2 percent of the pumped water, and increased leakage from and decreased ground-water seepage to the river and ditches accounts for about 80 percent of the pumpage. Decreased evapotranspiration accounts for the remaining percentage.

Surface-water outflow decreased 80,000 acre-ft/yr after 100 years (table 3); the same as simulated for scenario one (pumping concentrated at the south end of Carson Valley). A greater percentage of pumpage in scenario two is from increased leakage from the Carson River and ditches as compared to scenario one. This is balanced by a decrease in seepage to the river and ditches (figs. 6 and 8; table 3). The volume of water removed from storage (200,000 acre-ft/yr; table 3, fig. 8) is only half the volume removed in scenario one (400,000 acre-ft/yr; table 3, fig. 6) as pumping at the north end more efficiently increases leakage from the river and ditches and decreases ground-water seepage to them.

As in scenario one, streamflows and ground-water levels recover rapidly when pumping stops (fig. 8). Within 25 years, surface-water outflow from Carson Valley is 800 acre-ft/yr less than the initial flow, and water in storage is 11,000 acre-ft less than the initial volume (table 3). Storage is about 100 acre-ft of the initial volume after 300 years. This difference is within the accumulated error of the model simulation for the 600 years.

Pumping Concentrated Along East Side of Valley

Hypothetical scenario three simulates pumping concentrated along the east side of Carson Valley. A pumping rate of 3.88 ft^3/s (2,810 acre-ft/yr) is assigned to each of 18 model cells in layer one and 18 cells in layer two (table 2). Distribution of cells assigned a pumping rate is shown in figure 9.

Pumping along the east side of Carson Valley results in a drawdown exceeding 120 ft in both model layers (fig. 9). Although the maximum drawdown in both layers is considerably less than for scenarios one and two, a much larger area has drawdown exceeding 80 ft (compare figs. 5, 7, and 9). In model layer one, drawdown is less than 5 ft throughout the western third of the valley; drawdown in layer two, however, is generally more than 5 ft, except in a few model cells along the extreme western and southern edge (fig. 9).

Average drawdown in the pumped area increases rapidly in both model layers during the first 25 years, then slowly increases for another 275 years (fig. 10). Average drawdown in the pumped area after 300 years of pumping in layer one is about 105 ft, whereas the average drawdown in layer two is about 115 ft (fig. 10). Average drawdown in layer two is slightly more than the average drawdown in scenarios one and two (pumping concentrated in the south and north ends, respectively) but the average drawdown in layer one is 15 ft more than scenario one and 65 ft more than scenario two (compare figs. 6, 8, and 10).

Changes in leakage from the Carson River and ditches, ground-water seepage to the river and ditches, and evapotranspiration are similar to scenarios one and two in that rapid changes are simulated during the first 25 years (compare figs. 6, 8, and 10). Pumping along the east side reduces evapotranspiration by 24,000 acre-ft/yr after 100 years, more than pumping elsewhere in the valley (table 3). Evapotranspiration decreases about the same as the decrease in ground-water seepage to the river and ditches (fig. 10).

Water removed from storage is the major source of pumpage after 1.5 years, accounting for 67 percent (fig. 10). This percentage is greater than the 39 and

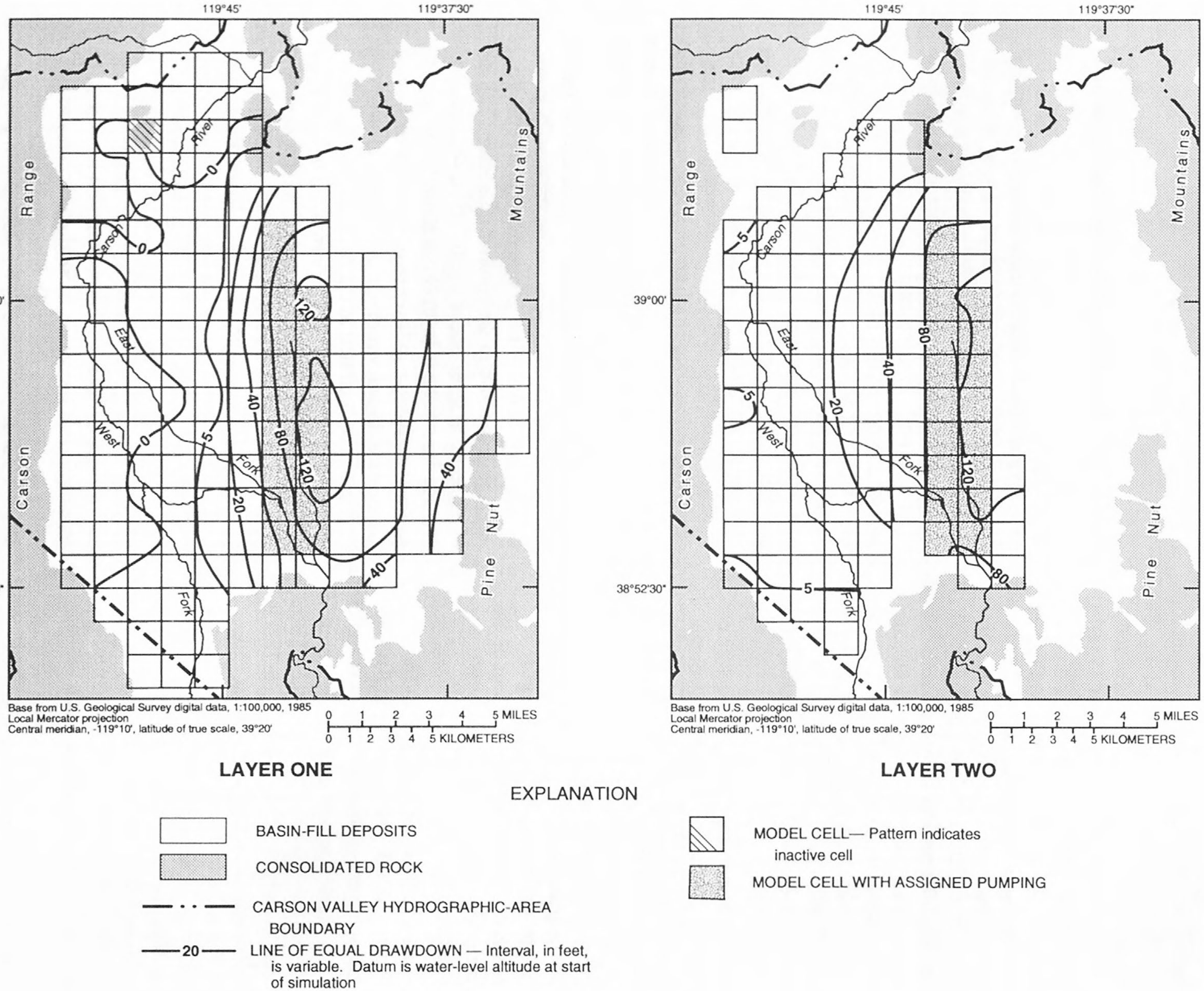


Figure 9. Location of model cells with pumping, and distribution of drawdown in layers one and two after 300 years of pumping for scenario three (hypothetical pumping concentrated along east side of Carson Valley).

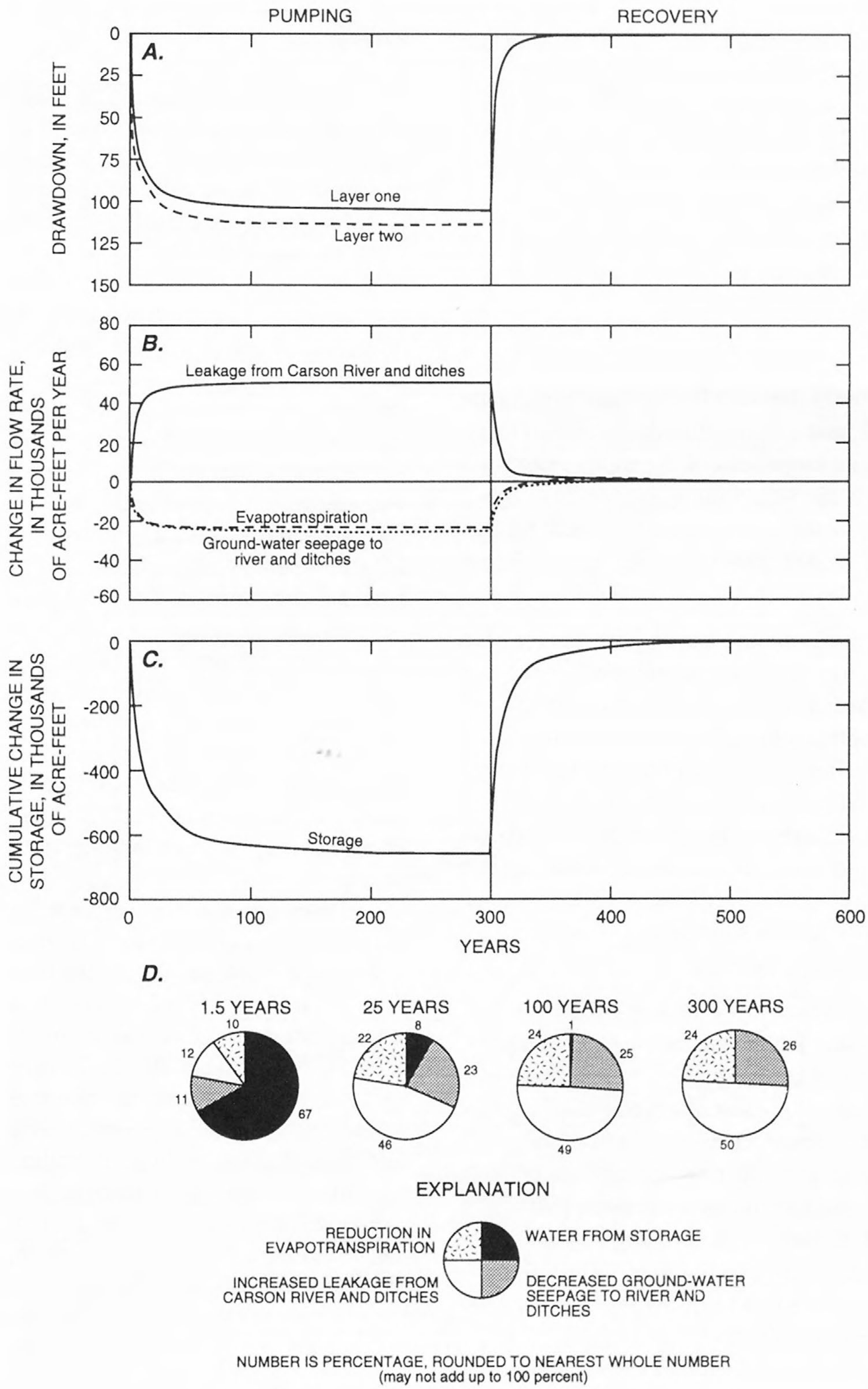


Figure 10. Simulated changes for scenario three (hypothetical pumping concentrated along east side of Carson Valley): *A*, average drawdown in model cells with pumping; *B*, changes in flow rates of leakage from Carson River and ditches, ground-water seepage to river and ditches, and evapotranspiration; *C*, cumulative change in storage; and *D*, sources of pumpage.

27 percent simulated in scenarios one and two, respectively. The remaining 33 percent of the pumpage is derived equally from increased leakage from and decreased ground-water seepage to the Carson River and ditches, and decreased evapotranspiration. Equilibrium is approached after 100 years because water removed from storage accounts for only 1 percent of the pumpage. Increased leakage from the river and ditches accounts for about half the pumpage and decreased ground-water seepage and evapotranspiration accounts for a fourth each. Decreased (captured) evapotranspiration is a greater percentage of the pumpage than simulated in the other four scenarios (compare figs. 6, 8, 10, 12, and 14), because drawdown in layer one extends over a larger area of the valley. Although more pumpage is accounted for by decreased evapotranspiration, pumping along the east side still results in a decrease of 76,000 acre-ft/yr of surface-water outflow from the valley.

Water continues to be removed from storage even after 100 years (fig. 10). Thus, pumping along the east side, which is farther from surface-water sources and the area of evapotranspiration, results in a longer period for the aquifer to reach equilibrium. The volume of water removed from storage after 300 years is 670,000 acre-ft; considerably more than the 420,000 and 200,000 acre-ft simulated in scenarios one and two (south and north ends), respectively. Also, this volume is the most removed from storage for any of the five hypothetical scenarios (table 3).

Recovery of water levels after pumping ceases is slower in this simulation than for the other scenarios, resulting in a slower recovery of water in storage and a slower return to initial rates of evapotranspiration, leakage from the Carson River and ditches, and ground-water seepage to the river and ditches (table 3). The volume of water in storage increases about 560,000 acre-ft 25 years after pumping stopped—110,000 acre-ft less than initial volume. The volume is about 14,000 acre-ft less than initial volume after 100 years of recovery and 600 acre-ft less after 300 years. Drawdown of 1 ft is simulated in layer one along the east side. The slower recovery to pre-pumping conditions is probably the result of the pumped area being the farthest away from areas of natural discharge and from the Carson River, which serves as the main source of water in all simulations.

Pumping Concentrated Along West Side of Valley

Hypothetical scenario four simulates pumping concentrated along the west side of Carson Valley. A pumping rate of 3.88 ft^3/s (2,810 acre-ft/yr) is assigned to each of 18 model cells in layer one and 18 cells in layer two (table 2). Distribution of cells assigned a pumping rate is shown in figure 11.

The drawdown exceeds 120 ft in both model layers after 300 years of pumping (fig. 11), but this drawdown is confined to a few cells along the southwest edge of the valley. In layer one, the drawdown is less than 5 ft throughout most of the modeled area, whereas in layer two, the drawdown is less than 5 ft only along the far eastern side (fig. 11). The area of drawdown exceeding 80 ft is smaller than scenario three—pumping concentrated on east side (compare figs. 9 and 11). Maximum drawdown in layer one after a simulation period of 300 years is 151 ft; maximum drawdown in layer two is 126 ft (table 3).

Average drawdown in the pumped area increases rapidly during the first few years of pumping but stabilizes after the first 25 years (fig. 12). Average drawdown in layer one is 37 ft after 25 years, whereas average drawdown in layer two is 64 ft. These averages are considerably less than the simulated drawdowns in scenarios one, two, and three (compare figs. 6, 8, 10, and 12).

Pumping along the west side of the valley results in extremely rapid changes in river and ditch leakage and ground-water seepage to the river and ditches (fig. 12 during the first 25 years). Leakage to the river and ditches decreases a maximum of 47,000 acre-ft/yr after 100 years (table 3), which is about the same decrease simulated in scenarios one and three. Ground-water seepage to the river and ditches decreases a maximum of 35,000 acre-ft/yr, also after 100 years (table 3). This decrease is more than the decrease simulated in scenarios one, two, and three. Evapotranspiration also decreases rapidly in the simulation (fig. 12) for the first 25 years. The maximum decrease of 19,000 acre-ft/yr, however, is less than when pumping was concentrated on the east side of the valley (scenario three, table 3).

The aquifer rapidly approaches equilibrium to the assigned pumping. Most of the water removed from storage is simulated during the first 25 years (fig. 12). The volume of water removed from storage is about 140,000 acre-ft after 25 years (table 3); it increases to about 150,000 acre-ft after 100 years and does not

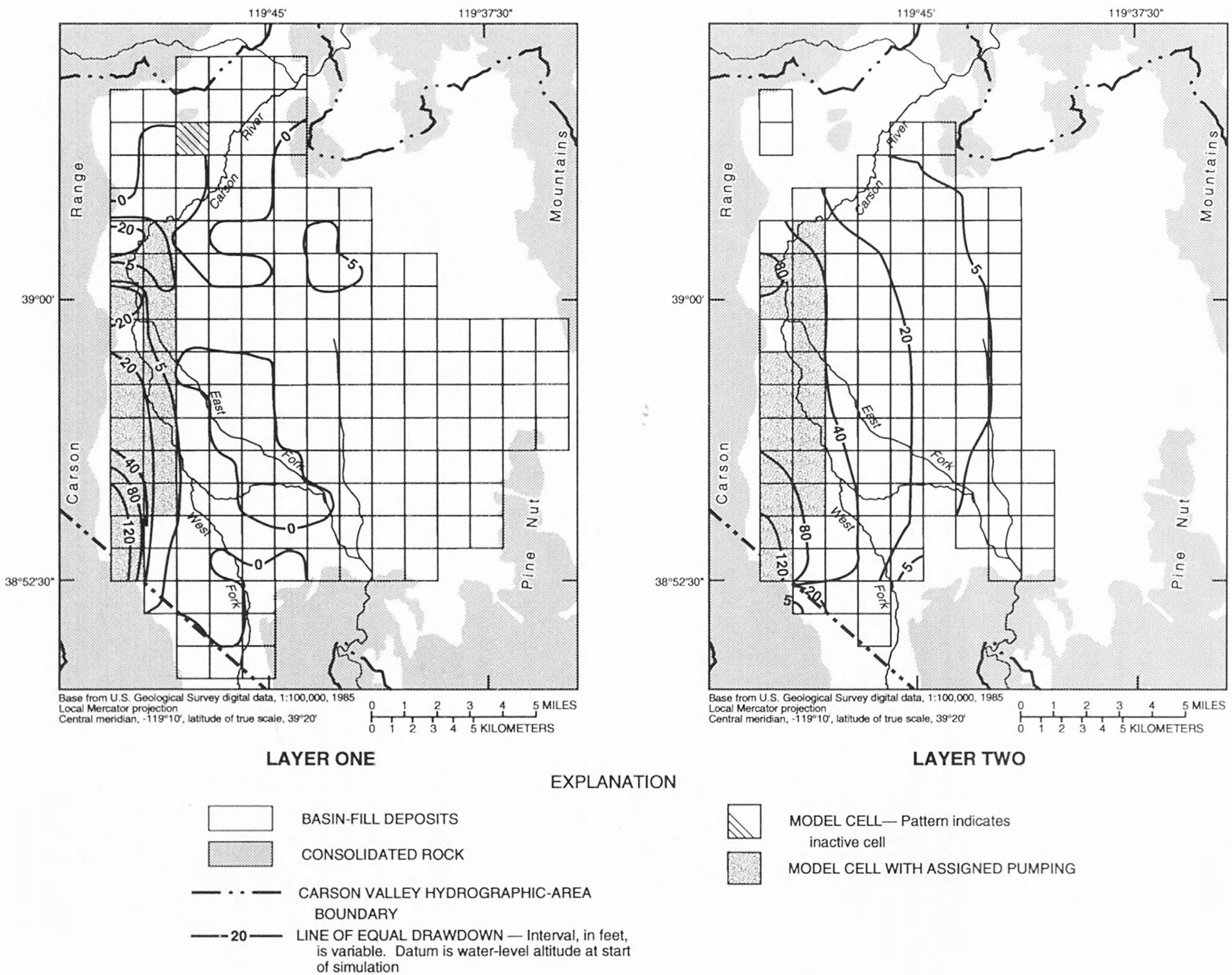


Figure 11. Location of model cells with pumping, and distribution of drawdown in layers one and two after 300 years of pumping for scenario four (hypothetical pumping concentrated along west side of Carson Valley).

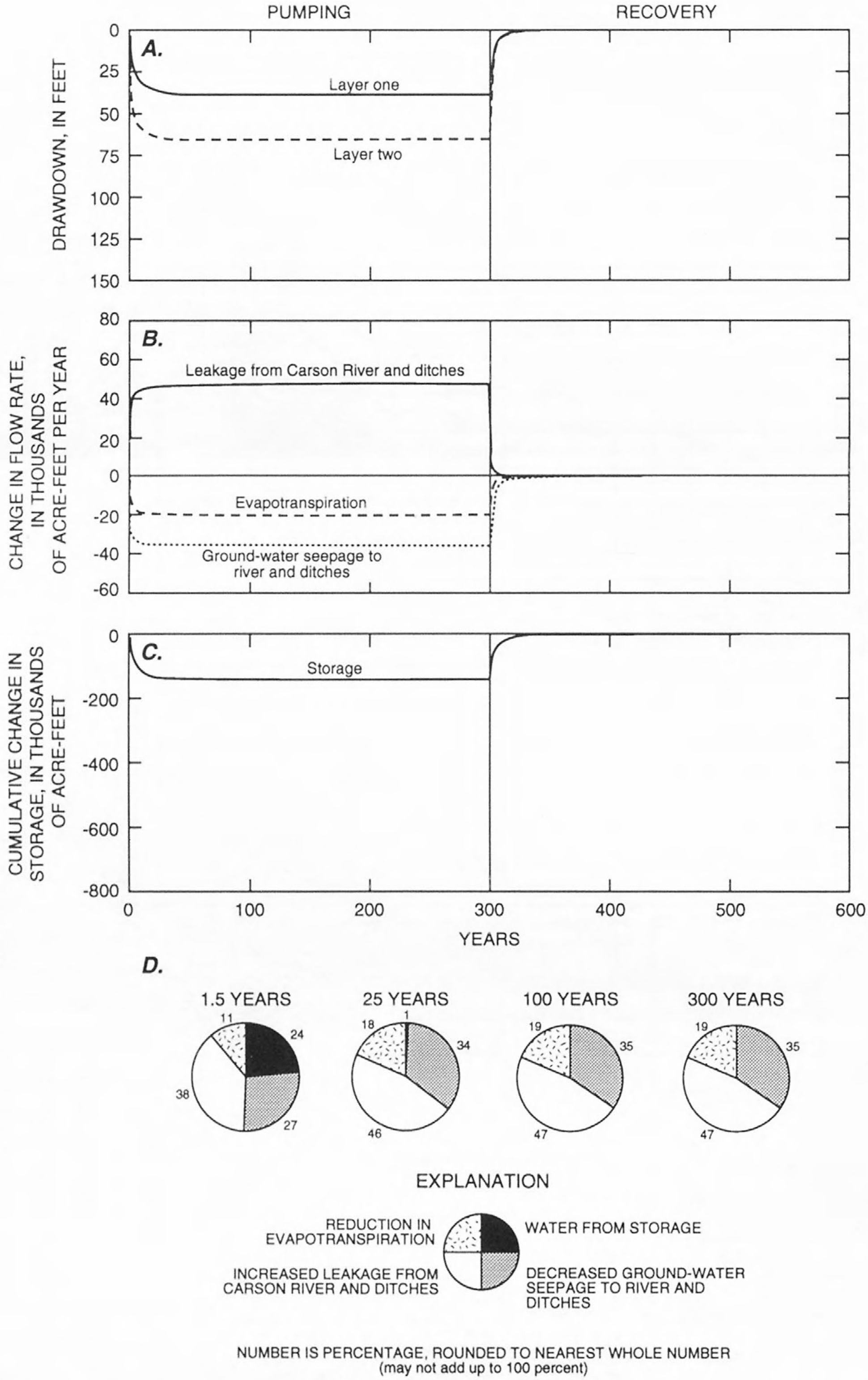


Figure 12. Simulated changes for scenario four (hypothetical pumping concentrated along west side of Carson Valley): *A*, average drawdown in model cells with pumping; *B*, changes in flow rates of leakage from Carson River and ditches, ground-water seepage to river and ditches, and evapotranspiration; *C*, cumulative change in storage; and *D*, sources of pumpage.

change thereafter. This volume is the least amount of water removed from the basin-fill aquifer in any of the five scenarios (table 3).

Pumping along the west side results in much of the pumped water being replaced by increased leakage from the Carson River and ditches and decreased ground-water seepage to the river and ditches (fig. 12). Together, increased leakage and decreased ground-water seepage account for 65 percent of the pumpage after 1.5 years. After 25 years, it accounts for about 80 percent with another 18 percent accounted for by a decrease in evapotranspiration (fig. 12). Thus, pumping along the west side results in rapid changes to surface-water outflow from the valley. After 25 years, surface-water outflow decreases 80,000 acre-ft/yr (table 3), which is the same reduction simulated in scenario two (pumping concentrated at the north end, table 3).

The basin-fill aquifer returns to initial conditions when pumping ceases faster than the other scenarios (compare figs. 6, 8, 10, 12, and 14). After 25 years of recovery, the maximum residual drawdown in layer one is 5 ft and the volume of water in storage is about 4,900 acre-ft/yr less than the initial volume (table 3).

Pumping Dispersed on Valley Floor

Hypothetical scenario five simulates pumping dispersed over the valley floor. A pumping rate of 0.71 ft^3/s (514 acre-ft/yr) is assigned to each of 105 model cells in layer one and 91 cells in layer two (table 2). Distribution of cells assigned a pumping rate is shown in figure 13.

Pumping dispersed over the valley floor results in drawdown after 300 years being less than 40 ft in both model layers, except for one cell in layer one and two cells in layer two (fig. 12). Drawdown in layer one is less than 10 ft in the central part, but exceeds 20 ft in seven cells along the east and west sides of the pumped area. Drawdown in layer two exceeds 20 ft throughout much of the modeled area. Maximum drawdown in layer one after a simulation period of 300 years is 45 ft; maximum drawdown in layer two is 44 ft (table 3) and is the least simulated in any of the five scenarios.

Average drawdown in the pumped area is less than 10 ft in layer one and about 25 ft in layer two (fig. 14). These averages are less than those simulated in the other hypothetical scenarios.

Pumping dispersed over the valley floor results in a rapid decrease in ground-water seepage to the river and ditches, more so than any of the other scenarios (compare figs. 6, 8, 10, 12, and 14), and results in the least reduction in evapotranspiration (table 3). Evapotranspiration decreases about 14,000 acre-ft/yr after 25 years (table 3); it decreases about 15,000 acre-ft/yr after 100 years.

Cumulative volume of water removed from storage increases rapidly during the first 25 years (fig. 14), totaling 140,000 acre-ft. The volume increases slowly to 160,000 acre-ft/yr during the next 75 years and does not change after 100 years (table 3). This volume is 10,000 acre-ft more than scenario four but is at least 40,000 acre-ft less than the other three scenarios.

Pumping dispersed over the valley floor captures more seepage to the rivers and ditches than the other hypothetical scenarios. Decreased seepage after just 1.5 years accounts for 38 percent of the pumpage (fig. 14) and after 25 years, it accounts for 43 percent. The combination of decreased seepage to and increased leakage from the river and ditches accounts for 86 percent of the pumpage after 100 years, resulting in a decrease in surface-water outflow of about 86,000 acre-ft/yr (table 3). This reduction is the most simulated for any of the hypothetical scenarios.

The aquifer did not recover as rapidly when pumping ceases as in scenario four (compare figs. 12 and 14; table 3). Still, the aquifer returns to initial conditions in less than 100 years; results are similar to simulations for scenarios one and two.

SUMMARY AND CONCLUSIONS

A computer model that simulates ground-water flow in Carson Valley, a north-trending alluvial basin that encompasses about 360 mi^2 in Douglas County, Nev., and Alpine County, Calif., was used to evaluate the effects of pumping ground water from a basin-fill aquifer. The simulations were done as part of the Great Basin Regional Aquifer-System Analysis project in Nevada, Utah, and adjacent states. The purpose of the simulations is to compare changes in ground-water flow resulting from different distributions of pumping in and between selected basins having different hydrologic and physical characteristics. Carson Valley was chosen to represent similar basins in the Great Basin where the basin-fill aquifer is in direct hydraulic connection with a river. Five hypothetical scenarios were selected to simulate the effects of pumping ground water on the overall water resources of the valley.

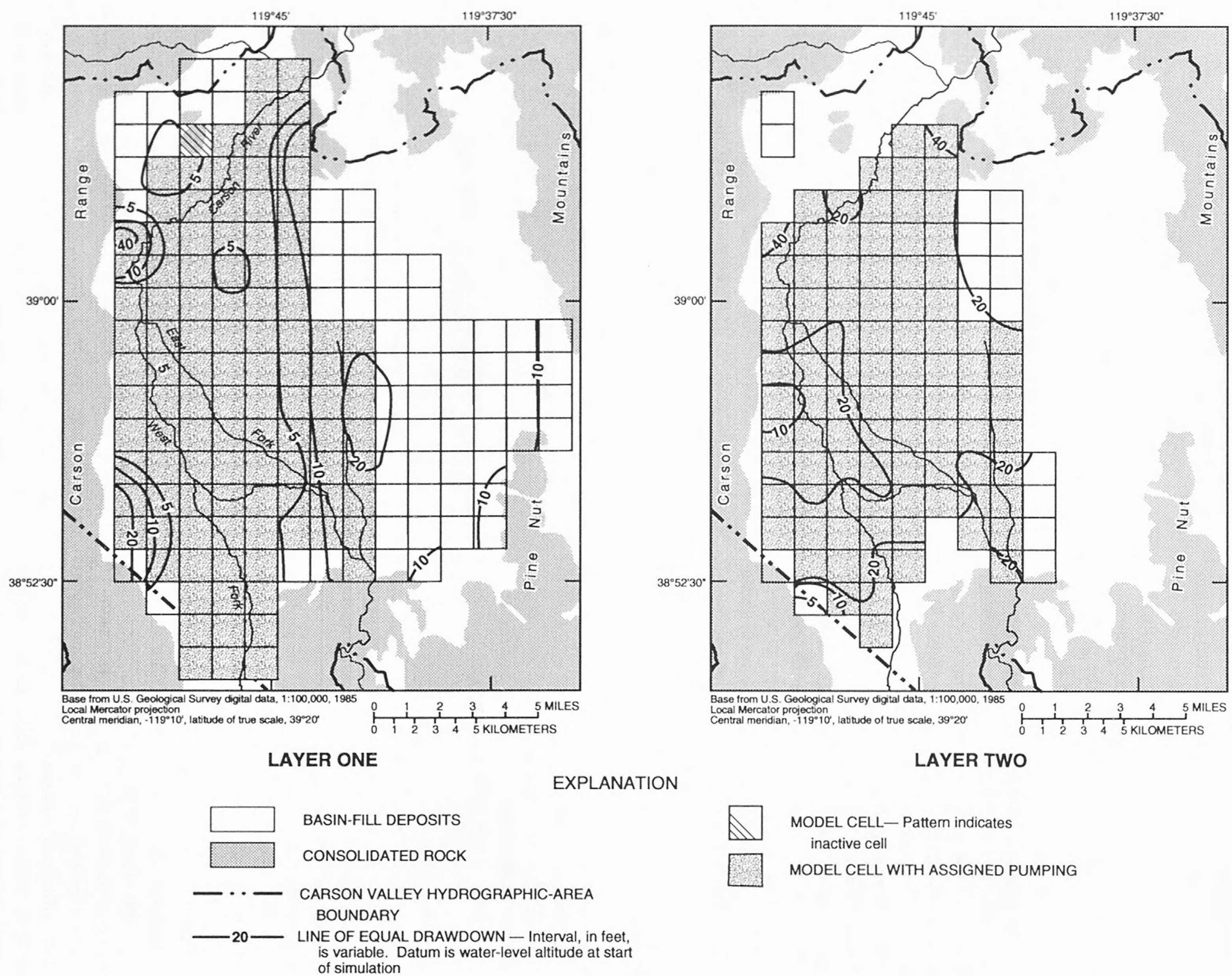


Figure 13. Location of model cells with pumping, and distribution of drawdown in layers one and two after 300 years of pumping for scenario five (hypothetical pumping dispersed on valley floor).

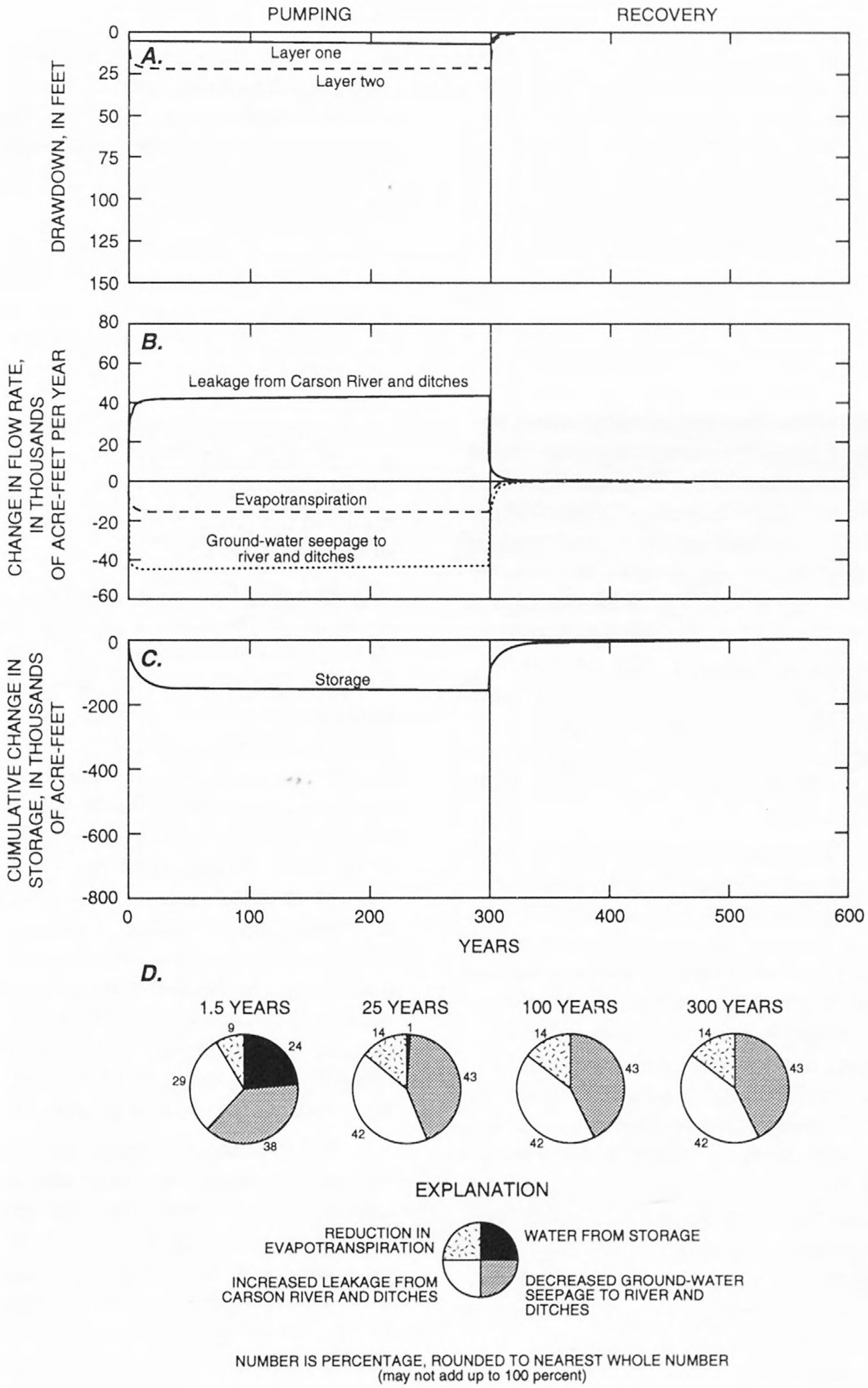


Figure 14. Simulated changes for hypothetical ground-water development scenario five (pumping dispersed on the valley floor): *A,* average drawdown in model cells with pumping; *B,* rates of leakage from Carson River and ditches, ground-water seepage to river and ditches, and evapotranspiration; *C,* cumulative change in storage; and *D,* sources of pumpage.

Ground-water flow in the aquifer is generally from the adjacent mountains to the center of the valley, then northward. Recharge to ground water is from direct precipitation on the valley floor, from subsurface inflow along the margins of the aquifer, and from leakage of water from both perennial and ephemeral streams and irrigation ditches. Average annual recharge simulated in the ground-water flow model of Carson Valley is about 207,000 acre-ft, of which about 47,000 acre-ft is simulated as direct precipitation on the valley floor; 55,000 acre-ft as subsurface flow from the adjacent mountains and as leakage from small perennial and ephemeral streams; and 105,000 acre-ft as leakage from the Carson River and irrigation ditches. The combined annual flow of the East and West Forks of the Carson River where they enter Carson Valley averages 358,000 acre-ft and greatly exceeds recharge to the aquifer. Discharge from ground water is from evapotranspiration on the valley floor and seepage to the Carson River and ditches. For the steady state model, average annual discharge is the same as recharge, of which about 149,000 acre-ft is simulated as evapotranspiration and 58,000 ft as seepage to Carson River and irrigation ditches. Average annual flow of the Carson River where it exits Carson Valley is about 295,000 acre-ft.

The basin-fill aquifer was divided into two model layers to represent ground-water flow through the unconfined and confined parts of the aquifer. Hypothetical scenarios of ground-water pumping were divided into two arbitrary periods totaling 600 years; the first 300 years simulate pumpage, whereas the last 300 years simulate recovery. The 600-year simulation period is designed to allow the aquifer to reach new equilibrium during the pumping period, to determine how long it would take for the aquifer to recover to initial conditions once pumping ceased, and to compare the results with those from similar scenarios of other selected basins in the Great Basin RASA study area.

In the hypothetical scenarios, pumping is concentrated at the (1) south end and (2) north end, and along the (3) east side and (4) west side, and is (5) dispersed over the valley floor. All five scenarios are assigned a pumpage of 100,000 acre-ft/yr. This quantity approximately equals the simulated steady-state recharge excluding leakage from the Carson River and irrigation ditches. To simplify the model simulations, secondary recharge of pumped water or redistribution of a percentage of pumped water into the Carson River is not considered. Some of the pumped water usually returns as secondary recharge or flows into streams or ditches. Thus, the scenarios represent conditions for maximum drawdown, and maximum decreases in storage and in surface-water outflow from the modeled area compared with what actually may occur.

Results from all five hypothetical scenarios indicate that leakage from the Carson River and ditches responds rapidly to pumping anywhere in the valley. Each scenario approaches a new steady state after 100 years. Scenarios where pumping is concentrated along the west side and dispersed over the entire valley floor approaches a new steady state after only 25 years. These two simulations result in the least volume of water removed from storage after 300 years of pumping (150,000 and 160,000 acre-ft/yr, respectively), whereas pumping concentrated along the east side results in the greatest volume of water removed from storage (670,000 acre-ft/yr).

Pumping for 300 years at the north end of the valley results in the greatest increase in leakage from the Carson River and ditches (59,000 acre-ft/yr), whereas pumping distributed evenly throughout the valley floor produces the least (43,000 acre-ft/yr). However, distributing pumping throughout the valley floor results in the greatest decrease in ground-water seepage to the river and ditches (43,000 acre-ft/yr). The combined effect of increased leakage from and decreased seepage to the Carson River and ditches results in surface-water outflow from the valley that is between 76,000 acre-ft/yr (pumping concentrated on the east side) and 86,000 acre-ft/yr (pumping dispersed on the valley floor) less than the initial long-term outflow. Thus, decreased surface-water outflow accounts for 76 to 86 percent of the pumping in all scenarios. Evapotranspiration decreases between 15,000 and 24,000 acre-ft/yr, and accounts for 15 to 24 percent of the pumping.

When pumping stops, water levels recover rapidly and the aquifer returns to near-initial conditions within 25 to 100 years. The simulation that concentrates pumping along the east side is the slowest to recover because the center of pumping is the farthest away from principal sources of recharge and areas of natural discharge. The simulation where pumpage is concentrated along the west side recovers the quickest.

In conclusion, pumping ground water from basin-fill aquifers that are hydraulically connected to rivers within the Great Basin likely will reduce surface-water outflow from the basins before capturing evapotranspiration. Consequently, the quantity of pumping may depend on how much reduction in surface-water outflow can be tolerated.

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