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MATHEMATICAL MODEL ANALYSIS OF THE EAGLE VALLEY GROUND-WATER BASIN, WEST-CENTRAL NEVADA

By Freddy E. Arteaga

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ILLUSTRATIONS

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CONVERSION FACTORS

The inch-pound system of measure is used in this report. Abbreviations and conversion factors from inch-pound to International System (SI) units are listed below.

Multiply	*By*	*To obtain*
Acres	0.4047	Hectares (ha)
Acre-feet (acre-ft)	0.001233	Cubic hectometers (hm^3)
Acre-feet per year (acre-ft/yr)	0.001233	Cubic hectometers per year (hm^3/yr)
Cubic feet per second (ft^3/s)	0.02832	Cubic meters per second (m^3/s)
Feet	0.3048	Meters (m)
Feet per day (ft/d)	0.3048	Meters per day (m/d)
Feet per day per day [(ft/d)/d]	0.3048	Meters per day per day [(m/d)/d]
Feet per mile (ft/mi)	0.1894	Meters per kilometer (m/km)
Gallons per minute (gal/min)	0.06309	Liters per second (L/s)
Gallons per minute per foot [(gal/min)/ft]	0.2070	Liters per second per meter [(L/s)/m]
Feet per second (ft/s)	0.3048	Meters per second (m/s)
Feet squared per day (ft^2/d)	0.0929	Meters squared per day (m^2/d)
Inches	25.40	Millimeters (mm)
Miles	1.609	Kilometers (km)
Square miles (mi^2)	2.590	Square kilometers (km^2)

ALTITUDE DATUM

The term "National Geodetic Vertical Datum of 1929" (abbreviation, NGVD of 1929) replaces the formerly used term "mean sea level" to describe the datum for altitude measurements. The NGVD of 1929 is derived from a general adjustment of the first-order leveling networks of both the United States and Canada. For convenience in this report, the datum also is referred to as "sea level."

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ABSTRACT

This study encompasses all of Eagle Valley (71 square miles) and small parts of the Carson Valley and Dayton Valley hydrographic areas. The main area of interest, approximately 23 square miles of valley floor, was modeled to evaluate the hydrodynamics of the ground-water system. The water budget, including ground-water recharge and discharge for equilibrium conditions, had been computed in a previous investigation. Recharge under 1964 steady-state conditions was about 4,900 acre-feet per year; the amount has increased to about 5,600 acre-feet annually in recent years due to infiltration of sewerage effluent used for irrigation. Discharge by evapotranspiration, 3,000 acre-feet per year, and subsurface flow to the Carson River, 2,700 acre-feet per year, also were computed for 1964 in the previous study.

Model development included definition of the thickness of the alluvium, which was determined using gravity and seismic techniques. The maximum measured thickness is about 2,000 feet. A two-layer Galerkin finite-element model, consisting of 422 elements and 274 nodes for each layer, was used to simulate the ground-water system. Simulation modeling of equilibrium conditions represented by water levels in 1964 indicated that (1) discharge of ground water through evapotranspiration was 2,900 acre-feet per year, which is in close agreement with recent findings, and (2) discharge of ground water by subsurface outflow to the river was 1,600 acre-feet per year, which is less than previously computed. Additional calibration and analysis accomplished by simulating transient conditions from 1964 to 1978 indicates that evapotranspiration has decreased to 2,000 acre-feet per year as water levels in the western part of Eagle Valley have declined, but that discharge by subsurface outflow has remained unchanged.

The model was used to predict water-level declines through the year 2000 under the water-withdrawal rates of 1978. This predictive simulation indicates water-level declines of as much as 150 feet in the western part of the valley, resulting in the suppression of evapotranspiration to a rate of 1,200 acre-feet per year and a decrease of subsurface outflow to 1,500 acre-feet per year. Using the same withdrawal rates until an ultimate steady state is achieved, the model indicates net water-level declines of as much as 350 feet in the western part of the valley, with evapotranspiration losses suppressed to a rate of 700 acre-feet per year and subsurface discharge to the river decreasing to 100 acre-feet per year.

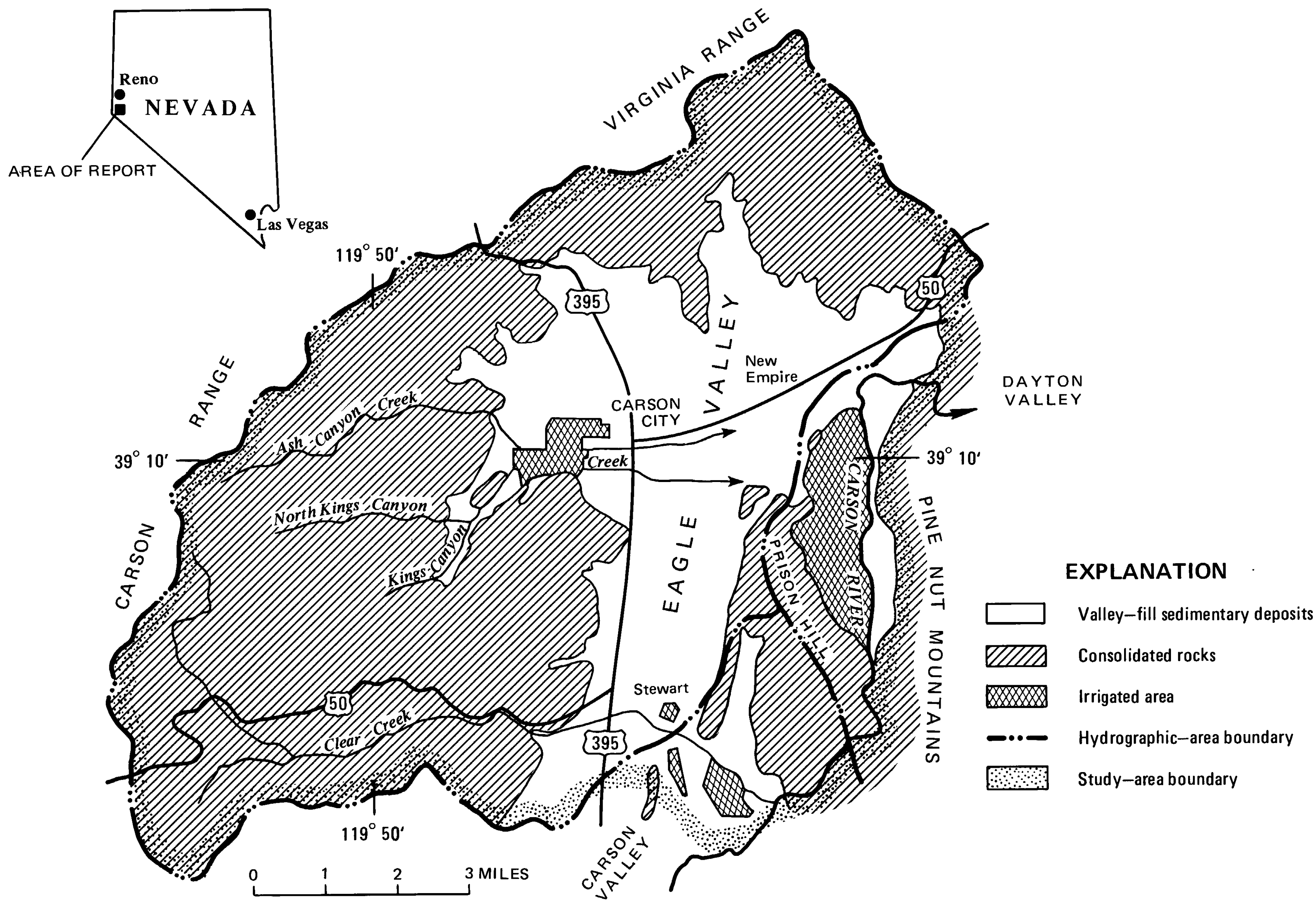

FIGURE 1.—Geographic setting, generalized geology, irrigated areas, and relation between study—area and hydrographic—area boundaries.

INTRODUCTION

Purpose and Scope

Eagle Valley is a small basin (approximate area, 71 square miles) encompassing Carson City, the capital of Nevada (figure 1). Carson City's population increased from about 5,000 in 1955 to about 35,000 in 1979. For water supply, the majority of residents depend in part upon pumpage from municipal wells; the remaining residents are served by privately owned domestic wells. Recent findings indicate that surface-water runoff and ground-water recharge are substantially less than previously thought, and there is concern that the ground-water supply may be inadequate to sustain the increasing population.

To evaluate the ground-water system in Eagle Valley in greater detail, the U.S. Geological Survey, in cooperation with the Nevada Division of Water Resources, embarked on the development and testing of a ground-water model. This modeling study, begun in 1977, will provide the information necessary to evaluate water-management alternatives for the distribution of ground-water pumping to avoid the detrimental effects of excessive water-level declines.

The scope of this study was to (1) obtain, organize, and evaluate the geohydrologic data required to develop a conceptual model of the ground-water basin of Eagle Valley, (2) develop a mathematical model of the basin, and (3) use the computer model to predict the effects of ground-water development on water levels, evapotranspiration, and subsurface outflow.

This report, the second and final of this investigation, deals with development and application of the ground-water model. The first report, by Arteaga and Durbin (1978), defined the water budget for the area and described the development of a relation for steady-state pumping.

Well-Numbering System

The well-numbering system used in this report indicates the location of the wells by hydrographic areas and by official rectangular subdivisions of the public lands. Nevada has been divided into 14 hydrographic regions and basins, and approximately 250 individual hydrographic areas (Rush, 1968). The local well number uses 12 to 16 digits and letters which locate the site by hydrographic area, township, range, section, and section subdivision.

The first segment of the local well number specifies the hydrographic area as defined by Rush. The remainder of the number specifies the township north of the Mount Diablo base line, the range east of the Mount Diablo meridian, the section, and subdivision of the section. Sections are divided into quadrants labeled A, B, C, and D, counterclockwise from upper right. Each quadrant is then similarly subdivided as many as three times, depending on the accuracy of available maps; thus, each section of about 640 acres may be subdivided into tracts of 2.5 acres (330 feet on a side). Lettered quadrants, from the largest to the smallest subdivision, are read from left to right. The number following the last letter indicates the sequence of wells in the subdivision. For example, as shown in figure 2, a well in Eagle Valley (hydrographic area 104) located within the shaded area of section 6, Township 15 north, Range 20 east, would have the number 104 N15 E20 6CCCC1. A second well within the same 2.5-acre tract would be numbered 104 N15 E20 6CCCC2.

Because all wells referred to in this report are in Eagle Valley, the hydrographic area number (104) is omitted throughout the report.

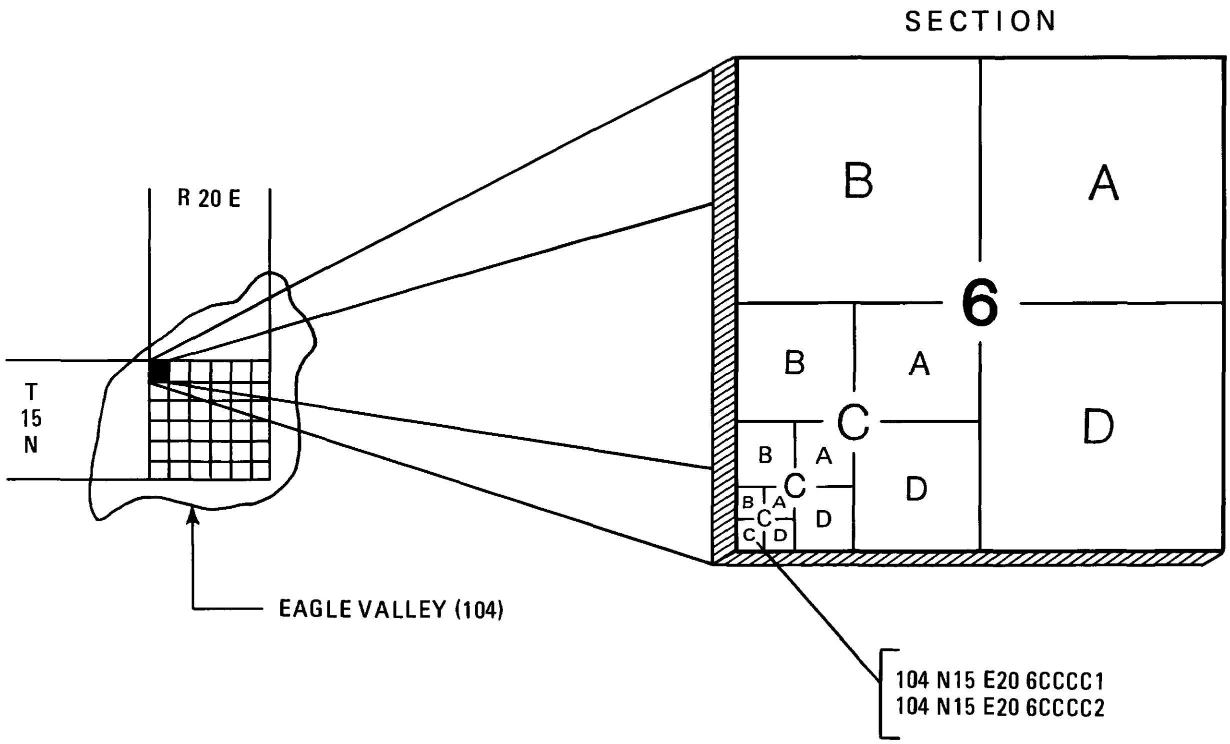

FIGURE 2.—Numbering system for wells.

Data Sources

Drillers' reports of well construction and geologic logs for approximately 1,000 wells in and adjacent to Eagle Valley were furnished by the Nevada Division of Water Resources. Of these, almost 400 wells were field-checked for exact location, land-surface altitude, and depth to water. The data, excluding geologic logs, are stored in the ground-water site inventory of the U.S. Geological Survey WATSTORE data base. Retrievals of this information may be made through the U.S. Geological Survey District Office in Carson City, or through any NAWDEX assistance center. Geologic logs for selected wells--including most deep wells in the valley--are available from the U.S. Geological Survey Office in Carson City. Water levels in three wells have been measured once-yearly by the U.S. Geological Survey since 1962, and the water level in one well has been measured monthly since 1972. An additional 16 wells were selected by the Nevada Division of Water Resources in 1975 for observation, and have been measured several times each year. In 1977, three continuous recorders were installed to augment the observation well network. Records of pumpage from municipal wells for the period 1966-78 were obtained from the Carson City Water Department.

Acknowledgments

The author wishes to acknowledge the cooperation of the Reproduction Section of the Nevada Department of Transportation, the Nevada Department of Prisons, the Carson City Public Works Department, the Carson City Water Department, Mrs. Eva R. Lompa, and Mr. I. R. Anderson for providing data, logistics support, and general information about the area.

DESCRIPTION OF THE STUDY AREA

Geographic Setting

Eagle Valley is a semiarid ground-water basin in the west-central part of Nevada. Average annual precipitation in Carson City is about 10 inches. The valley is bordered on the west by the Carson Range of the Sierra Nevada, on the north by the Virginia Range, on the east by Prison Hill and the Pine Nut Mountains, and on the south by Carson Valley (figure 1). In addition to the 71-square-mile Eagle Valley Hydrographic Area as defined by Glancy and Katzer (1975, plate 1), the overall study area includes small parts of the Carson Valley and Dayton Valley Hydrographic Areas (6 and 7 square miles, respectively). The ground-water basin modeled in this report comprises 23 square miles of valley floor and adjacent areas, mostly in Eagle Valley (plate 1).

The major streams draining Eagle Valley are Clear, Ash Canyon, Kings Canyon, and North Kings Canyon Creeks. Average runoff from these four perennial streams is about 7,800 acre-ft/yr, which constitutes practically the entire water yield, 9,000 acre-ft/yr, from the basin (Arteaga and Durbin, 1978, page 14).

Geologic and Hydrologic Setting

For the purpose of this study, geologic units described by Worts and Malmberg (1966, page 5-7) have been grouped as follows: (1) unconsolidated water-bearing sedimentary deposits yielding large quantities of ground water, (2) partly consolidated[1] sedimentary deposits yielding smaller quantities of ground water, and (3) the basement complex of virtually non-water-bearing consolidated rocks.

The unconsolidated alluvial deposits are Quaternary in age and are composed mostly of granitic and metamorphic detritus dominated by sand and coarser materials, with lesser proportions of silt and clay. In general, the unconsolidated deposits in the area west of Lone Mountain and the area south of Fairview Drive (plate 1) are more permeable and, where saturated, yield water freely to wells. Specific capacities in these two areas range from as much as 25 to as little as 4 gal/min per foot of drawdown, respectively. Corresponding well yields range from 2,200 to 600 gal/min.

The partly consolidated alluvial deposits, also Quaternary in age, are primarily southeast of Lone Mountain and north of Fairview Drive. These deposits are dominated by heterogeneous mixtures of sand, silt, and clay, along with discontinuous layers of clay that collectively serve as a confining unit. Specific capacities of wells generally are less than 5 (gal/min)/ft, and well yields are less than 1,000 gal/min.

The basement complex underlies the sedimentary deposits and makes up the bordering hills and mountains. These rocks are nearly impermeable except where fractured or weathered, and are not an important source of water. Tertiary sandstone, which is exposed near the Nevada Maximum Security Prison (Bingler, 1977), may be localized in occurrence west of the river; it is included herein as part of the basement complex along with Tertiary volcanic rocks, Cretaceous granitic rocks, and Triassic and Jurassic metavolcanic and metasedimentary rocks (Moore, 1961; Bingler, 1977; Trexler, 1977; and Pease, 1980). Figures 1 and 3 and plate 2 show the areal distribution of consolidated (basement-complex) rocks and valley-fill sedimentary (alluvial) deposits, and plate 2 shows the distribution of faulting in the study area.

The altitude and configuration of the predevelopment water table in Eagle Valley is shown by the 1964 water-level contour map of Worts and Malmberg (1966, figure 4). The map was developed, in part, from 28 depth-to-water measurements made in 1964 and an additional 37 measurements available for the period 1949-66. Predevelopment water-level altitudes determined from land-surface altitudes used by Worts and Malmberg (1966, table 13) have been corrected where necessary due to the availability of more detailed topographic maps, and their 1964 water-table contour map has been redrawn for this report (figure 3).

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[1] "Partly consolidated" denotes differing degrees of consolidation (lithification), both areally and at a single site.

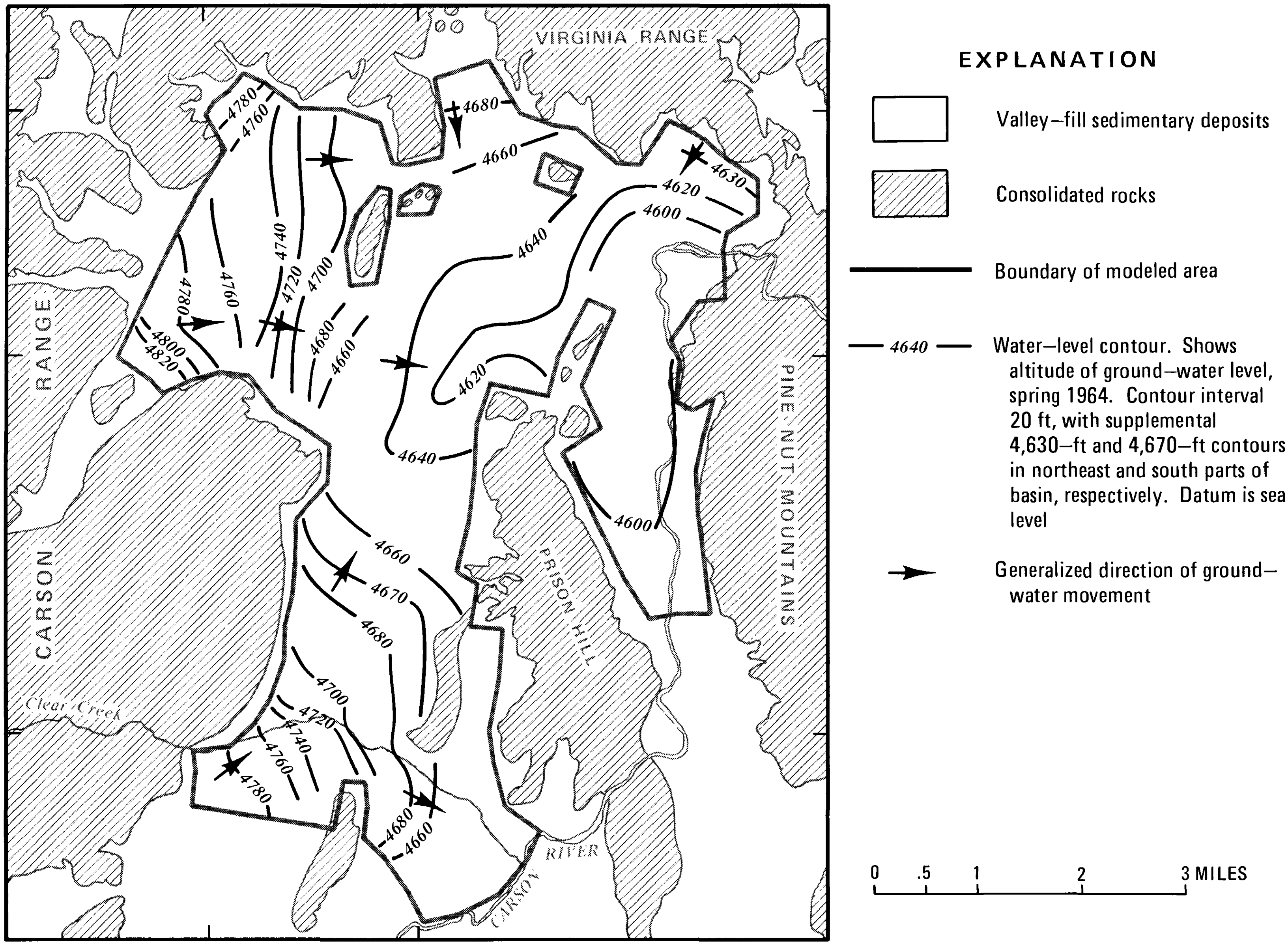


FIGURE 3.—Altitude of ground—water level, spring 1964 (modified from Worts and Malmberg, 1966, fig. 4).

Ground water in Eagle Valley moves from the bases of the Carson Range and Virginia Range toward the central part of the basin. Consolidated rocks that form Lone Mountain act as a barrier to the easterly flow from the Carson Range and force ground water to move around both the north and south edges of this rock mass as evidenced by the 4,700-foot water-level contour. Part of the ground water from the Virginia Range moves directly to the Carson River. In the vicinity of Clear Creek, part of the ground water moves northeasterly toward Carson City and the remainder southeasterly toward the Carson River. Movement toward Prison Hill, reflected by water-level contours 4,670 and 4,680 in figure 3, may be influenced by the fault just east of Edmonds Drive. Water-level data needed to better define the effect of this fault on the ground-water movement are lacking. This ground-water movement from the west, north, and south, as evidenced by the 4,640-foot water-level contour, converges in the vicinity of the Nevada Maximum Security Prison. The confluence of this ground-water movement (figure 3) is in the area of greatest alluvial thickness. The ground water becomes confined as it moves between the clay beds that are interspersed within the alluvium (individual clay beds are locally as thick as 270 feet).

The contours in figure 3 are based on water levels in wells of differing depth. Thus, in areas of confined (artesian) ground water, deeper wells tend to have higher potentiometric heads than nearby shallower wells. Figure 4 depicts a simplified view of the movement and disposition of water in a part of the ground-water system. Figure 5 illustrates the different water levels to be expected in wells of various depths in the artesian areas of Eagle Valley.

Major faults in Eagle Valley that may act as at least partial barriers to the movement of ground water occur primarily south and east of Lone Mountain (plate 2). The water table is several tens of feet higher on the upgradient side of the faults than on the downgradient side. Two wells that illustrate this abrupt change in water level, wells N15 E20 8DCBB1 and N15 E20 17AAAB1, are on opposite sides of a fault zone and have water-level altitudes of 4,679 feet and 4,645 feet, respectively. This 34-foot water-level displacement occurs within a distance of approximately 2,000 feet, and the apparent barrier effect may be due to local and incomplete vertical offsetting of sand beds against clay beds along the fault zone.

A few springs occur along the faults. Worts and Malmberg (1966, page 30) discussed the two major springs on the valley floor--Carson Hot Springs and Steinheimer Springs--which were estimated to collectively discharge about 180 acre-ft/yr. Carson Hot Springs is presently used for swimming and the Steinheimer Springs has dried up due to lowering of water levels by nearby pumping wells.

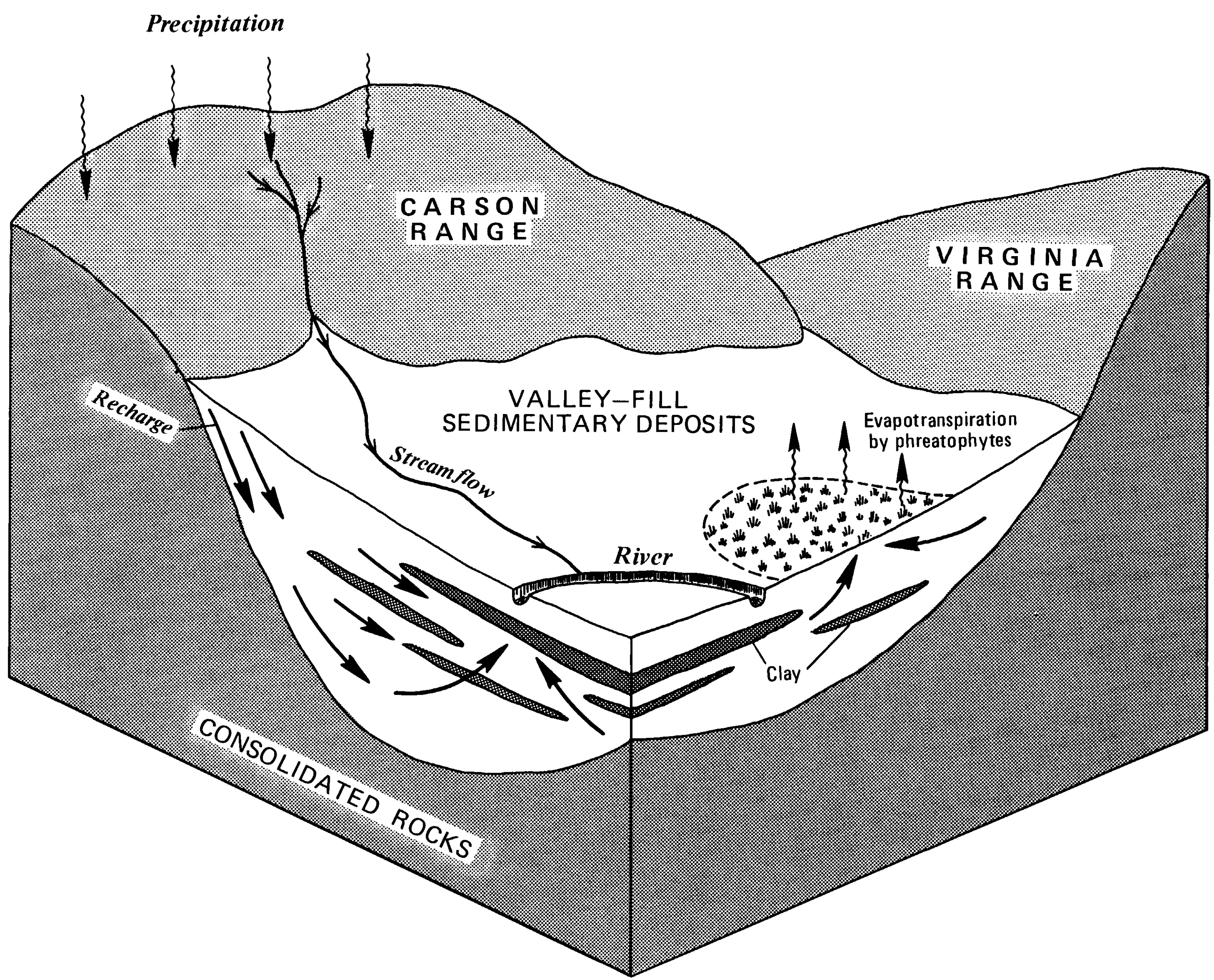


FIGURE 4.—Schematic block diagram showing water cycle in Eagle Valley.

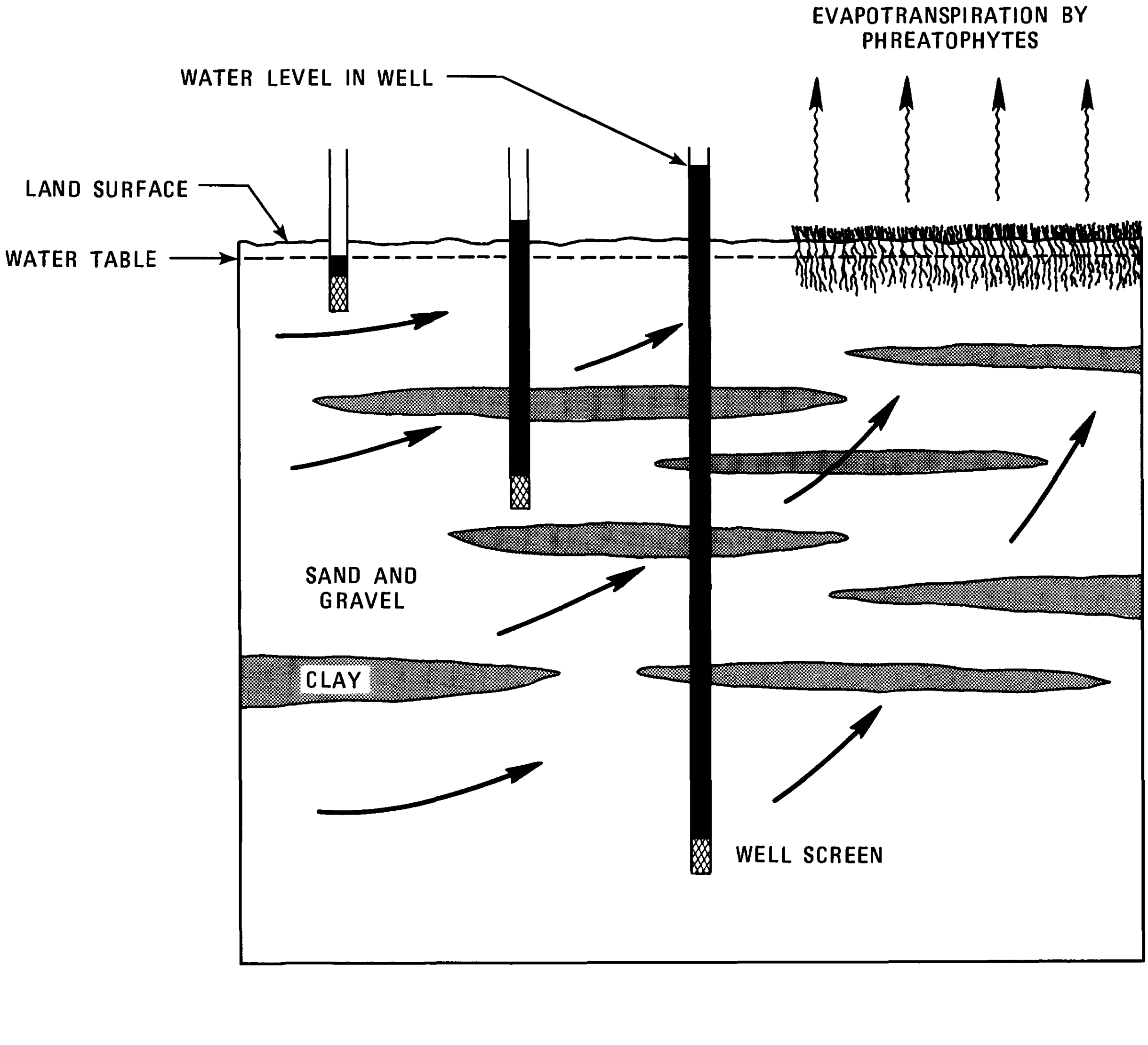


FIGURE 5.—Schematic cross section showing increasing potentiometric head with increasing well depth in vicinity of Nevada Maxium Security Prison. Arrows show generalized directions of ground—water movement.

DESCRIPTION OF THE MODEL

Development of a Perspective

Alluvial materials of the Eagle Valley ground-water basin were deposited by streams carrying sediments mostly from the nearby mountain areas. These streams have laid down discontinuous, generally alternating layers and lenses of fine-grained and coarse-grained deposits. The accumulation of these deposits over the past several million years, and their saturation with water, have formed the present ground-water basin.

Water that saturates the alluvial deposits is in motion, both horizontally and vertically. Horizontal movement occurs, for the most part, through the coarse-grained deposits. Water flows around and generally parallel to the nearly horizontal layers and lenses of fine-grained materials. Vertical movement occurs in two general manners, by circuitous flow paths around lenses of fine-grained deposits or by vertical flow through a lens or layer.

The cause and result of ground-water movement are water-level gradients. Ground water moves from areas of high water level to areas of lower water level. The frictional force of moving water against sediment particles composing the aquifer deposits dissipates energy and results in a head decline in the direction of movement. Regardless of the perspective, the horizontal movement of ground water is expressed by the geographic variation of water levels in wells in the Eagle Valley ground-water basin. Vertical movement is expressed by water-level differences in nearby wells of different depth.

Translation of the Perspective into a Mathematical Model

The development of a ground-water model involves the translation of a conceptual model of the actual system into a mathematical model. The conceptual model is a more or less qualitative description of the important attributes of the physical system under consideration. For the Eagle Valley ground-water basin, the conceptual model is that of an alluvial basin comprised of alternating layers and lenses of coarse-grained and fine-grained deposits (figure 6). Horizontal and vertical components of ground-water movement through these deposits are expressed as geographical and vertical differences in ground-water level in wells.

The model of the Eagle Valley ground-water basin simulates the movement of ground water and the variations in water level as a three-part system. The fine-grained layers that occur at various depths in the basin are, for the sake of simplicity, aggregated in the mathematical model into a single equivalent layer. Similarly, the coarse-grained layers are aggregated into two equivalent layers separated by the single fine-grained layer. Coarse-grained deposits within the upper 50 feet of saturated material constitute the top layer of the model. The remaining coarse-grained deposits constitute the bottom layer.

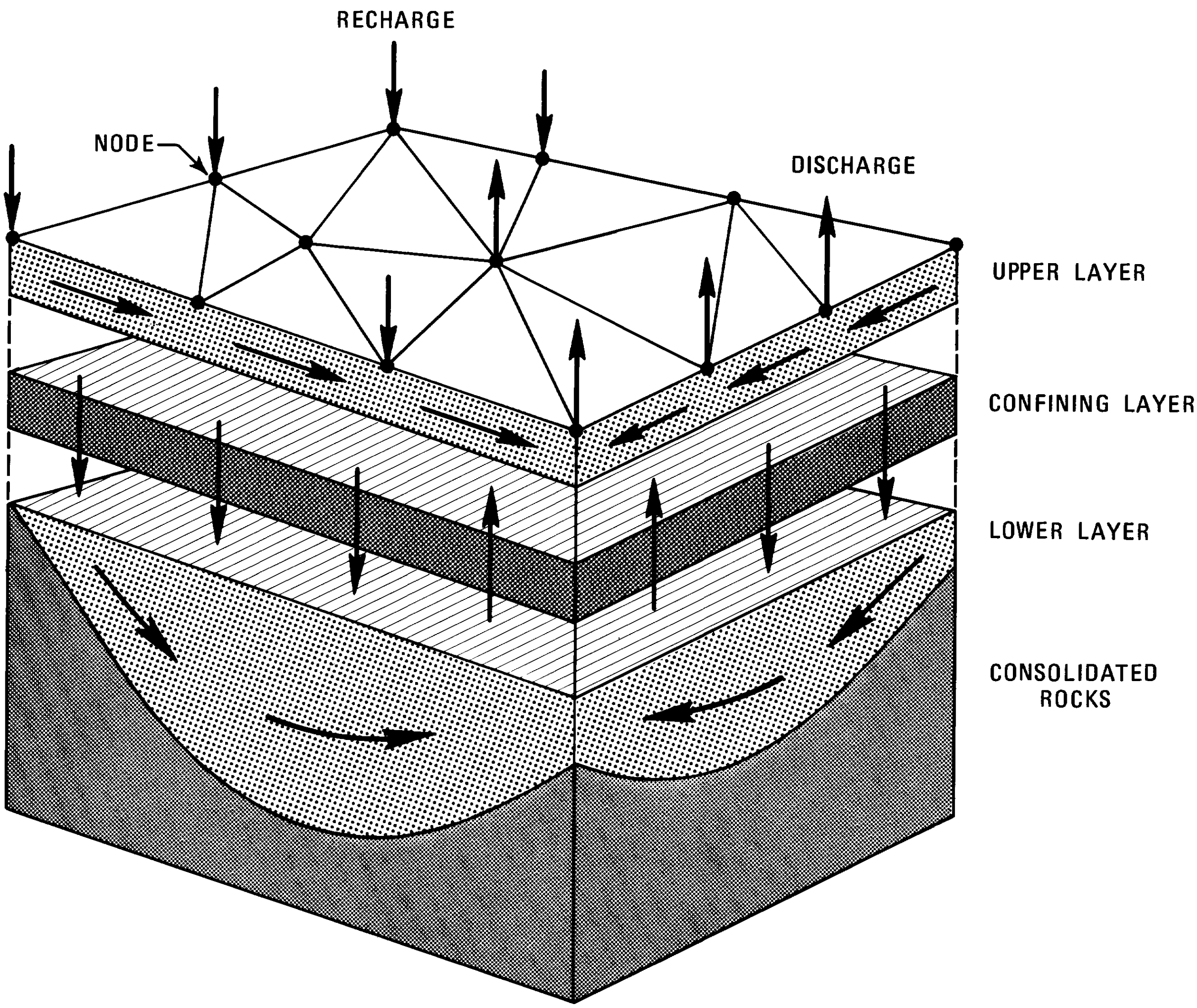


FIGURE 6.—Schematic block diagram showing conceptual model of Eagle Valley ground—water basin.

This construction allows for the simulation of ground-water movement and water-level variations as they most likely occur in the actual ground-water basin. The upper layer of the model allows for the simulation of horizontal ground-water movement and geographic water-level variations in the shallower zones of the basin. The lower layer allows for the simulation of these attributes in the deeper zones. Finally, the middle layer allows for the simulation of vertical ground-water movement and water-level variations between shallower and deeper zones of the basin.

Therefore, the conceptual model of the Eagle Valley ground-water basin, as a three-dimensional system having both areal and vertical flow, is replaced by a simplified digital model having a two-aquifer system, which is linked in the model through a leakage term that represents vertical flow through the fine-grained deposits.

The general equations that approximate flow of water in a two-aquifer ground-water system (Durbin, 1978, page 37) are:

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right)-S\frac{\partial h}{\partial t}-W-\frac{K}{b}(h-h')=0 \qquad (1)$$

and

$$\frac{\partial}{\partial x}\left(T'\frac{\partial h'}{\partial x}\right)+\frac{\partial}{\partial y}\left(T'\frac{\partial h'}{\partial y}\right)-S'\frac{\partial h'}{\partial t}-W'-\frac{K}{b}(h'-h)=0, \qquad (2)$$

where x and y = cartesian coordinates,

T = transmissivity of the upper aquifer,

T' = transmissivity of the lower aquifer,

h = hydraulic head in the upper aquifer,

h' = hydraulic head in the lower aquifer,

S = storage coefficient of the upper aquifer,

S' = storage coefficient of the lower aquifer,

W = flux of a source or sink (recharge or discharge) at the upper aquifer,

W' = flux of a source or sink (recharge or discharge) at the lower aquifer,

K = vertical hydraulic conductivity of the confining layer that separates the two aquifer systems, and

b = thickness of the confining layer.

Each of the terms in equations 1 and 2 can be related to physical attributes of the ground-water basin. The terms of the form $\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right)$ and $\frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right)$ represent the horizontal movement of ground water. Terms of the form $S\frac{\partial h}{\partial t}$ represent changes in water stored in the ground-water basin resulting from changes in ground-water level. Terms W and W' represent the addition or subtraction of water to or from the ground-water basin by recharge, pumping, or other mechanisms. Terms of the form $(K/b)(h-h')$ represent the vertical movement of ground water through or around fine-grained deposits.

Equations 1 and 2 have been solved simultaneously, using the Galerkin finite-element method. The Galerkin procedure was chosen because it is more flexible than the finite-difference approach in that irregular boundaries and faults are more precisely simulated. This elemental method was applied by Pinder and Frind (1972) to a single-aquifer ground-water system. Durbin (1978) in a study of Antelope Valley, Calif., extended this model method to a two-aquifer system with triangular-shaped elements. In that study, he also presented the theoretical development of the method, which is not repeated here.

In the current study, identical grid patterns have been used in the upper and lower layers of the mathematical model, with the elements and nodes numbered the same for each layer. The model grid consists of 422 elements and 274 nodes (plate 3). Physical properties of the aquifer, such as transmissivity, storage coefficient, and leakance coefficient, are assigned to the elements (triangles), and the recharge and initial hydraulic head are assigned to the nodes (vertices of the triangles).

The geohydrologic relations in the ground-water basin are complex, and known only in an approximate sense. Model development required the use of assumptions that simplify the physical system. Thus, the model output should be evaluated with the limiting factors in mind. Some of the more important simplifying assumptions that relate directly to the mathematical model are:

1. The physical parameters of the system do not change with the state of the system. The upper layer of the model is assumed to have a constant saturated thickness. Hydraulic continuity between the upper and lower layers is assumed to be maintained even though the saturated thickness of the lower layer changes.

2. The aquifers are isotropic.

3. Ground-water movement in an aquifer is only horizontal.

4. Ground-water movement in the confining unit is only vertical and is simulated through the use of the leakance coefficient.

5. Changes in ground-water storage in the aquifers occur instantaneously with changes in hydraulic head.

6. Recharge occurs instantaneously.

7. Evapotranspiration occurs as a linear function of depth to water and, for modeling purposes, is insignificant at depths to water in excess of 10 feet.

DEVELOPMENT OF THE STEADY-STATE MODEL

Sources and Sinks

The three-dimensional ground-water model was calibrated by using sources (recharge) and sinks (discharge) for input. The sources and sinks include municipal recharge and pumpage, recharge by seepage from perennial streams, recharge from irrigated pasture lands, natural recharge from ephemeral streams, evapotranspiration, and subsurface discharge to the Carson River, all for steady-state conditions as of 1964.

Natural Recharge

In a previous study (Arteaga and Durbin, 1978, page 14), the total water yield from the basin was estimated to be about 9,000 acre-ft/yr, made up of 7,800 acre-ft/yr of surface-water outflow from Clear, Ash Canyon, and Kings Canyon Creeks and 1,200 acre-ft/yr of natural recharge to the ground-water reservoir. The natural recharge is supplied by surface-water runoff from the small, peripheral drainage basins, which infiltrates the upper part of the alluvial fans and percolates downward to the water table.

An additional 60 acre-ft/yr, representing recharge from the Pine Nut Range and the east side of Prison Hill, was also included.

Recharge from Seepage

The recharge of seepage from Clear, Ash Canyon, and Kings Canyon Creeks was derived from the application of a small-streams model. The model simulates recharge to the ground-water basin by infiltration along the channels of the three perennial streams and two irrigation ditches in the valley.

The amount of recharge through a channel reach can be approximated from the relation:

$$Q_i = \overline{f}\overline{w}L_i, \qquad (3)$$

where Q_i is the recharge occurring along a reach of length L_i, with an average infiltration $\overline{f}$ and average width of flow $\overline{w}$ (Durbin and others, 1978, page 62).

The term $\overline{w}$ can be expressed:

$$\overline{w} = aQ^b, \tag{4}$$

where a and b are numerical coefficients and Q is the discharge associated with the width of flow at the time of measurement. Substituting the expression for $\overline{w}$ (equation 4) into equation 3 yields:

$$Q_i = \overline{I}aQ^bL_i \ . \tag{5}$$

Measurements of flow width and discharge for several streamgaging sites in and near Eagle Valley are plotted in figure 7, along with a line representing the average relation among the data. The coefficient a is the log-intercept of the line and the coefficient b is the slope of the line. The relation represented by the line in figure 10 is:

$$\overline{w} = 3.37\ Q^{0.37} \ . \tag{6}$$

Seventy-one discharge measurements were made during September-November 1978 along segments of Ash Canyon, Kings Canyon, and Clear Creeks, a small ditch off Kings Canyon Creek, and a ditch just south of Clear Creek. The data were used to compute infiltration rates, $\overline{I}$, for different reaches. Because infiltration rates may vary throughout the year, the computed rates are only an approximation of average annual infiltration.

The small-streams model was designed to be used in conjunction with flow-duration curves for a stream, to evaluate recharge within a particular reach by determining inflow to and outflow from the reach. Model input for the study area is the annual runoff from the three streams at the edge of the ground-water basin. Model output consists of (1) ground-water recharge along segments of the channels and ditches and (2) the residual surface water that either is used for irrigation of pasturelands or flows into the Carson River, or both. Total recharge computed by the model amounts to 1,700 acre-ft/yr.

Recharge from Agricultural Water and Municipal Uses

In the earlier study (Arteaga and Durbin, 1978, page 25), recharge from agricultural water, 3,100 acre-ft/yr, included the 1,700 acre-ft/yr of recharge from seepage along the three streams and two ditches. Thus, the recharge solely from irrigation of pasture lands is 1,400 acre-ft/yr. Recharge from municipal use is estimated on the basis of data presented by Arteaga and Durbin (1978, table 3) as the average recharge rate during the 11-year period 1967-77, or 540 acre-ft/yr.

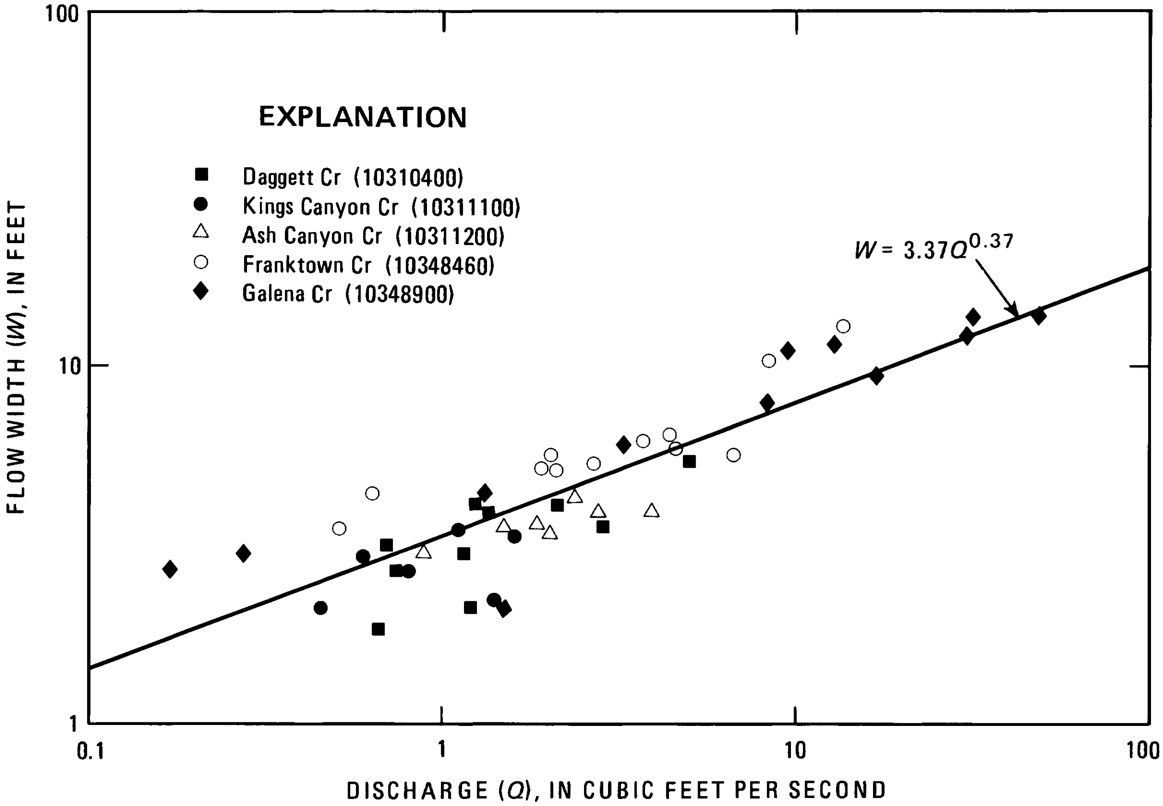


FIGURE 7.—Relation between width of flow and discharge for selected small streams.

Total Recharge

Recharge from all sources, under steady-state conditions as of 1964, totaled 4,900 acre-ft/yr, as follow:

Source	Amount (acre-ft/yr)
Natural recharge	1,260
Seepage	1,700
Irrigation of pasturelands	1,400
Municipal use	540
Total	4,900

Ground-Water Pumpage

The average pumpage from three municipal wells in Eagle Valley from 1962 to 1965 was 300 acre-ft/yr, and rural domestic and stock-water use during this same period was about 400 acre-ft/yr (Worts and Malmberg, 1966, pages 24, 25). Average pumpage from one well at the Nevada Indian Agency at Stewart was estimated by the Agency to be 100 acre-ft/yr. Pumpage from the three municipal wells and the well at Stewart was assigned in the model at nodes 127, 155, 161, and 232 (plate 4). This pumpage, 400 acre-ft/yr, was assigned to the lower-layer nodes only. Most water withdrawn for household use from domestic wells outside the Carson City Water Department service areas returns to the ground-water system through septic tanks. Thus, the net withdrawal of ground water from these domestic wells is, for modeling purposes, assumed to be negligible.

Irrigation wells, for the most part, do not constitute a major source of ground-water withdrawal. Historically, most watering of pastures was by flood irrigation, using surface-water runoff from Ash Canyon, Kings Canyon, and Clear Creeks. At present (1979) only one irrigation well is used in the valley, and it withdraws approximately 30 acre-ft/yr.

Subsurface Discharge to the Carson River

Subsurface flow to the Carson River, estimated at 2,700 acre-ft/yr in the previous study (Arteaga and Durbin, 1978, page 32), is one of the sink terms computed by the model. Three possible situations can occur within the modeled reach of the river. The river may gain water, it may lose water, or it may remain in a state of equilibrium. These three possibilities will vary in space and time, depending on the relations between hydraulic head and stream stage.

Figure 8 illustrates how hydraulic head and stream stage are related. The situation described by sketch A is a recharge condition that could occur during periods of high flow. Sketch B portrays a transitional phase of interaction between the river and the ground-water basin, where the ground-water level coincides with that of the stream. Sketch C depicts a period of low flow in the river, when it becomes a gaining stream. This latter condition is prevalent in the reach represented by nodes 236, 246, 248, 260, and 265, south of the Nevada Medium Security Prison. The gain in this reach was estimated to be 1,200 acre-ft/yr (Arteaga and Durbin, 1978, page 32). A similar gain occurs near New Empire and was estimated in that report (page 32) as 1,500 acre-ft/yr.

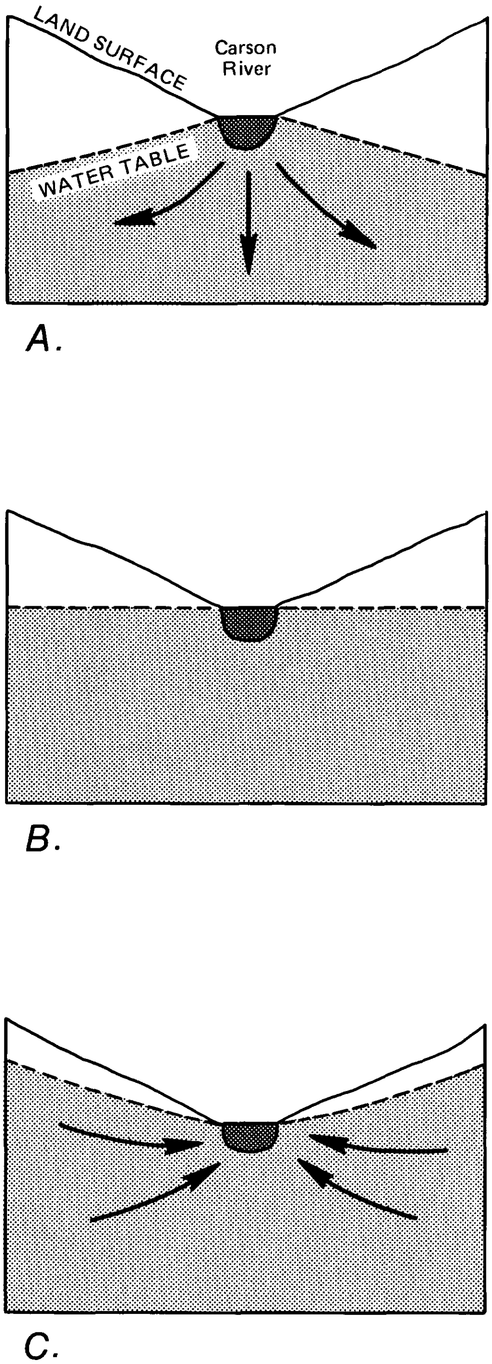
Discharge by Phreatophytes

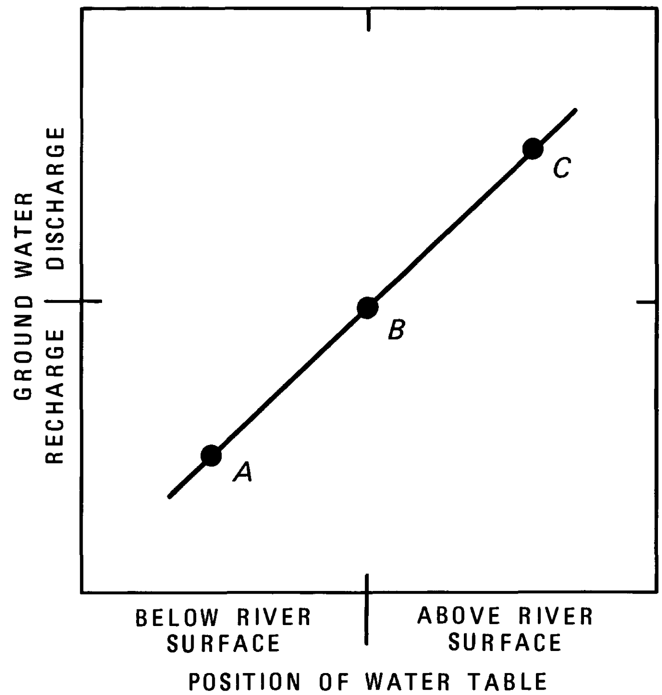
The discharge of ground water through evapotranspiration depends in part on the type and areal extent of vegetation, and also on the depth to water. Appreciable evapotranspiration occurs when the water table is within about 10 feet of the land surface, and the rate decreases as the depth to water increases. Under this condition, some plant species obtain their water supply from both the ground-water body and the capillary fringe; consumption of ground water by this vegetation is an important part of ground-water discharge (Meinzer, 1923, page 82). In some instances, ground-water evapotranspiration may be stopped by lowering the ground-water level to such a depth that the process ceases (Robinson, 1958, page 22). Using a maximum consumptive-use rate of 3 acre-ft/yr for irrigated pasture (Arteaga and Durbin, 1978, page 25) and, for modeling purposes, a depth of 10 feet at which evapotranspiration ceases, a linear relation between depth to the water table and ground-water discharge was developed (figure 9) and incorporated into the model to simulate evapotranspiration. The amount of ground water consumed in Eagle Valley through evapotranspiration was previously estimated to be about 3,000 acre-ft/yr (Arteaga and Durbin, 1978, page 32).

Boundary Conditions

The equations of ground-water flow (equations 1 and 2) have an infinite number of solutions. The question naturally arises as to how one may choose the proper solution for a particular problem. Differences in solutions are related, in part, to (1) differences in boundaries defining the ground-water basin and (2) the conditions that are imposed at those boundaries. A no-flow boundary condition is used in the model of the Eagle Valley ground-water basin.

No-flow boundaries are used where the model boundary is coincident with a contact between consolidated rock and valley-fill sedimentary deposits. It is assumed that ground water cannot flow perpendicular to such a boundary. In the actual situation, however, some water may enter the ground-water basin from fractures in the consolidated rock or from tongues of alluvium that extend far up into canyons. But this source of ground-water recharge, previously described as natural recharge, was treated as a point source in the model.





EXPLANATION

A Ground–water recharge from river when river stage is higher than water table

B No net exchange when river stage and water table are at same level

C Ground–water discharge to river when river stage is lower than water table

FIGURE 8.—Schematic diagrams showing interaction between Carson River and Eagle Valley ground–water reservoir.

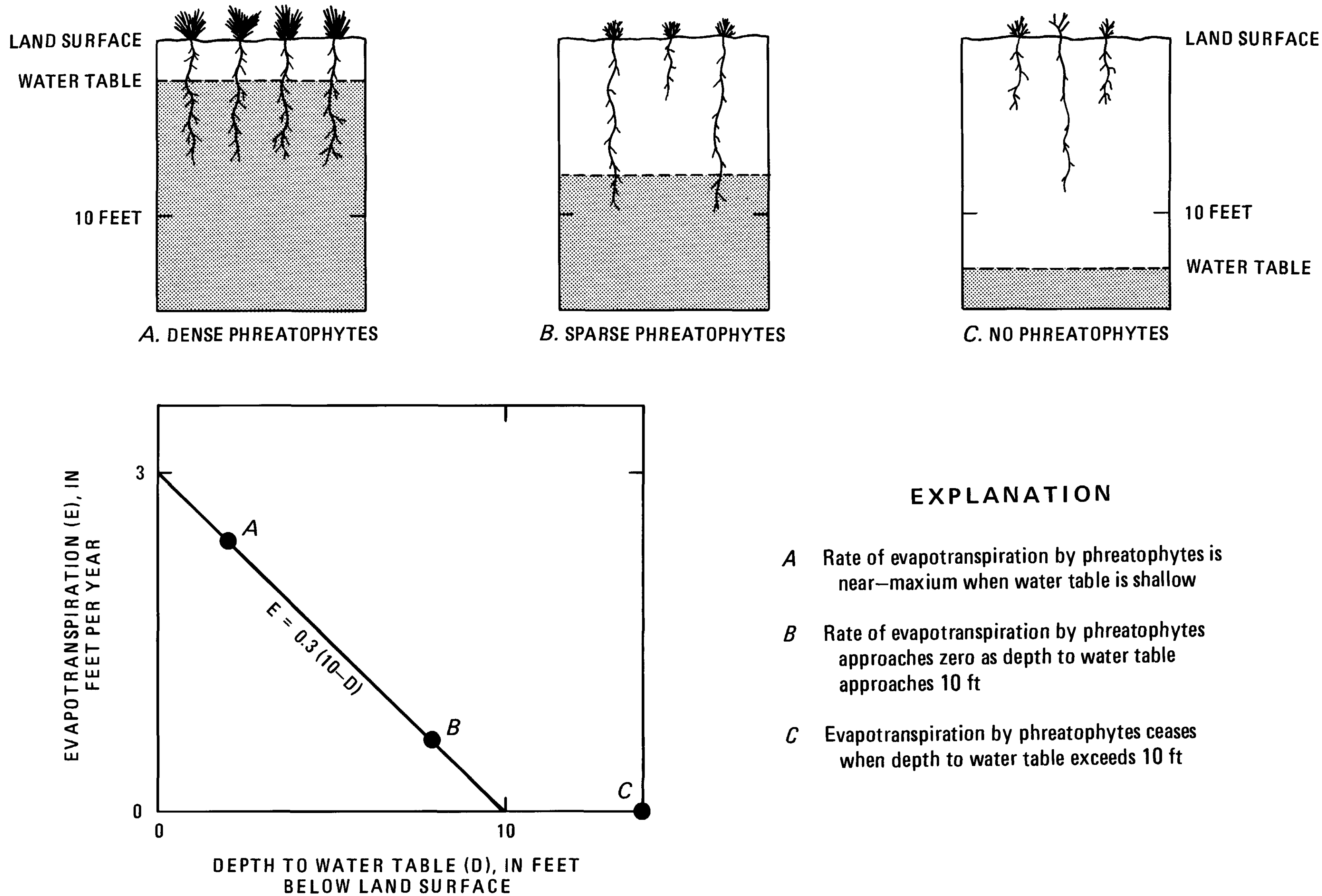


FIGURE 9.—Schematic diagrams showing conceptual interpretation of evapotranspiration rate for modeling purposes.

Transmissivity

An important aquifer parameter for the steady-state model is transmissivity--the capacity of an aquifer to transmit water horizontally through its entire thickness. Transmissivity is formally defined as the rate at which water of the prevailing kinematic viscosity would be transmitted through a unit width of the aquifer under a unit hydraulic gradient (Lohman, 1972, page 6). Transmissivity varies geographically over the ground-water basin due to variations in the permeability and thickness of the aquifer. All other things being equal, the thicker an aquifer or the greater its permeability, the greater is its transmissivity.

The Eagle Valley ground-water basin has been conceptualized as consisting of alternating layers of coarse-grained and fine-grained alluvial deposits. Furthermore, previous discussion indicated that water moving horizontally in the ground-water basin was conducted for the most part through the layers of coarse-grained deposits (very little water moves horizontally through the fine-grained layers).

The concepts discussed in the preceding paragraphs were used to develop estimates of the geographic distribution of transmissivity. However, some theoretical background is needed: First, the transmissivity of an aquifer can be expressed as the product of its average permeability (which in turn is expressed quantitatively as its hydraulic conductivity) and its thickness. Mathematically:

$$T = Kb, \qquad (7)$$

where T = transmissivity,

K = hydraulic conductivity, and

b = thickness.

Second, the transmissivity of a column intersecting a group of aquifers is equal to the sum of the transmissivities of the individual aquifers.

With that background, the transmissivity of a column of alternating layers of coarse-grained and fine-grained deposits can be expressed as:

$$T = K_c b(1-P) + K_f bP, \qquad (8)$$

where T = transmissivity,

b = the cumulative thickness of the layers under consideration,

K_c = the hydraulic conductivity of course-grained deposits,

K_f = the hydraulic conductivity of fine-grained deposits, and

P = the part of the cumulative thickness comprised of fine-grained layers, expressed as a decimal percentage.

However, because the fine-grained deposits conduct very little water, the term $K_f bP$ will be relatively small, and the transmissivity can be closely approximated by the relation:

$$T = K_c b(1-P) \quad . \qquad (9)$$

Therefore, the geographic distribution of transmissivity for the Eagle Valley ground-water basin can be estimated by evaluating the local thickness of the ground-water basin, the hydraulic conductivity of the coarse-grained deposits, and the proportion of the local basin thickness occupied by fine-grained deposits. Development of values for these quantities is discussed below.

Alluvial Thickness

In most of Eagle Valley, wells do not completely penetrate the consolidated rocks, so the total saturated thickness (b) of the aquifer is not known. Therefore, gravity and seismic surveys were made as an aid in estimating the saturated thickness.

Gravity Survey.--The gravitational attraction of the Earth at any specific point is affected in part by the density of the underlying materials. Unconsolidated materials have lower densities, hence lower gravitational attraction than the higher-density consolidated rocks that underlie, and are adjacent to, the unconsolidated materials. In addition, materials having the same density have higher gravitational attraction if located at the Earth's surface than if buried at depth. Differences in gravitational attraction are proportional to the thickness of alluvial materials (or depth to bedrock) in the valley and the density contrast between alluvium and bedrock.

One hundred thirty-eight gravity measurements were made with a gravimeter. Additional measurements were obtained from a gravity data map compiled by J. W. Erwin (Nevada Bureau of Mines and Geology, written commun., 1977) that includes Eagle Valley. Values of observed gravity were referenced to the datum of the Carson City gravity base station U.S. Coast and Geodetic Survey G323, adjacent to the Carson City Administrative Building at Carson and Ann Streets. These measurements were reduced to complete Bouguer anomalies (Dobrin, 1976, page 370) using methods described by Dobrin (1976, page 404) and Grant and West (1965, page 235). Complete Bouguer anomalies obtained from 29 stations on or near bedrock were used to define the regional gradient of the gravity field. A final adjustment to these anomalies was made by subtracting the regional gradient from the complete Bouguer anomalies to obtain residual anomalies which reflect the depth to bedrock.

The residual anomalies were used to construct the gravity residual map shown in figure 10. Three pronounced gravity lows are evidenced by the -3 mgal (milligal) line west of Lone Mountain, the -12 mgal line intersecting Fifth Street, and a -6 mgal line in the vicinity of the Carson River. The -12 mgal line indicates that the alluvium probably is thickest in this area.

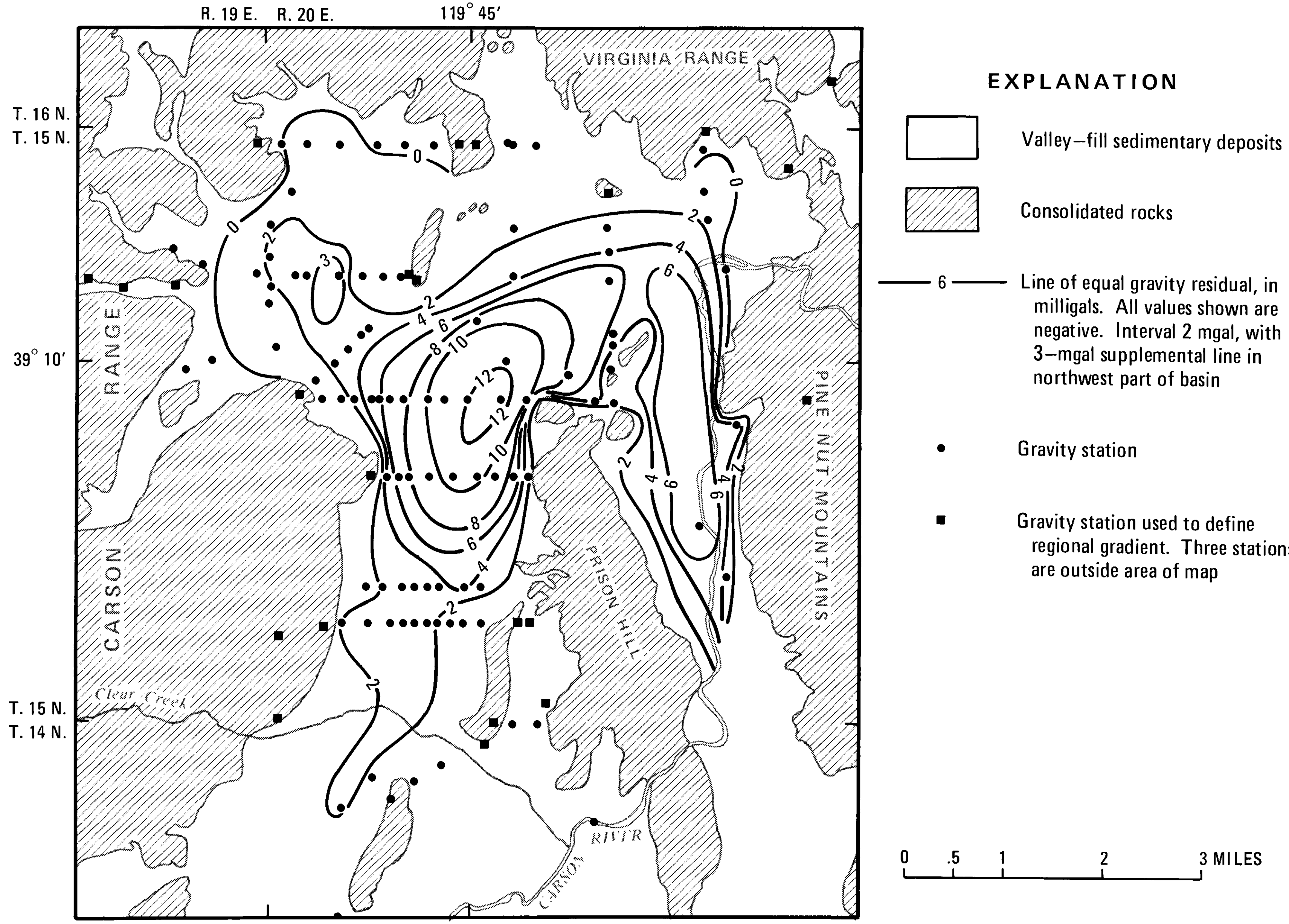


FIGURE 10.—Gravity residuals.

Seismic Survey.--A seismic survey was made within the valley to augment the interpretation of the gravity survey. This survey employed seismic refraction and reflection techniques to estimate the depth to the basement complex. The refraction method consists of measuring surface-to-surface velocities of shots (detonations of dynamite at a depth of 4 feet) with a seismometer which measures the arrival time of seismic pulses induced by the shot. By moving the seismometer farther away with each succeeding shot, the travel time of seismic waves can be determined as a function of distance, and the average velocity of the wave through the alluvium can be computed. Several sets of measurements were made at two locations in the valley (figure 11) at various distances within a mile of the shot hole. The velocities of the waves through the alluvium determined by this method at both locations were about 6,250 feet per second.

Seismic reflection is a technique whereby the timed arrival of seismic waves from an explosive source, coupled with the known velocity of the wave through the alluvium (obtained from refraction measurements), yields the depth to consolidated rocks. The methodology is explained in greater detail by Grant and West (1965, pages 127-163). Fifty-two seismic reflection shots were made throughout the valley during the summer of 1978 (table 1).

Data obtained from this survey were combined with the results of the gravity survey, and the depth to bedrock throughout most of the valley was determined (figure 11). The results indicate the presence of three major depressions in the study area. These depressions vary from approximately 800 feet to 2,000 feet in depth, with the deepest zone near the Nevada Maximum Security Prison. This information was then combined with water-level data from wells to determine the saturated thickness of the alluvium. Water levels in the valley range generally from 25 to 50 feet in depth; thus, the alluvial thickness shown in figure 11 is indicative of the saturated thickness throughout most of the valley fill.

Hydraulic Conductivity

Hydraulic conductivity (K) is a measure of the capacity of porous material to transmit water under the influence of a hydraulic gradient. A common expression for hydraulic conductivity in terms of this property is:

$$K = - \frac{q}{dh/dl} , \qquad (10)$$

where q = the volume of water discharged per unit time, per unit area, and

dh/dl = the hydraulic gradient in the direction of flow (Lohman, 1972, page 6).

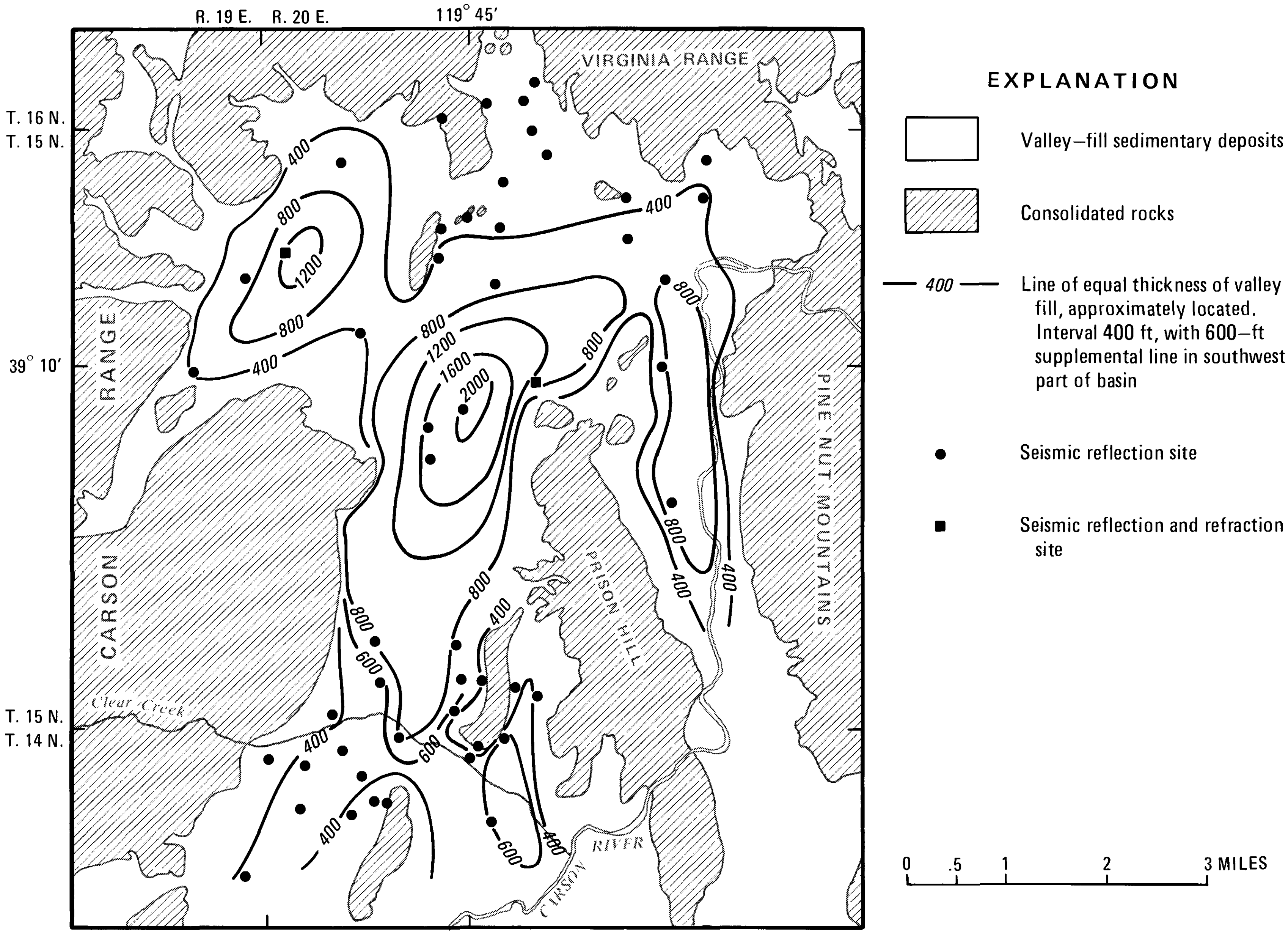


FIGURE 11.—Approximate thickness of valley—fill sedimentary deposits and location of seismic stations.

TABLE 1.--*Results of seismic survey*

Location	Depth to bedrock (feet)[1]	Location	Depth to bedrock (feet)[1]
N14 E19 12DAB	530	N15 E20 8ADB	650
N14 E20 4BAAD	880	N15 E20 9CAB	750
N14 E20 4BBBD	280	N15 E20 10ABA	560
N14 E20 4BCAB	520	N15 E20 11BCC	800
N14 E20 4CDCC	640	N15 E20 14BCBC	640
N14 E20 5BAAC	800	N15 E20 16CCA	2,000
N14 E20 5CBB	540	N15 E20 16DABB[2]	1,100
N14 E20 5CCA	300*	N15 E20 17DCC	1,240
N14 E20 5CDB	300*	N15 E20 18AAA	400
N14 E20 6AADC	520	N15 E20 18CABC	240
N14 E20 6BCB	250	N15 E20 20ACAA	1,760
N14 E20 6BDDA	500	N15 E20 23CBD	960
N14 E20 6CDA	500	N15 E20 31DCD	300*
N14 E20 6DDD	300	N15 E20 32AAD	620
N15 E19 12DABB	700	N15 E20 32BBDB	800
N15 E19 13BDDB	500	N15 E20 32CBA	550
N15 E20 2BDA	300	N15 E20 32DDD	580*
N15 E20 2CAD	380	N15 E20 33CBA	600*
N15 E20 3DBD	270	N15 E20 33CBB	650
N15 E20 4AADC	300	N15 E20 33DAB	320
N15 E20 4BBAD	450	N15 E20 33DBB	320
N15 E20 4BDD	100	N16 E20 32DDCA	120
N15 E20 4CDD	250	N16 E20 33CAC	500
N15 E20 4CCCB	75	N16 E20 33DAB	250
N15 E20 5DDC	250	N16 E20 33DBD	150
N15 E20 6ADB	600	N16 E20 33DDC	200
N15 E20 7BBD[2]	1,200		

[1] Accuracy of all depths considered fair, except those indicated by asterisk, which are of poor accuracy.

[2] Refraction and reflection site. All others are reflection sites only.

The hydraulic conductivity of the Eagle Valley alluvial aquifer was estimated from the results of 12 aquifer tests and an additional 143 well drillers' reports. Each aquifer test consisted of pumping a well at a known rate of discharge, measuring the drawdown of water level in the well or in a nearby observation well, and transforming the field data into calculated values of hydraulic conductivity (Lohman, 1972, page 11). The aquifer test yields a value representative mostly of the average hydraulic conductivity over the interval of the aquifer in which the pumped well is perforated. Hydraulic conductivity values obtained from the 12 aquifer tests ranged from 1.5 to 49 feet per day. Estimates of hydraulic conductivity from well drillers' reports were derived by (1) multiplying the well's specific capacity (in gallons per minute per foot of drawdown) by 270, which, assuming the well is fully efficient, yields an estimate of the transmissivity (in feet squared per day), in accordance with a method similar to that described by Thomasson and others (1960, page 222), and (2) dividing T by the estimated total thickness of saturated coarse-grained sedimentary materials at that site. Figure 12 shows the magnitude and distribution of K values based both on aquifer tests and well data. The values range from 0.3 to 50 ft/d. The smallest values are from two sites in the western part of the valley, where the best water-yielding zones are known to occur. This contradictory result suggests that hydraulic conductivities calculated from well logs or from specific capacities can be unreliable.

Final conductivities have been calculated by using model-generated final transmissivities (see below) and equation 9. The values range from 0.02 to 20 ft/d (plate 5). The smallest values are east of the Carson River, in the southeast part of the model area. The larger values generally correspond to areas where the transmissivity values are the largest and the proportion of fine-grained deposits is lowest.

Proportion of Fine-Grained Deposits

The proportion of fine-grained deposits in a vertical column through the ground-water basin (P) was estimated directly from analysis of 261 geologic logs. These logs are from driller's reports for wells ranging in depth from 17 to 830 feet. Only 18 of the wells are deeper than 400 feet, however. The resulting paucity of representative data for deeper parts of the basin limits the usefulness of this approach.

The quantity P, expressed as a decimal percentage of the overall local thickness for the ground-water basin (b), is shown in figure 12. Extensive fine-grained deposits that cause confined (artesian) ground water in the vicinity of East Fifth Street (plate 1) are indicated in figure 12 by the 40-percent line in that area.

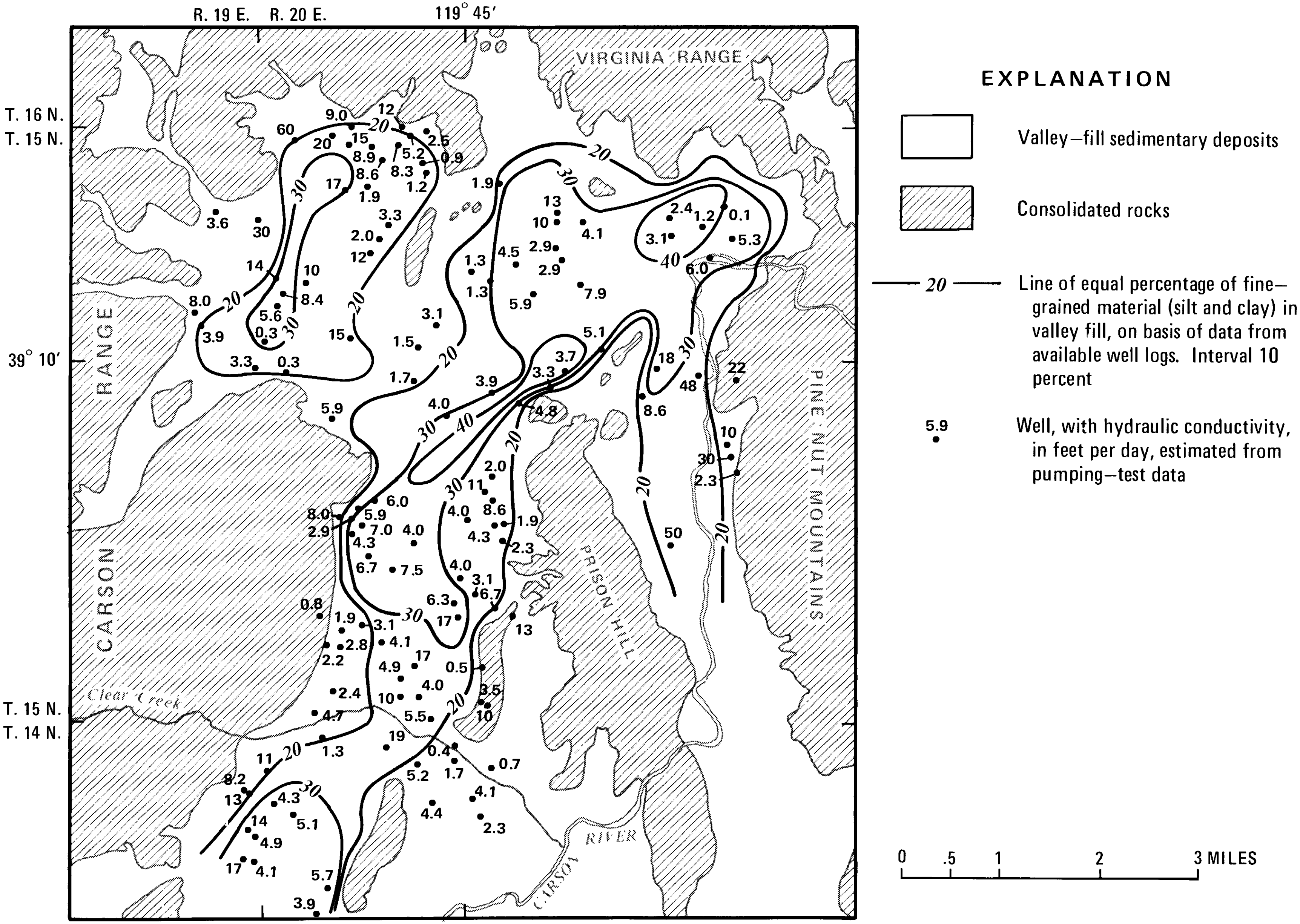


FIGURE 12.—Areal distribution of fine—grained material and hydraulic conductivity in valley—fill sedimentary deposits.

Distribution of Transmissivity

Given the limitation of the existing data, values of b, K_c, and P were used with equation 9 to derive initial values of T for input to the ground-water model. Subsequent calibration of the model produced final estimates of T, listed in table 4. These values range from 5 to 12,100 ft^2/d, with lower values being primarily along the edges of the modeled area. High T values are located mostly in the areas where K and b are large and P is small.

Vertical Leakage

Initial estimates of upward leakage of water through clay beds were made by assigning ratios of horizontal to vertical hydraulic conductivity for three zones (figure 13). These ratios, ranging from 20 to 200, depict unconfined aquifers (20), confined aquifers (200), and a transition from unconfined to confined aquifers. These are crude estimates, both quantitatively and areally. The vertical hydraulic conductivity (K_v) at each element was then determined from the product of the horizontal conductivity of coarse-grained materials (K_c) and the inverse of the horizontal to vertical ratios assigned to each of the 422 elements. The potential for vertical leakage through a confining bed can be expressed quantitatively as the leakance coefficient (L), which is the ratio of vertical hydraulic conductivity to the thickness of the confining bed (K_v/b). Leakage of water through the confining clay beds was computed by the mathemat-ical model from inputs of vertical hydraulic conductivity (permeability), initial hydraulic heads of both layers, and a value of b equal to one half the total thickness of saturated materials (a crude approximation of the confining layers' aggregate thickness).

Leakance coefficients resulting from calibration of the ground-water model are listed in table 4 and shown in plate 6. The final values range from 0.0002 to 0.05 (ft/d)/ft.

Calibration Results

In applying the model to the study area, the following approximations were used:

1. The Eagle Valley ground-water basin consists of unconfined and confined aquifers that are to some extent hydraulically connected. As a practical matter, the basin model was conceptualized as a two-layer aquifer system. The upper layer (layer 1) represents the aquifer from the land surface to a depth 50 feet below the top of the saturated material, and the lower layer (layer 2) represents the remaining saturated section to the bottom of the ground-water basin. The mechanics of the model program required a separation between model layers, even in the unconfined areas where none is present. By assuming appreciable vertical leakage (a large leakance coefficient) in the unconfined area, however, the head differential between layers is minimized, and the water table can be represented as one surface.

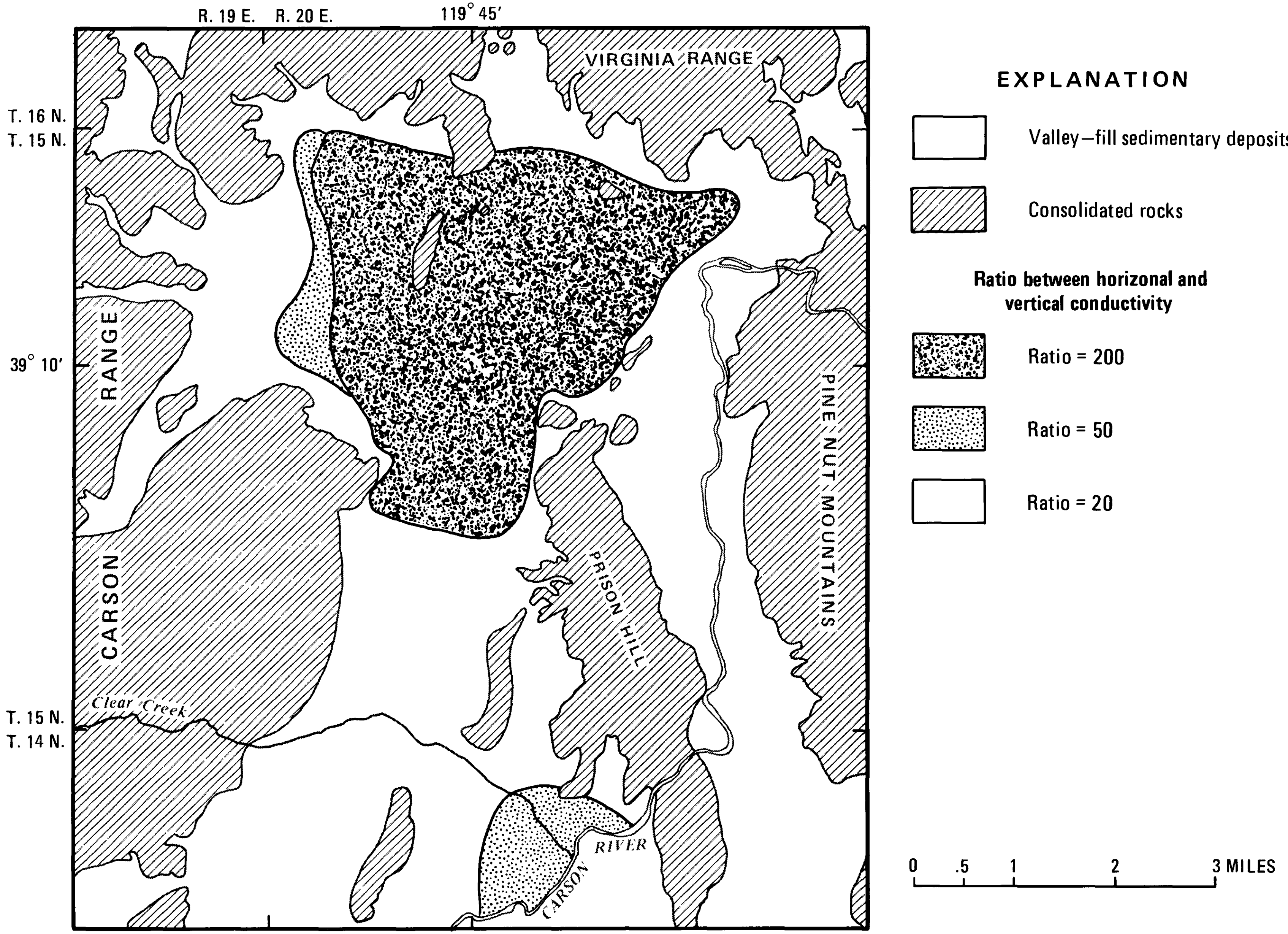


FIGURE 13.—Areal distribution of estimated ratio between horizontal conductivity and vertical conductivity in valley—fill sedimentary deposits.

2. Transmissivity values applied to the model do not decrease as dewatering of the saturated thickness of the basin takes place. The model thus requires that the change in saturated thickness of the actual basin be small over the period of interest, and that values of hydraulic conductivity along a vertical section be constant with depth. Except for the western part of the valley, where water-level declines of as much as 50 feet have occurred, the change in saturated thickness over the period of interest (1964-78) has indeed been small.

3. Rates of recharge and discharge applied to or simulated by the model are constant over a designated period. Quantities of recharge to the actual basin, however, are highly variable in space and time. The model does not accommodate these variations, and applies only an average rate over a particular simulation period.

4. Pumpage from the basin was simulated on an annual basis instead of using the more variable monthly data.

Model calibration was accomplished in two phases. The first phase was the simulation and calibration of steady-state (or time-invariant) conditions. This phase was used to test the conceptual model and to evaluate the hydrodynamics of the system. The steady-state model was calibrated to the water levels for 1964; it consisted of determining, by trial and error, reasonable values of transmissivities and leakance coefficients. The second phase of calibration analyzed the response of the simulated aquifer to historical changes in pumping stress (a transient state) for the period 1964-78, with the objective of reproducing water-level changes observed during that time period. Calibration was done by changing transmissivity and leakance estimates obtained from the steady-state calibration.

Using the 1964 configuration of water-level altitude (figure 3) as the basis of comparison with model-computed altitudes, the transmissivities of elements surrounding nodes that exhibited poor comparisons were changed to improve the results. The multitude of possible ways of modifying the transmissivities was apparent throughout the calibration runs. In general, however, the greater the distance between (1) an element whose transmissivity was changed and (2) nearby nodes, the less pronounced the effect at those nodes became. The leakance coefficients for some of the elements were also adjusted during the calibration.

Seventy-three steady-state calibration runs were made. During the early phase of calibration, transmissivity values in both the upper and lower layers were adjusted. During later calibration runs, leakance coefficients and lower-layer transmissivities were adjusted. Changes made to element transmissivities are reflected by changes in previously computed water levels, which in turn impose a cause-and-effect influence on the mass balance of the hydrologic system. This mass balance is computed by the model so that the inflow (recharge) equals the outflow (pumpage, evapotranspiration, and subsurface flow to the Carson River). Because the recharge (4,900 acre-ft/yr) and pumpage (400 acre-ft/yr) were specified as model inputs, the distribution and magnitude of outflow became an additional criterion for determining an acceptable steady-state model. The evapotranspiration computed by the model, 2,900 acre-ft/yr, agrees with the estimate of 3,000 acre-ft/yr reported by Arteaga and Durbin (1978, page 32). The model-derived natural discharge to the Carson River is 900 acre-ft/yr near Clear Creek and 700 acre-ft/yr near New Empire. These are lower than the 1,200 and 1,500 acre-ft/yr estimated by Arteaga and Durbin (1978, page 32) for those respective areas. Development and calibration of the model involved a more quantitative definition of the ground-water basin, and the modeling results thus may be better than the estimates of outflow made in the previous report.

The map of simulated water-level contours for 1964 (figure 14) compares reasonably well with the reconstructed water-level contour map for 1964 (figure 3), except in the partly confined area where the simulated potentiometric surface of the lower layer is considerably higher than that of the upper layer. Lower-layer water levels at five nodes, Nos. 152, 164, 165, 178, and 179, ranged from 15 to 19 feet higher than those of the companion upper-layer nodes. Six lower-layer nodes, Nos. 66, 73, 141, 142, 144, 154, and 167, had computed water levels ranging from 5 to 14 feet higher than the companion upper-layer values. Water levels computed at the remaining nodes for both layers differed by less than 4 feet. The computed lower-layer potentiometric surface denotes uniform ground-water movement toward the Carson River and indirectly simulates the upward movement of ground water depicted earlier in figure 5. Sufficient data to properly define the hydraulic-head distribution in this layer are not available. The difference between water levels generated by the model and those measured in 1964 ranged from 22 feet higher to 37 feet lower. However, the majority of extreme values occur primarily in the edges of the modeled area where water levels were unknown, and the deviations are not considered important.

DEVELOPMENT OF THE TRANSIENT-STATE MODEL

A transient-state model was developed to refine estimates of transmissivity (*T*) and leakance coefficients (*L*) while concurrently attempting to reproduce observed water-level changes for the period 1964-78 and water-level contours for 1978. Values of storage coefficients were not changed during the calibration period because such changes would not have had a major effect on modeling results. The period 1964-78 is the only one for which sufficient water-level data are available.

Sources and Sinks

Recharge

The amount and distribution of recharge used in the steady-state model were also used in the transient-state model. This recharge rate, 4,900 acre-ft/yr, is the source input to the model for the years 1964-76. For the years 1977-78, an additional 700 acre-ft/yr of recharge was added to simulate recharge occurring at the municipal golf course and adjacent softball fields by specifying this condition at nodes 56 and 57.

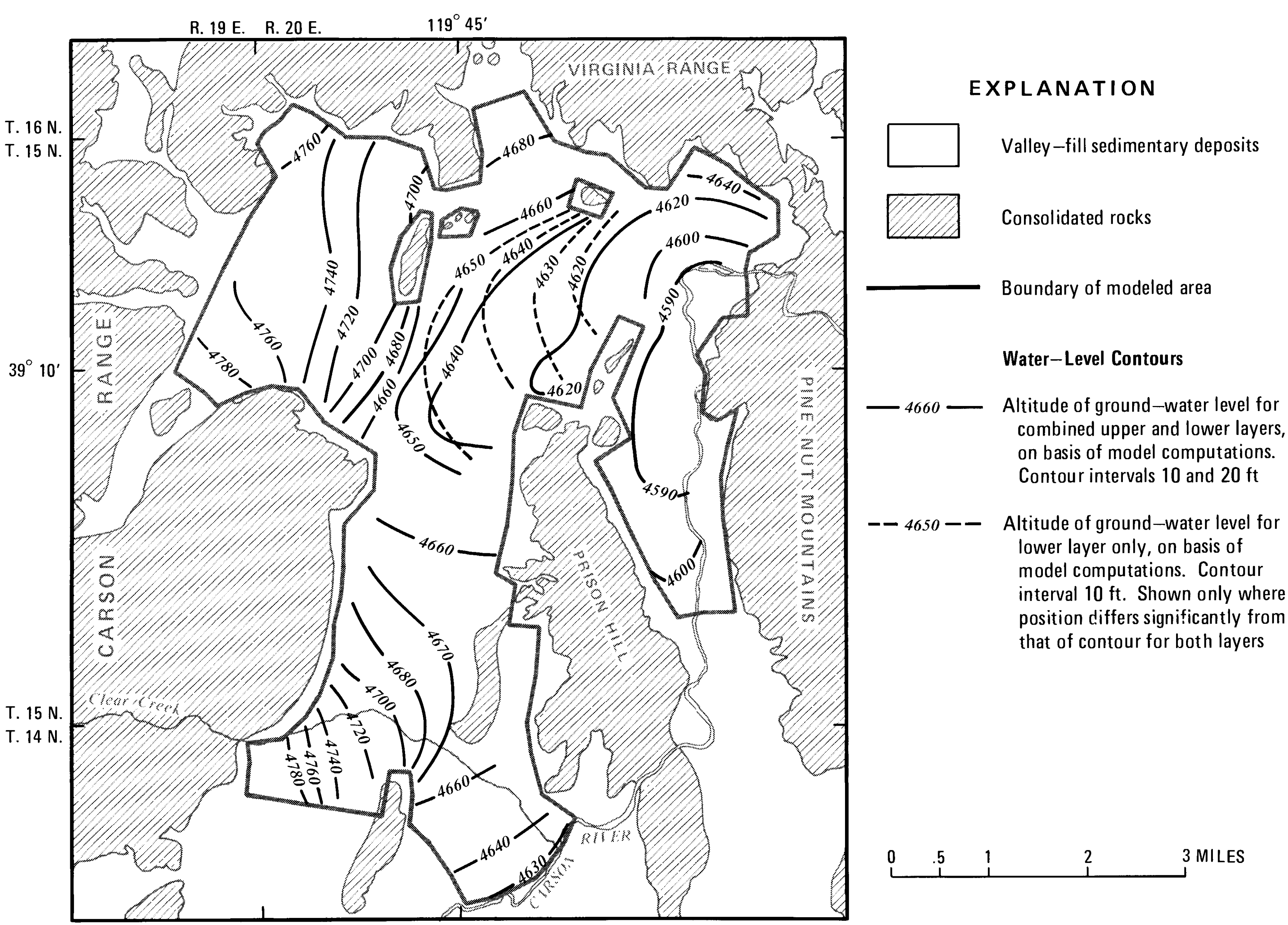


FIGURE 14.—Altitude of ground–water level based on model–generated data for spring 1964. Datum is sea level.

Ground-Water Pumpage

With the increase in population, annual ground-water pumpage for municipal use has increased nearly 16-fold, from about 300 acre-feet in 1964 to about 4,700 acre-feet in 1978. In conjunction with this increase, domestic wells in the expanded municipal service area have been phased out. The annual municipal pumpage during 1964-78, and the wells used, are indicated in table 2. Wells 2, 3, 5, 6, 7, and 10, in the western part of the valley (figure 15), account for nearly all of the pumpage.

Pumpage for the period 1964-78 was simulated as yearly rates at 14 nodes matching actual well locations (table 3). Node 108 was used to depict pumping by three wells which have provided about 20 acre-ft/yr to a trailer court since about 1973. Node 225 is used to represent pumpage at one well which has been used to irrigate approximately 5 acres with about 30 acre-ft/yr, also since about 1973. Pumpage was assigned only to the lower layer because most of the wells used are perforated below the upper layer. The net withdrawal of ground water from domestic wells was assumed to be negligible, as previously discussed.

Storage Coefficient

The storage coefficient is an additional parameter needed in the transient-state model. It is a dimensionless number defined as the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer, per unit change in head. The storage coefficient, which is equated to specific yield for an unconfined aquifer, was estimated by Worts and Malmberg (1966, page 11) to be 0.15 in the upper 100 feet of saturated material. This value is assigned to the upper layer. A confined, or artesian, storage coefficient is several orders of magnitude smaller than a value for an unconfined aquifer and represents a pressure response rather than a dewatering of the sediments. The storage coefficient for the lower layer was estimated by multiplying the thickness of the lower layer by 0.000001, a technique discussed by Lohman (1972, page 53). The resulting values range from 0.0001 to 0.0019. Pumping-test data for two wells, N15 E20 14CAAA1 and 29BDDC1, indicate the storage coefficient to be about 0.002 for those two sites.

Initial Conditions

When a transient-state (or time-variant) simulation is performed, the distribution of hydraulic head depends on the initial conditions (or initial hydraulic heads) specified. The initial conditions for this calibration stage consisted of water levels for 1964, computed from the steady-state model. As values of transmissivity and leakance were modified, the cause-and-effect relations obtained from the steady-state calibration tended to change. Thus, the steady-state model required recalibration to incorporate these new estimates of T and L and obtain the corresponding initial conditions.

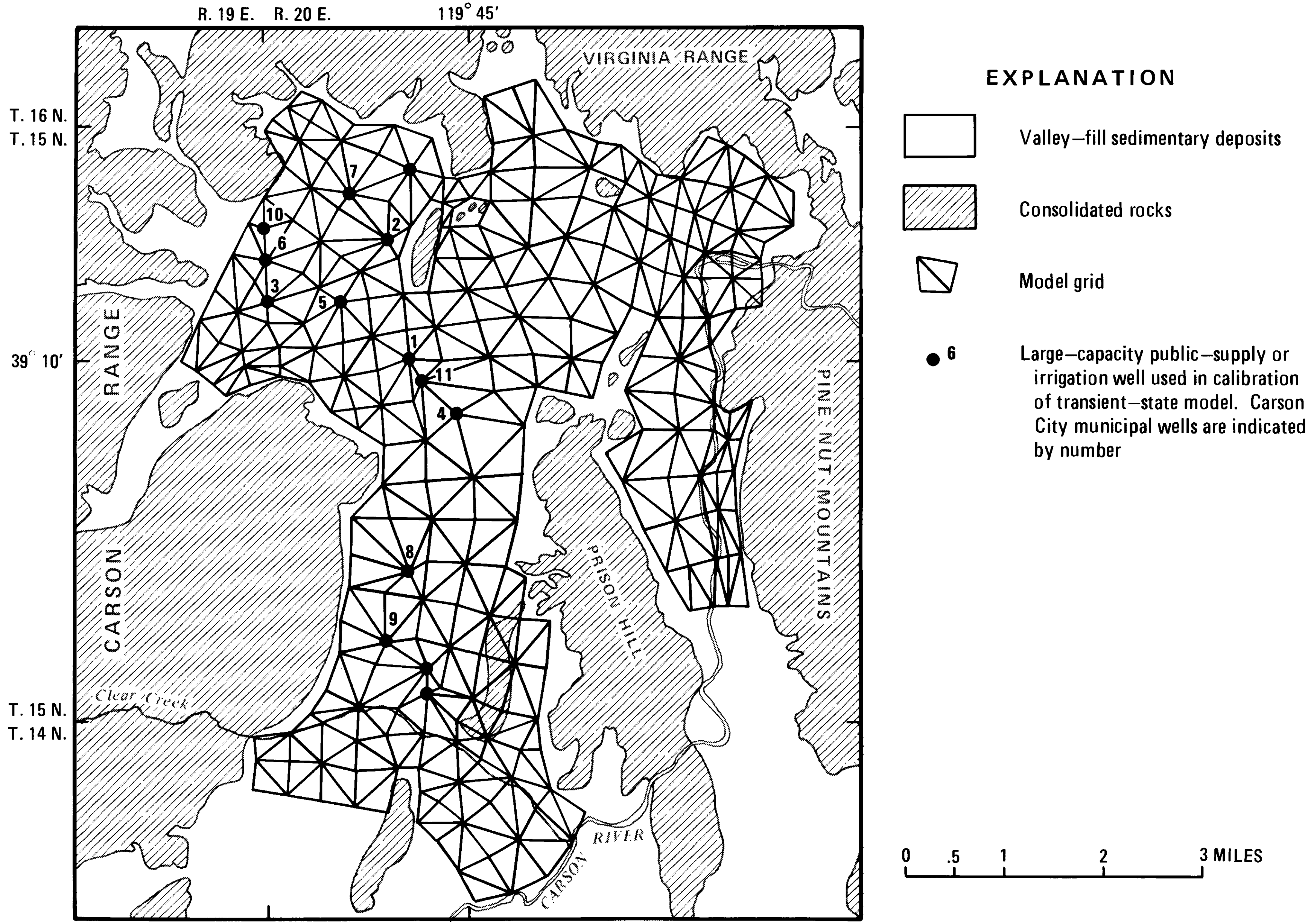


FIGURE 15.—Location of large–capacity wells used in calibration of transient–state model.

TABLE 2.--*Pumpage by municipal wells*

[Data for 1966-78 from Carson City Water Department]

Year	Pumpage (acre-feet per year)	Wells used[1]	Percentage pumped from western part of valley
1964	300	1-3	--
1965	300	1-3	--
1966	632	1-3	73
1967	899	1-3	78
1968	863	1-3	71
1969	961	1-4	70
1970	1,494	1-4	60
1971	1,385	1-5	70
1972	2,040	1-6	76
1973	2,576	1-6	73
1974	2,847	1-8	77
1975	3,028	1-10	77
1976	3,991	1-10	86
1977	3,674	1-10	85
1978	4,673	1-11	75

[1] Carson City well numbers (for example, "1-3" indicates that wells 1, 2 and 3 were used).

TABLE 3.--*Pumping nodes used in model, 1964-78*

Node number	Location	Period of use	Remarks
108	N15 E20 5BDBC1	1973-78	Public supply well
119	N15 E20 6DAAC1	1974-78	Carson City well No. 7
127	N15 E20 8BACB1	1964-78	Carson City well No. 2
147	N15 E20 7DDBB1	1971-78	Carson City well No. 5
150	N15 E19 12ADAA1	1972-78	Carson City well No. 6
155	N15 E20 17BDAD1	1964-78	Carson City well No. 1
161	N15 E19 12DADD1	1964-78	Carson City well No. 3
166	N15 E20 17DBBD1	1978	Carson City well No. 11
179	N15 E20 17DDDA1	1969-78	Carson City well No. 4
205	N15 E20 29BDDC1	1974-78	Carson City well No. 8
219	N15 E20 32BBDA1	1975-78	Carson City well No. 9
225	N15 E20 32ACCD1	1973-78	Irrigation well
232	N15 E20 32DCAB1	1964-78	Stewart well No. 4
274	N15 E19 1DDDD1	1975-78	Carson City well No. 10

Calibration Results

Thirty-three transient-state calibration runs were made while attempting to match observed and computed water-level declines for the period 1964-78 and water-level contours for 1978. The computed water-level declines for this entire period (figure 16) are not substantiated by observed declines due to the lack of observation wells in the heavily pumped western area until 1972 when measurements at well N15 E20 7BCDD1 began (observation wells measured since 1962, N15 E20 8BAAD1, 17CAAD1, and 20CCBB1, indicate no net changes in water level). The majority of observation wells established in 1975 are also outside the area of major declines. Hydrographs for three wells (figure 17) indicate differing degrees of agreement between computed and observed water levels. Good results were obtained at well N15 E20 6DAAC1 (node 119), whereas at the other two sites, N15 E20 7BCDD1 (node 149) and N15 E19 12DADD1 (node 161), the computed and observed water-level altitudes differ by as much as 36 and 20 feet, respectively, although the computed and observed net declines are about 50 feet at each well (figure 17).

Computed and observed water-level contours for 1978 are shown in figures 18 and 19. The observed contours were based on measurements made throughout the basin in 1977 and 1978. Changes in the configuration of the water-table contours between 1964 and 1978 reflect the effects of pumpage in the western part of the valley. Three cones of depression have developed because of this pumpage, and they are indicated by the closed 4,680-, 4,690-, and 4,740-foot contour lines in figure 19. The model reproduced the 4,690-foot cone of depression reasonably well (figure 18). The depression indicated by the 4,740-foot hachured contour line was not reproduced by the model. Instead, the model depicts a depression noted by the 4,695-foot contour line within the latter depression. This is due in part to (1) unavoidable errors in the steady-state model, which were inherited by the transient-state model in the form of initial conditions, or (2) improper values of transmissivity, storage coefficients, or pumpage. Because most of the pumpage is metered, it is not thought to represent more than a small error. The third depression (the 4,680-foot contour), caused primarily by pumping at well N15 E20 7DABB1, was not reproduced by the model, which indicates that the transmissivities or storage coefficients in that vicinity were too large, or the pumpage data for that well were in error. The rise in water levels in the vicinity of the golf course, denoted by the 4,650-foot contour, probably results from assigning recharge solely to nodes 56 and 57 in simulating the effects of irrigation with sewerage effluent, from using low transmissivity values for surrounding elements, or both. Water-level data needed to define both prior and current conditions in that area do not exist.

The net effect of transmissivity adjustments to both the upper and lower layers was to increase the initial transmissivity estimates in about 60 percent of the elements and reduce them in about 40 percent (figure 20). Adjusted transmissivities of the upper layer ranged from 5 to about 5,900 ft^2/d, and those of the lower layer ranged from 20 to about 12,000 ft^2/d (table 4). Two areas in the basin required unusually high values of transmissivity to properly simulate the directions of ground-waterflow indicated by water-level measurements. The first area, north of Lone Mountain, includes elements 148, 149, 150-153, 164, and 165.

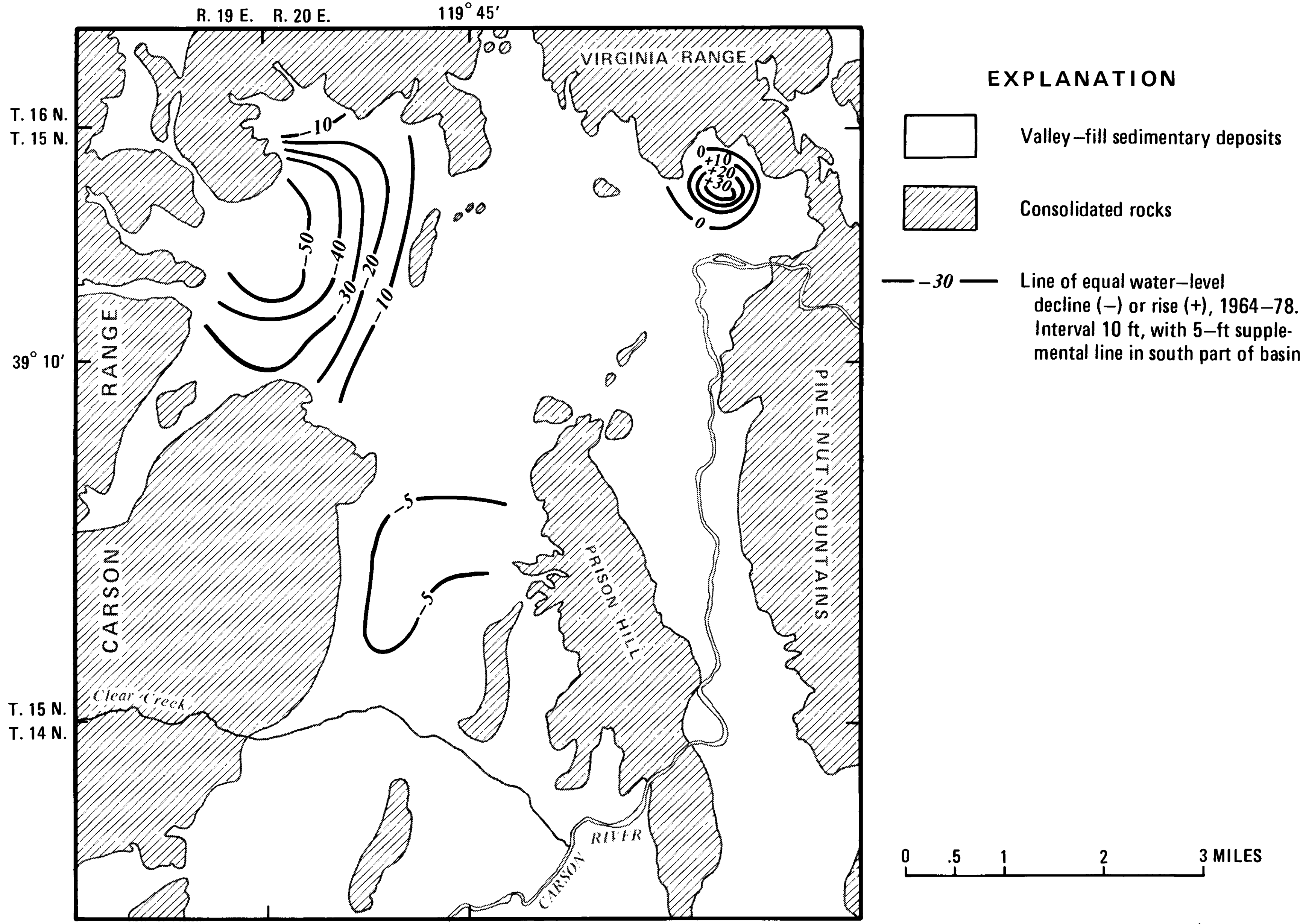


FIGURE 16.—Computed net water–level changes during the period 1964–78.

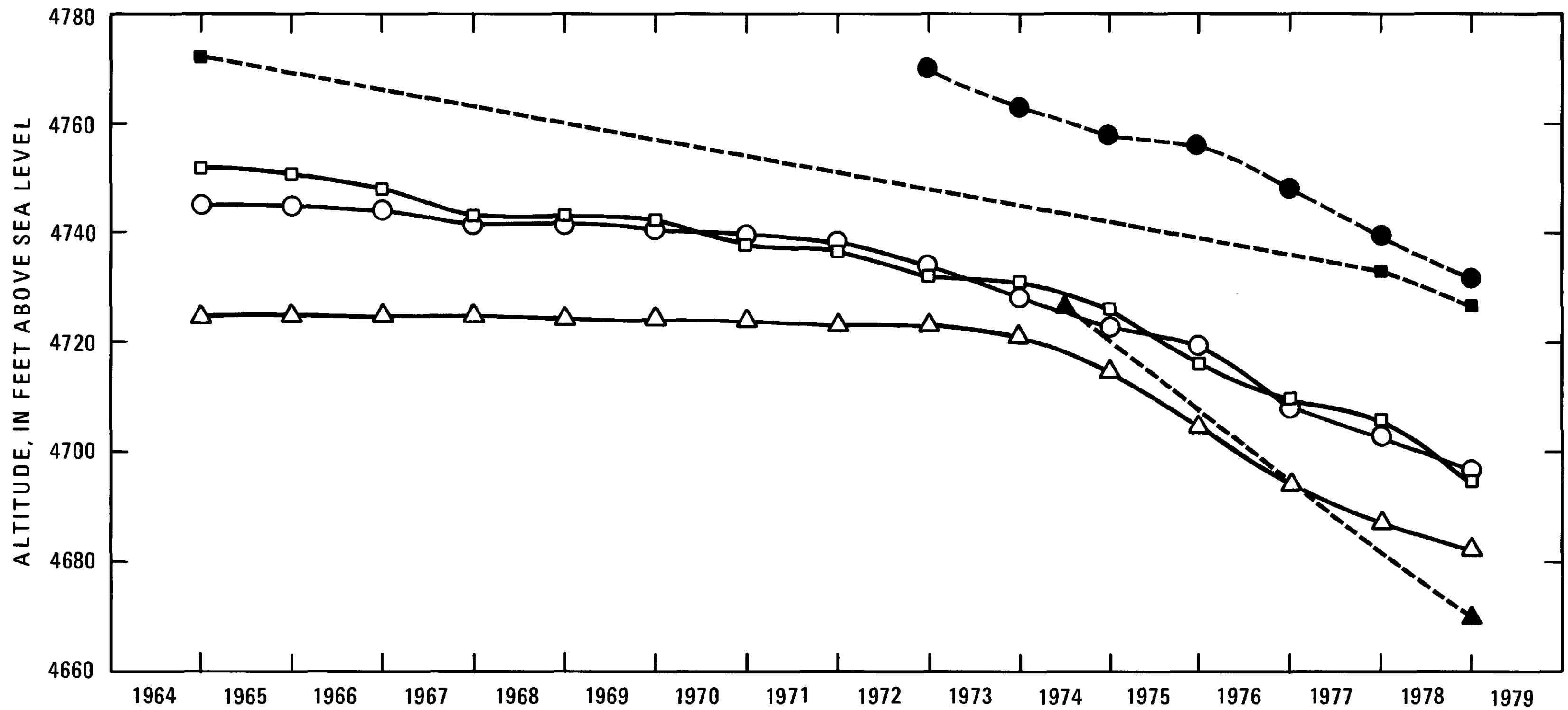


FIGURE 17.—Comparison of measured and model—computed water levels (solid and open symbols, respectively) in wells N15 E19 12DADD1 (node 161; squares), N15 E20 6DAAC1 (node 119; triangles), and N15 E20 7BCDD1 (node 149; circles).

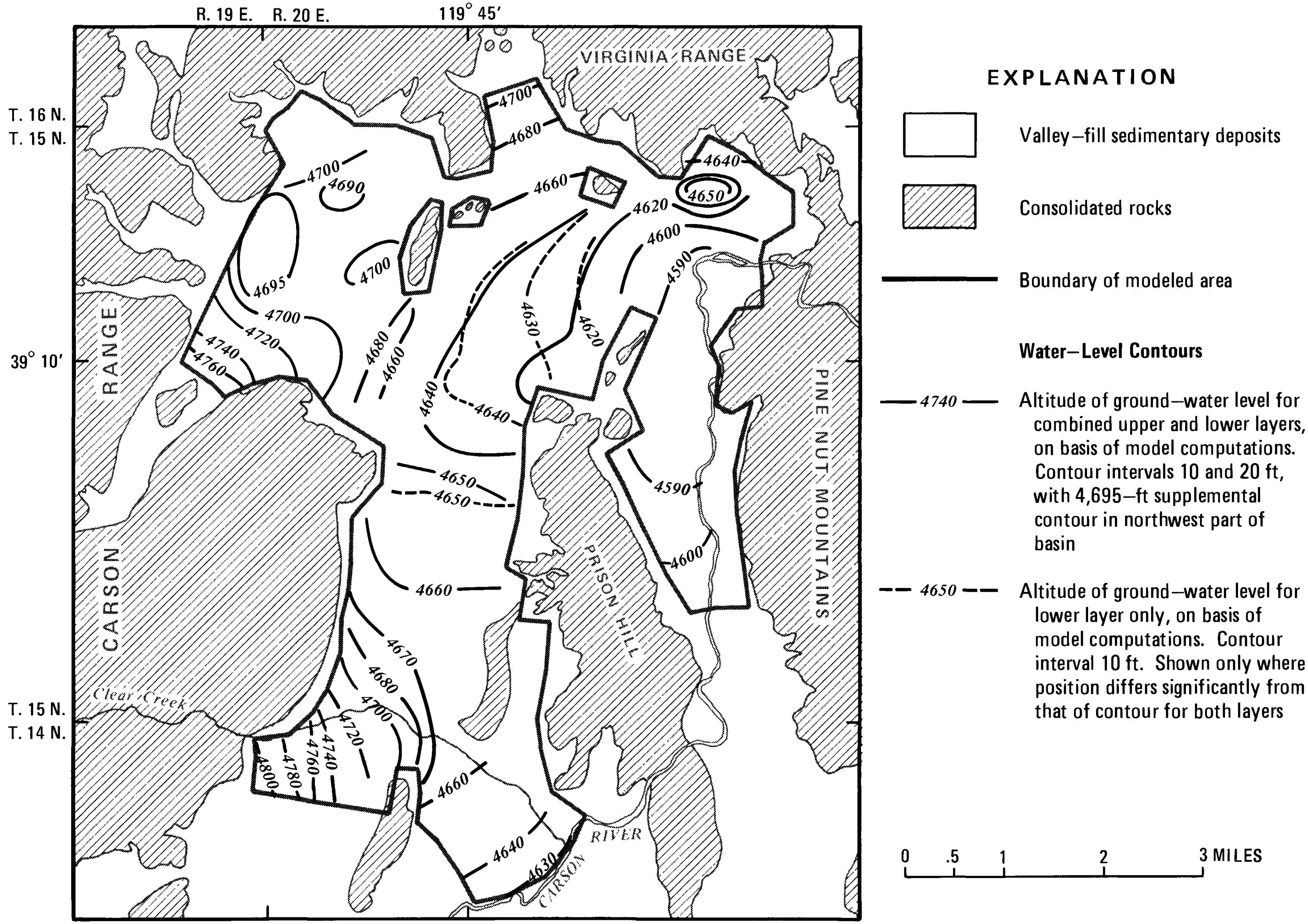


FIGURE 18.—Altitude of ground–water level, based on model–generated data for winter 1978. Datum is sea level.

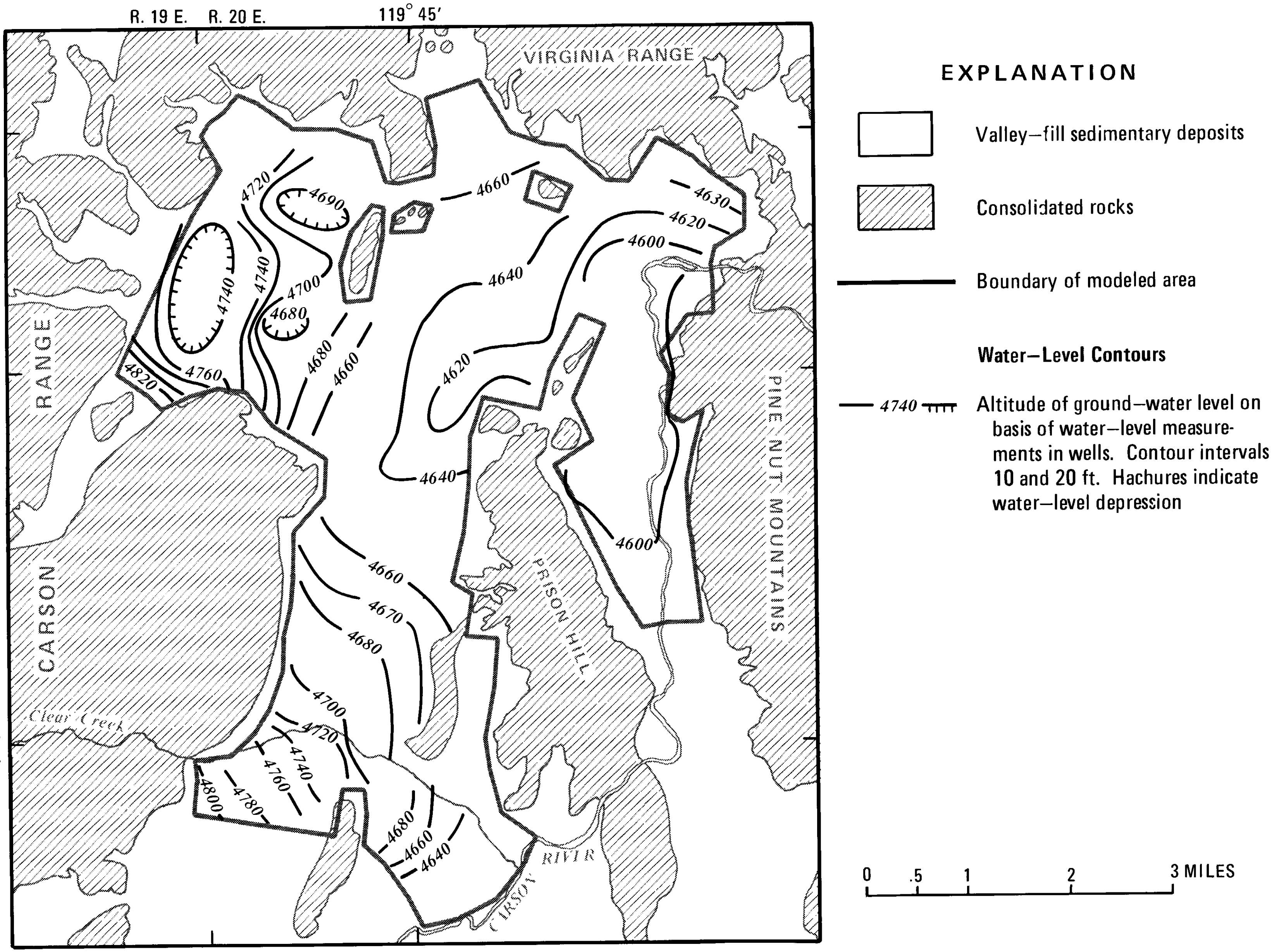


FIGURE 19.—Altitude of ground—water level, based on measurements for winter 1978. Datum is sea level.

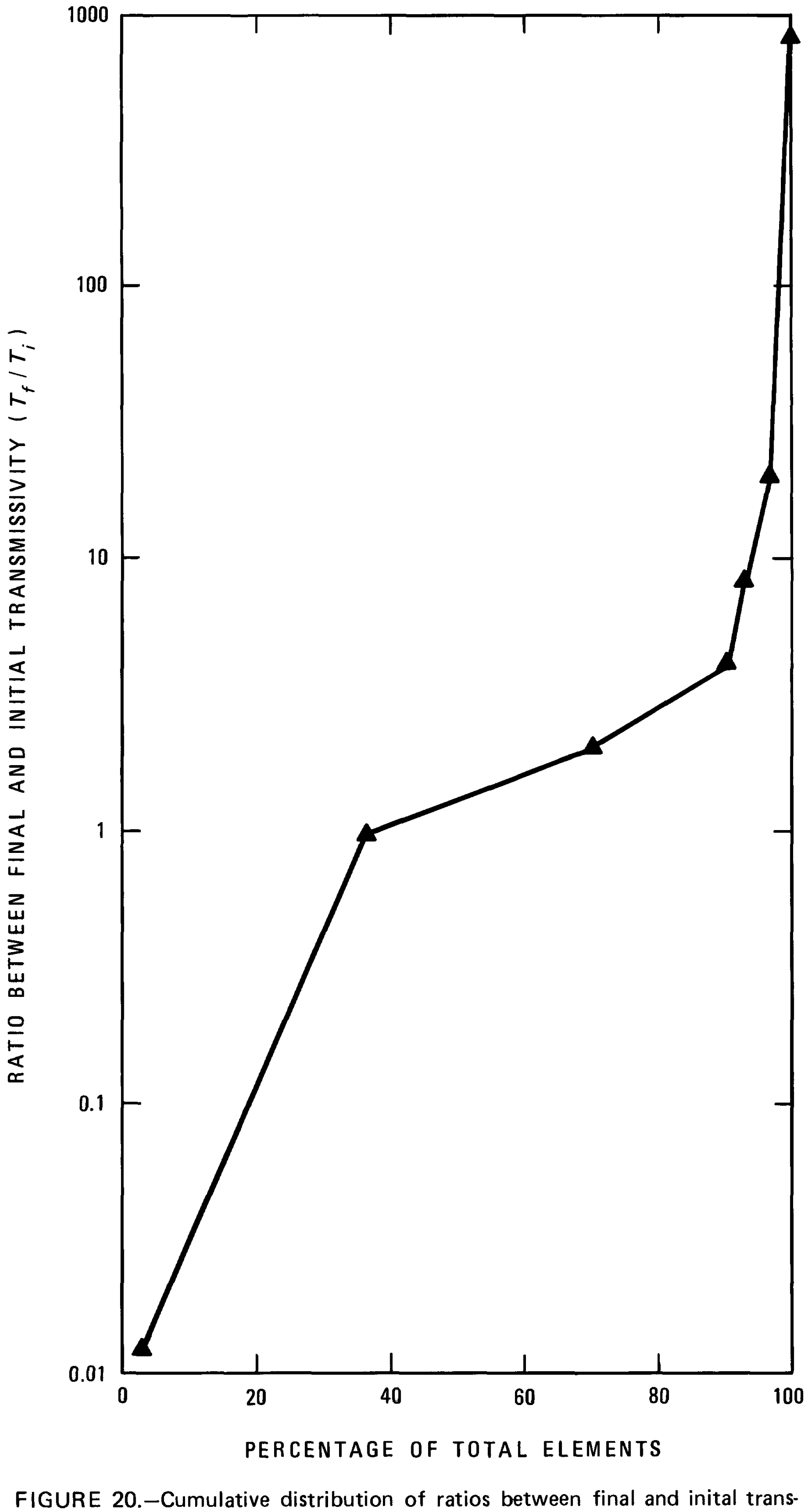


FIGURE 20.—Cumulative distribution of ratios between final and inital transmissivity estimates used in model.

Computed *T* values ranged from about 360 to 1,000 ft^2/d in the upper layer and were about 1,300 ft^2/d in the lower layer. These values are not realistic because consolidated rocks in that vicinity impede the flow of ground water. The second area, southwest of Prison Hill, involves elements 321-324, 333-336, and 346-349. Computed upper-layer *T*'s ranged from about 140 to 5,900 ft^2/d and lower-layer *T*'s ranged from about 1,000 to 7,800 ft^2/d. These exceedingly high values are used in and adjacent to an area where consolidated rocks are exposed and were needed to simulate the direction of ground-water movement shown by the 1964 water-level contours in figure 3. Faulting immediately east of the 4,670- and 4,680-foot contour lines may have caused enough fracturing to permit flow through the consolidated rocks.

Revised estimates of hydraulic conductivity (plate 5) have been made on the basis of final transmissivities listed in table 4, as discussed above.

As a result of adjustments to the original estimates of leakance coefficients, 82 percent of the values were increased and 18 percent were decreased (figure 21). Final values range from 0.0002 to 0.05 foot per day per foot (table 4, plate 6).

Reduction of Natural Discharge

The modeling results indicate that evapotranspiration has decreased during the period 1964-78. The 2,900 acre-ft/yr computed by the steady-state model for 1964 has decreased to about 2,000 acre-ft/yr as of 1978. As expected, most of the decrease was in the western part of the valley. Subsurface discharge to the Carson River, in the eastern part of the valley, has as yet been largely unaffected by the ground-water development in the western part.

USE OF THE GROUND-WATER MODEL

Predicted Impacts of Present Management Practices

The preceding sections have developed qualitative and quantitative information that describes the ground-water system in its natural state and in its current state of development. Given the limitations of the existing model, predictions of water-level change can be made under various management assumptions such as continued pumping at current rates and sites or pumping from additional sites at varying rates of withdrawal. As evidenced from the transient-state calibration, the decline of water levels may also bring about changes in the current recharge-discharge relations.

As an example of the predictive utility of the model, water-level trends for the period 1964-2000 were computed by specifying a pumping pattern and amount identical to that of 1978 for the extended period 1978-2000. The maximum predicted water-level declines would be 150 feet in the western part of the valley and 15 feet in the south-central part of the valley (figure 22). The simulated evapotranspiration would decrease to 1,200 acre-ft/yr in the year 2000. Simulated subsurface discharge to the Carson River would decrease slightly, from 1,600 to 1,500 acre-ft/yr.

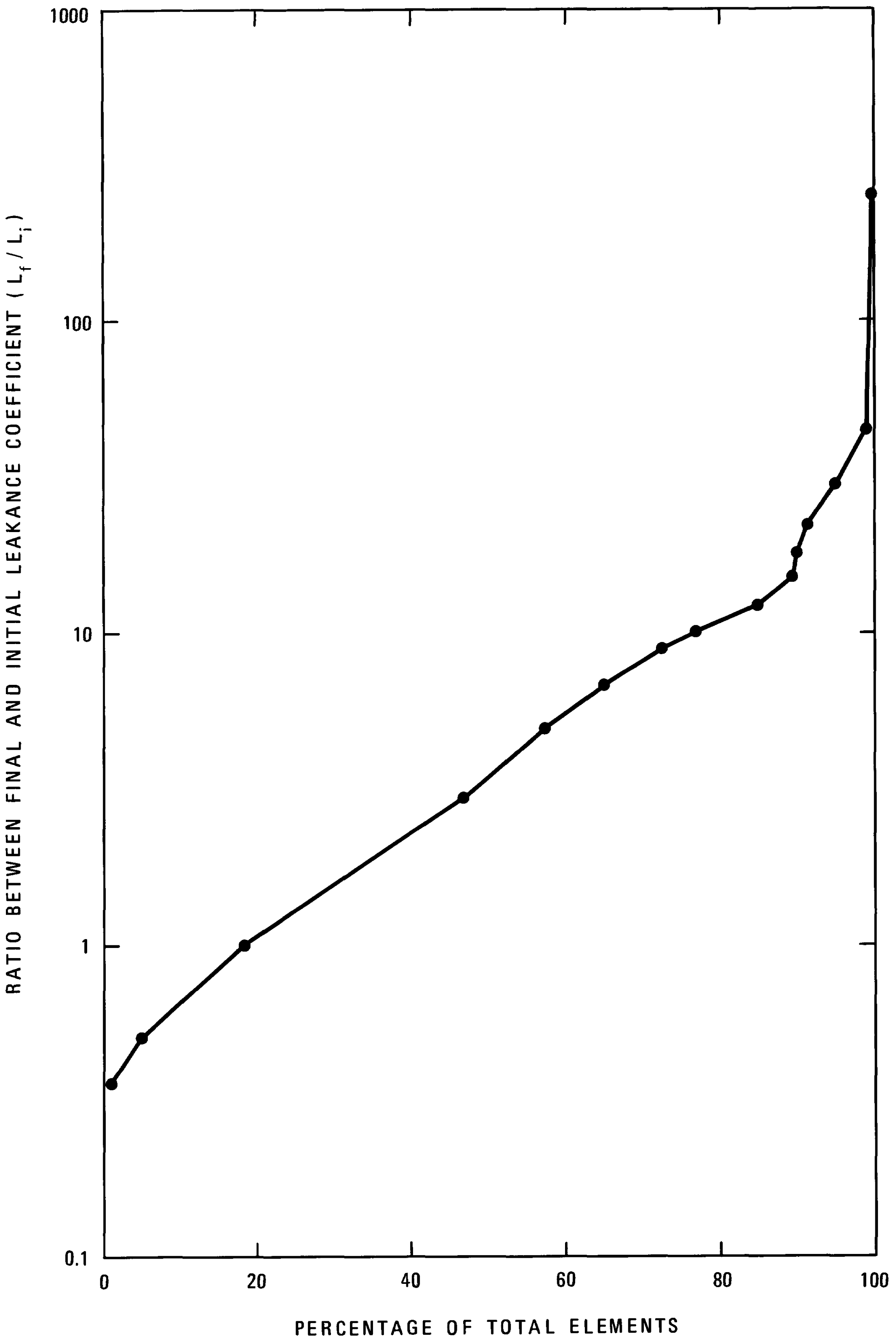


FIGURE 21.—Cumulative distribution of ratios between final and initial leakance coefficients used in model.

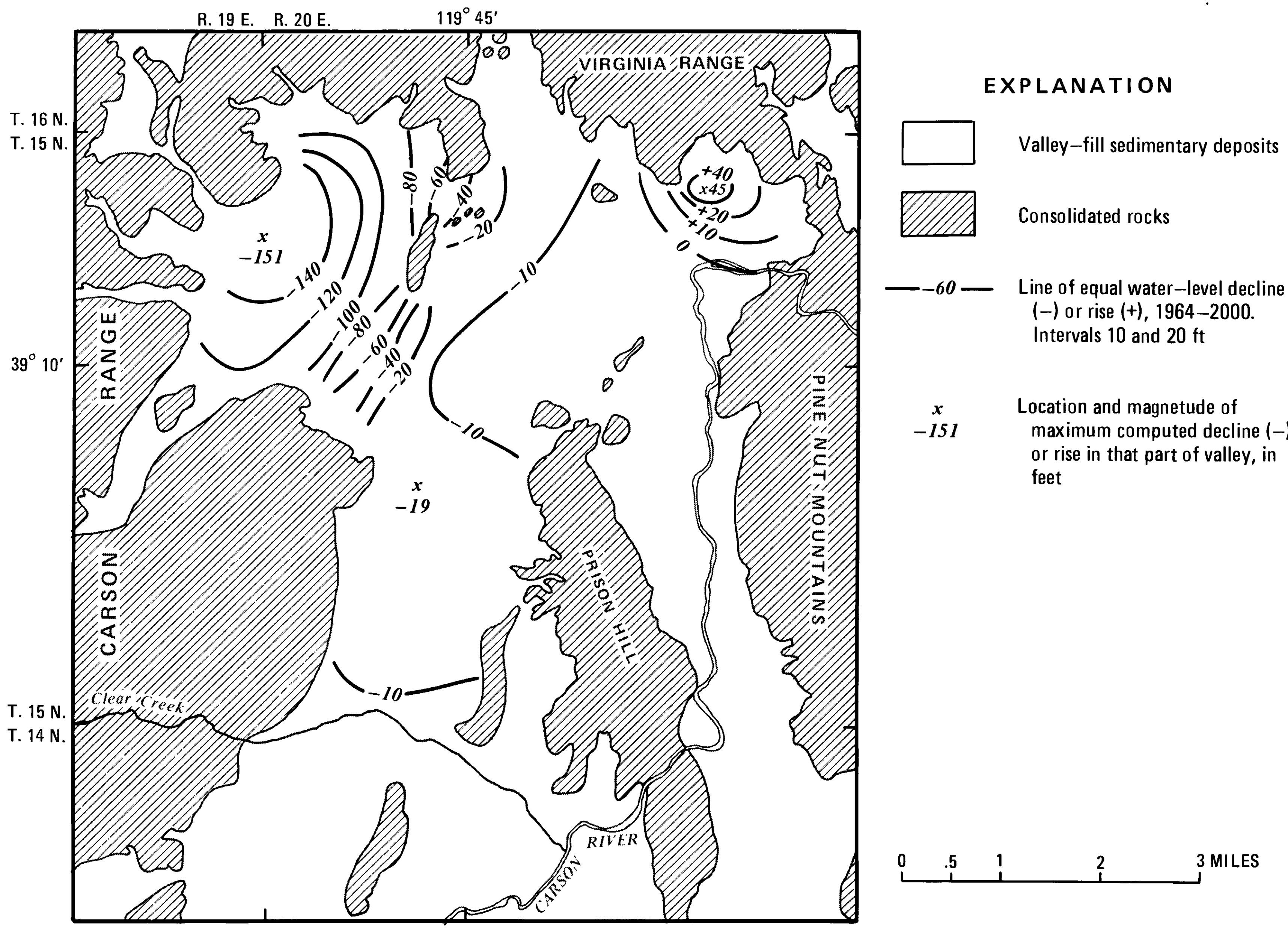


FIGURE 22.—Computed net water—level changes during the period 1964—2000, assuming maintenance of 1978 pumpage rate and distribution.

Another example of the model's predictive utility is an examination of the nature of the ground-water system resulting from an indefinite continuation of the 1978 pumpage and recharge patterns until steady-state conditions are attained. Using 1964 as the year for comparison, the maximum computed water-level decline would be 350 feet, in the western part of Eagle Valley (figure 23), while evapotranspiration losses would be reduced to 700 acre-ft/yr and the subsurface discharge would decrease to 100 acre-ft/yr. This magnitude of decline poses a potential for compaction of the fine-grained materials (in the area of confined flow), and the associated land subsidence resulting from this compaction could be significant.

Limitations

The correspondence of the predicted water-level changes to future field conditions depends both on how closely the future pumpage matches the hypothesized pumpage and, equally important, on how well the calibrated model simulates the ground-water system. The model should not be considered verified until additional long-term water-level data become available for use in testing its predictiveness.

The model was developed against conditions in the actual ground-water basin representing a limited hydrologic stress. Consequently, the model is most valid or reliable in the simulation or prediction of small changes from present conditions. As larger departures from present conditions are simulated, the model predictions become less quantitative and more qualitative. For very large departures, the model results indicate only the general magnitude and direction of the possible regions of the actual ground-water basin.

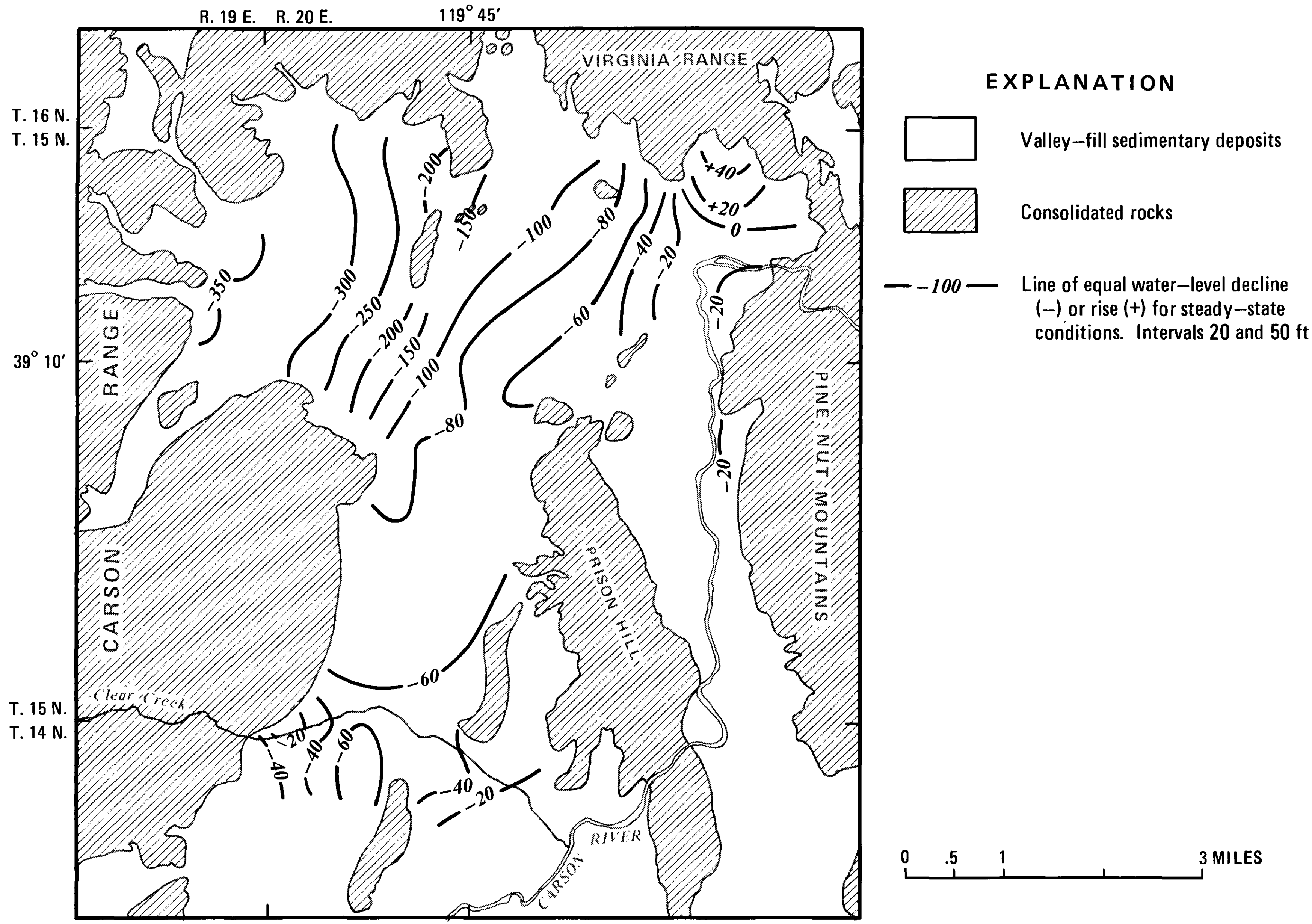


FIGURE 23.—Computed net water—level changes during period between 1964 and ultimate attainment of steady—state conditions, assuming maintenance of 1978 pumpage rate and distribution.

SUMMARY AND CONCLUSIONS

The Eagle Valley ground-water basin, which has a thickness of as much as 2,000 feet, consists of unconfined and partly confined alluvial aquifers. The sedimentary basin fill consists of (1) unconsolidated deposits, predominately sand and coarser materials, which yield large quantities of generally unconfined ground water to properly constructed wells, and (2) partly consolidated, generally finer grained deposits yielding less water, which are located primarily southeast of Lone Mountain and north of Fairview Drive. The aquifer system in this part of the valley is partly confined, and some wells flow at times.

Currently (1979), recharge is about 5,600 acre-ft/yr, primarily by infiltration of streamflow and percolation of irrigation and municipal water. Before the extensive use of ground water for municipal purposes, the ground-water system was in equilibrium, with recharge equaling discharge; the latter occurred mainly by evapotranspiration and subsurface discharge to the Carson River.

Pumping of ground water in the western part of the valley has resulted in water-level declines of as much as 50 feet during the period 1964-78. This in turn has caused the suppression of evapotranspiration from an estimated 2,900 acre-feet in 1964 to about 2,000 acre-ft/yr as of 1978. Subsurface discharge to the Carson River has been unaffected, and remains at about 1,600 acre-ft/yr.

Two hydrologic models, a small-streams model and a two-layered Galerkin finite-element model of the ground-water system, were developed for a 23-square-mile lowland area, most of which is in Eagle Valley. The small-streams model simulates ground-water recharge from Ash Canyon, Kings Canyon, and Clear Creeks and two irrigated ditches. The ground-water model simulates variations of hydraulic head with depth, evapotranspiration, and subsurface flow to the Carson River; the model was developed on the basis of a simplified conceptualization of the ground-water system. It was calibrated by comparing the computed hydraulic heads with the corresponding observed water levels for both steady-state and transient-state conditions. The computed water levels in some parts of the valley were lower than measured values, whereas computed net declines for the period 1964-78 are in close agreement with existing data. Additional information is needed to verify that the model accurately simulates the hydrologic system under higher stress.

The model was used to predict conditions as of the year 2000, assuming that the amount (4,720 acre-ft/yr) and distribution of pumpage remain as they were in 1978. Results indicate that water levels would decline 150 feet in the western part of the valley and 15 feet in the south-central part. Evapotranspiration would decrease to about 1,200 acre-ft/yr, and subsurface flow to the Carson River would decrease slightly to 1,500 acre-ft/yr.

A steady-state analysis, also using 1978 pumping amounts and distribution, indicates that water levels ultimately would decline 350 feet in the western part of Eagle Valley. The evapotranspiration losses would decrease from 2,000 to 700 acre-ft/yr, and subsurface discharge to the Carson River would decrease from 1,600 to 100 acre-ft/yr.

BASIC DATA

TABLE 4.--*Transmissivities and leakance coefficients used in the model*

Element number	Transmissivity[1] Upper layer (ft^2/d)	Transmissivity[1] Lower layer (ft^2/d)	Leakance coefficient [(ft/d)/ft]
1	39	201	0.005
2	41	383	.004
3	161	1,745	.008
4	54	599	.008
5	57	632	.007
6	14	100	.007
7	15	100	.010
8	148	816	.006
9	549	3,415	.005
10	427	5,339	.003
11	619	8,763	.002
12	479	7,187	.002
13	319	4,152	.004
14	76	689	.002
15	84	581	.003
16	135	745	.007
17	535	4,283	.004
18	558	8,828	.002
19	688	10,901	.001
20	331	5,630	.003
21	481	7,218	.002
22	774	8,517	.002
23	405	2,837	.0007
24	276	323	.004
25	205	1,642	.004
26	410	5,470	.003
27	698	9,882	.002
28	585	8,290	.002
29	441	6,623	.002
30	444	6,663	.002
31	115	1,270	.010
32	40	1,000	.010
33	234	1,041	.006
34	972	6,051	.003
35	769	10,901	.001
36	769	10,901	.001
37	709	10,638	.001
38	400	2,800	.001
39	212	638	.002
40	186	651	.002
41	105	841	.005
42	725	5,075	.002
43	824	10,901	.001
44	364	5,470	.003
45	347	5,901	.002
46	642	7,059	.002
47	183	1,376	.003
48	416	5,178	.002
49	455	7,743	.002
50	727	10,901	.001
51	231	4,177	.0002
52	249	4,177	.0002
53	222	3,000	.004
54	416	4,806	.002
55	504	6,665	.003
56	376	3,799	.005
57	381	4,078	.005
58	140	1,520	.007
59	5	20	.005
60	5	20	.007
61	132	1,664	.005
62	212	2,664	.005
63	330	3,347	.005
64	333	3,371	.005
65	188	1,767	.005
66	234	2,032	.005
67	290	2,030	.005
68	231	1,258	.005
69	7	20	.004
70	6	20	.006
71	19	101	0.005
72	19	101	.005
73	20	101	.010
74	20	101	.010
75	40	102	.005
76	48	102	.005
77	67	102	.005
78	60	102	.005
79	46	30	.005
80	15	30	.005
81	17	50	.010
82	11	50	.005
83	11	50	.005
84	14	75	.005
85	21	75	.005
86	19	75	.005
87	50	75	.005
88	50	75	.009
89	25	75	.008
90	25	75	.005
91	19	75	.009
92	21	75	.008
93	25	75	.007
94	25	75	.008
95	25	75	.009
96	25	75	.010
97	25	75	.008
98	25	75	.009
99	97	851	.0002
100	144	1,267	.0003
101	86	1,267	.0003
102	103	1,836	.0002
103	107	1,818	.0004
104	65	1,154	.0005
105	237	4,227	.0002
106	59	800	.0003
107	47	587	.0002
108	100	1,061	.0002
109	5	50	.0002
110	8	50	.0002
111	17	50	.010
112	16	50	.010
113	139	1,727	.0002
114	117	2,569	.0002
115	163	3,636	.0002
116	181	3,981	.0002
117	271	5,402	.0002
118	162	3,218	.0002
119	148	2,012	.0002
120	57	780	.0003
121	56	530	.0004
122	44	450	.0004
123	32	91	.005
124	29	91	.005
125	29	91	.005
126	67	1,336	.0002
127	78	1,068	.0002
128	58	787	.0002
129	63	593	.0002
130	84	788	.0003
131	75	470	.0004
132	438	613	.0003
133	237	497	.0004
134	107	255	.006
135	202	255	.006
136	301	301	.007
137	301	301	.007
138	101	854	.0002
139	67	515	.0002
140	131	368	.0002
141	122	395	0.0002
142	98	137	.0002
143	274	384	.0002
144	188	450	.0003
145	202	257	.0004
146	301	301	.005
147	301	301	.007
148	1,000	1,275	.0002
149	1,000	1,275	.0002
150	1,000	1,275	.0002
151	1,000	1,278	.0002
152	1,000	1,278	.0002
153	1,000	1,278	.0002
154	161	502	.001
155	188	502	.002
156	188	502	.050
157	207	864	.050
158	15	100	.025
159	17	100	.050
160	23	100	.050
161	38	100	.050
162	86	100	.050
163	100	100	.050
164	364	1,275	.0002
165	364	1,275	.0002
166	161	502	.001
167	83	502	.001
168	46	500	.001
169	46	500	.001
170	40	500	.002
171	40	500	.002
172	12	100	.005
173	14	100	.014
174	86	100	.050
175	86	100	.050
176	23	217	.0002
177	19	217	.0002
178	12	140	.0002
179	10	102	.0002
180	160	500	.001
181	59	501	.001
182	50	500	.001
183	31	500	.001
184	26	500	.001
185	37	500	.001
186	8	100	.005
187	8	100	.010
188	30	100	.050
189	86	100	.050
190	70	832	.0002
191	46	587	.0005
192	16	217	.0002
193	16	217	.0002
194	67	572	.002
195	43	500	.002
196	46	500	.001
197	35	500	.001
198	42	600	.001
199	338	5,000	.002
200	744	11,000	.010
201	790	10,000	.010
202	467	5,000	.010
203	64	964	.0002
204	65	1,124	.0002
205	53	930	.0002
206	38	515	.0002
207	7	109	.0002
208	16	245	.0002
209	36	500	.0002
210	59	766	.002

TABLE 4.--*Transmissivities and leakance coefficients used in the model*--Continued

Element number	Transmissivity[1] Upper layer (ft^2/d)	Transmissivity[1] Lower layer (ft^2/d)	Leakance coefficient [(ft/d)/ft]
211	77	823	0.002
212	102	1,000	.002
213	87	1,000	.002
214	81	1,010	.001
215	71	1,010	.001
216	404	7,070	.005
217	450	8,621	.005
218	615	11,000	.010
219	615	11,000	.010
220	836	11,000	.010
221	622	8,000	.010
222	168	5,121	.0002
223	41	1,191	.0002
224	47	1,310	.0002
225	61	1,707	.0002
226	52	1,309	.0002
227	27	465	.0002
228	35	562	.0002
229	49	602	.0002
230	143	889	.0003
231	389	1,727	.002
232	162	1,010	.002
233	360	1,500	.002
234	257	1,500	.002
235	164	1,500	.005
236	81	1,010	.005
237	203	3,000	.010
238	245	4,000	.010
239	229	4,000	.010
240	331	5,000	.010
241	429	6,000	.010
242	462	6,000	.010
243	184	6,030	.0002
244	191	7,100	.0002
245	267	9,090	.0002
246	66	2,007	.0002
247	78	1,862	.0002
248	249	5,424	.0002
249	378	6,381	.0002
250	45	717	.0002
251	120	1,243	.0002
252	209	987	.0002
253	91	500	.003
254	96	500	.003
255	318	1,321	.005
256	315	999	.010
257	218	681	.010
258	345	2,010	.010
259	267	2,001	.010
260	172	2,001	.010
261	146	2,000	.010
262	151	2,000	.010
263	71	1,000	.010
264	76	1,001	.010
265	122	1,501	.010
266	251	6,063	.0002
267	240	8,600	.0002
268	319	12,120	.0002
269	189	6,060	.0002
270	271	6,060	.0002
271	388	7,433	.0002
272	289	6,021	.0002
273	51	500	.0002
274	75	500	.002
275	91	500	.003
276	452	2,010	.010
277	345	2,010	.010
278	219	2,010	.010
279	199	2,010	.010
280	152	2,012	.010
281	273	3,417	0.010
282	35	402	.010
283	44	503	.010
284	91	500	.010
285	96	501	.010
286	63	501	.010
287	12	103	.010
288	8	101	.010
289	9	101	.010
290	17	101	.010
291	218	6,463	.0002
292	254	9,090	.0002
293	267	9,045	.0002
294	368	9,038	.0002
295	311	6,360	.0002
296	118	3,001	.0002
297	162	4,500	.0002
298	248	8,117	.0002
299	256	8,854	.0002
300	256	7,248	.0002
301	103	2,476	.0002
302	17	300	.0002
303	366	6,060	.005
304	210	4,287	.005
305	325	7,911	.005
306	220	5,000	.005
307	253	4,200	.0002
308	253	4,200	.0002
309	26	420	.005
310	28	451	.005
311	818	2,454	.005
312	515	2,430	.005
313	513	6,060	.005
314	367	5,000	.005
315	324	5,000	.005
316	325	5,000	.005
317	306	4,200	.005
318	182	2,500	.005
319	27	350	.005
320	25	350	.005
321	403	2,015	.005
322	2,015	2,015	.005
323	1,415	4,010	.005
324	446	4,427	.005
325	308	3,080	.005
326	370	3,696	.005
327	348	5,372	.005
328	324	5,372	.005
329	176	2,500	.005
330	189	2,500	.005
331	28	350	.005
332	27	350	.005
333	144	1,008	.005
334	288	2,015	.005
335	1,144	4,010	.005
336	682	7,795	.005
337	302	3,232	.005
338	155	2,820	.005
339	210	4,325	.005
340	324	5,372	.005
341	176	2,500	.005
342	200	2,500	.005
343	26	250	.005
344	24	251	.005
345	112	1,008	.005
346	524	4,719	.005
347	745	6,706	.005
348	5,850	7,218	.005
349	5,857	7,226	.005
350	162	1,848	.005
351	221	3,234	0.005
352	201	3,331	.005
353	201	3,331	.005
354	89	1,112	.005
355	105	1,000	.005
356	61	520	.005
357	888	6,706	.005
358	375	3,893	.005
359	295	2,500	.005
360	276	2,500	.005
361	238	2,500	.005
362	306	2,500	.005
363	66	616	.005
364	46	616	.005
365	162	2,681	.005
366	56	840	.005
367	105	983	.005
368	86	733	.005
369	70	557	.005
370	83	500	.005
371	100	500	.005
372	34	200	.005
373	342	400	.005
374	718	2,378	.005
375	362	3,575	.005
376	412	5,000	.005
377	412	5,000	.005
378	251	3,050	.005
379	373	4,001	.005
380	403	4,000	.005
381	246	2,440	.005
382	243	2,414	.005
383	242	2,406	.005
384	74	1,000	.005
385	22	252	.005
386	39	420	.005
387	60	528	.005
388	36	313	.005
389	33	250	.005
390	25	200	.005
391	23	200	.005
392	23	200	.005
393	45	200	.005
394	57	200	.005
395	412	5,000	.005
396	503	5,000	.005
397	503	5,000	.005
398	503	5,000	.005
399	403	4,000	.005
400	252	2,500	.005
401	129	1,000	.005
402	141	1,000	.005
403	503	5,000	.005
404	503	5,000	.005
405	503	5,000	.005
406	252	2,500	.005
407	324	2,500	.005
408	119	918	.005
409	194	918	.005
410	40	200	.005
411	36	249	.005
412	23	200	.005
413	27	200	.005
414	20	140	.005
415	15	140	.005
416	39	200	.005
417	39	200	.005
418	106	501	.010
419	265	9,090	.0002
420	641	300	.005
421	752	11,000	.010
422	652	11,000	.010

[1] Model-generated values reported to as many as five significant figures should not be construed to imply that degree of accuracy.

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