Steady-State and Transient Ground-Water Modeling of Washoe Valley Washoe County, Nevada

Washoe County Department of Water Resources

December 31, 1997

Department of

Water Resources

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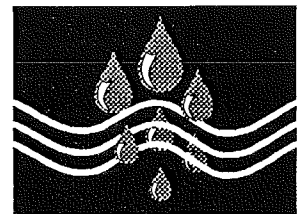
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Washoe County Department of Water Resources

December 31, 1997

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PREFACE

Given the rapid growth and proposed subdivision developments within Washoe Valley, Washoe County has used a series of ground-water models to estimate ground-water resources and development impacts on the basin. The first modeling effort was contracted to the Desert Research Institute (DRI) with support from the Washoe County Utility Division. That work was reported in "Final Documentation, Washoe Valley Groundwater Model" (Peterson, et.al., 1994). It represented a steady state model and was built upon previous work by Ronald Peterson in his graduate studies at the University of Nevada, Reno. However, it was felt that more work could be accomplished and that a transient model should also be constructed. The follow-up work, accomplished by the Washoe County Utility Division, is presented herein.

A revised DRI steady state model was constructed by Washoe County (Widmer, 1994a). Concurrently, Washoe County began contracting airborne geophysical surveys for water resource investigations in various basins within Washoe County and an airborne survey was conducted over Washoe Valley (Dighem, 1994). These data are included in the new modeling effort which revised the steady state model again and produced a transient model. Consequently, several versions of a Washoe Valley model have been completed in the last four years; Ron Peterson's Masters Thesis (Peterson, 1993), the DRI model (Peterson, et.al., 1994), the revised DRI model (Widmer, 1994a) and the modeling in this report. Further work will be accomplished in the form of continued modeling of the New Washoe City area by Washoe County and a nitrate study of the New Washoe City area by DRI.

It may also be of interest to the reader that the modeling efforts also saw several advances in modeling software. Data sets were initially constructed on LOTUS™ spreadsheets or with ARC INFO™ files. The Washoe County efforts first used the preprocessor MODELCAD 386™ by Geraghty and Miller, Inc. Finally, during the construction of the last steady state model and the transient modeling, the County began using a pre and post processing program called GROUNDWATER VISTAS™ by Environmental Simulations, Inc. While this progression increased the computing power and efficiency of the modeling efforts, the learning process in using these tools resulted in delaying the completion of the project.

Much was learned of the hydrogeology of Washoe Valley. Yet, the biggest problem was in how to realistically treat Washoe Lake in terms of boundary conditions. The modeling code used was the USGS's program MODFLOW, which at the time did not (and still may not) have a package that could treat this particular lake adequately since at times the lake is dry. Until overcome, this problem will continue to limit the ultimate success of modeling Washoe Valley.

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ABSTRACT

A ground-water flow model was developed for Washoe Valley in order to estimate ground water resources more accurately than previous water resource investigations. This model can also be used in resource management efforts. The steady state model was further refined through a transient model that simulated ground water conditions from 1965 to 1997. Washoe Lake, a dominant resource feature, was modeled as a constant head or general head and therefore the model does not always accurately simulate the physical processes in lake and ground water interactions.

The calibration of the steady state model resulted in approximating the average annual mountain front recharge at 6,760 acre-feet (8.3 hm^3) of which 5,740 acre-feet (7.1 hm^3) emanates from the Carson Range and 1,020 acre-feet (1.2 hm^3) emanates from the Virginia Range. Additional ground-water recharge occurs from irrigation and precipitation processes on the west valley floor (4,490 acre-feet or 5.5 hm^3). Ground water discharges primarily through evapotranspiration in the wetlands (7,020 acre-feet or 8.6 hm^3) and discharges to Washoe Lake (3,350 acre-feet or 4.1 hm^3).

Ground-water pumpage for both irrigation and domestic uses has increased steadily since 1965. Domestic pumpage in New Washoe City appears to exceed the natural recharge on the eastern side and water is being supplied from Washoe Lake infiltration and from ground-water storage. Water level declines have occurred mainly in New Washoe City (10 to 50 ft or 3 to 15 m) as a result of overpumpage, drought and consequent lower lake level. The decline is expected to continue at a lesser rate at the present level of development. Annual pumpage of all ground-water rights in the valley will develop significant cones of depression in the southeast and southwest, resulting in the capture of lake-water.

INTRODUCTION

Washoe Valley (see figure 1) has recently been viewed as a basin rich in water resources on the western side and lacking water resources on the eastern side. Unfortunately, most of the rural development today occupies the eastern side and more eastside development is being proposed though, increased density development is also occurring on the western side. The ability to develop is strongly tied to water resources and in fact, different rules for development apply based on where the development is being proposed. Therefore, adequate investigations are needed to better estimate the available water resources, whether they are abundant or depleted and what the long-term outlook is. This present investigation should set the basis for resource estimations and future investigations.

Purpose

The purpose of this investigation was to describe and analyze the ground-water system. The resultant model can be used, within limits, as a resource management tool. This management tool is used essentially to estimate the ground-water resources of Washoe Valley, to describe present movement and occurrence and to predict future impacts of ground-water development. To meet this purpose, the objectives were to adequately describe the steady state conditions assumed in 1965 and then calibrate the model to conditions in 1981, 1994 and 1997. This work is referred to as "transient modeling" or "model verification."

Previous Hydrogeologic Work

The first significant water resource investigation was conducted by Eugene Rush of the USGS as part of Nevada's Water Resources Reconnaissance Series (Rush, 1967). This cursory investigation defined available surface and ground water resources through a water balance approach. While limited in terms of field data collection, the investigation did achieve an appropriate analysis of the major water budget components, a record of Washoe Lake and a water well survey that was used in the steady state modeling effort. In the early 1980's,

STEAM BOAT CREEK

WASHOE CITY

LITTLE WASHOE LAKE

OPHIR CREEK

HWY 395

CARSON RANGE

FRANKTOWN CREEK

NEW WASHOE CITY

JUMBO CREEK

EAST LAKE BLVD

VIRGINIA RANGE

MUSGROVE CREEK

WASHOE LAKE
LAKE ELEVATION
5029 FEET

FRANKTOWN RD

LEWERS CREEK

WASHOE VALLEY
LOCATION MAP

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SCALE IN FEET

AREA OF DETAIL
WASHOE VALLEY NEVADA

RENO
VIRGINIA CITY
CARSON CITY

Department of Water Resources

WASHOE COUNTY NEVADA
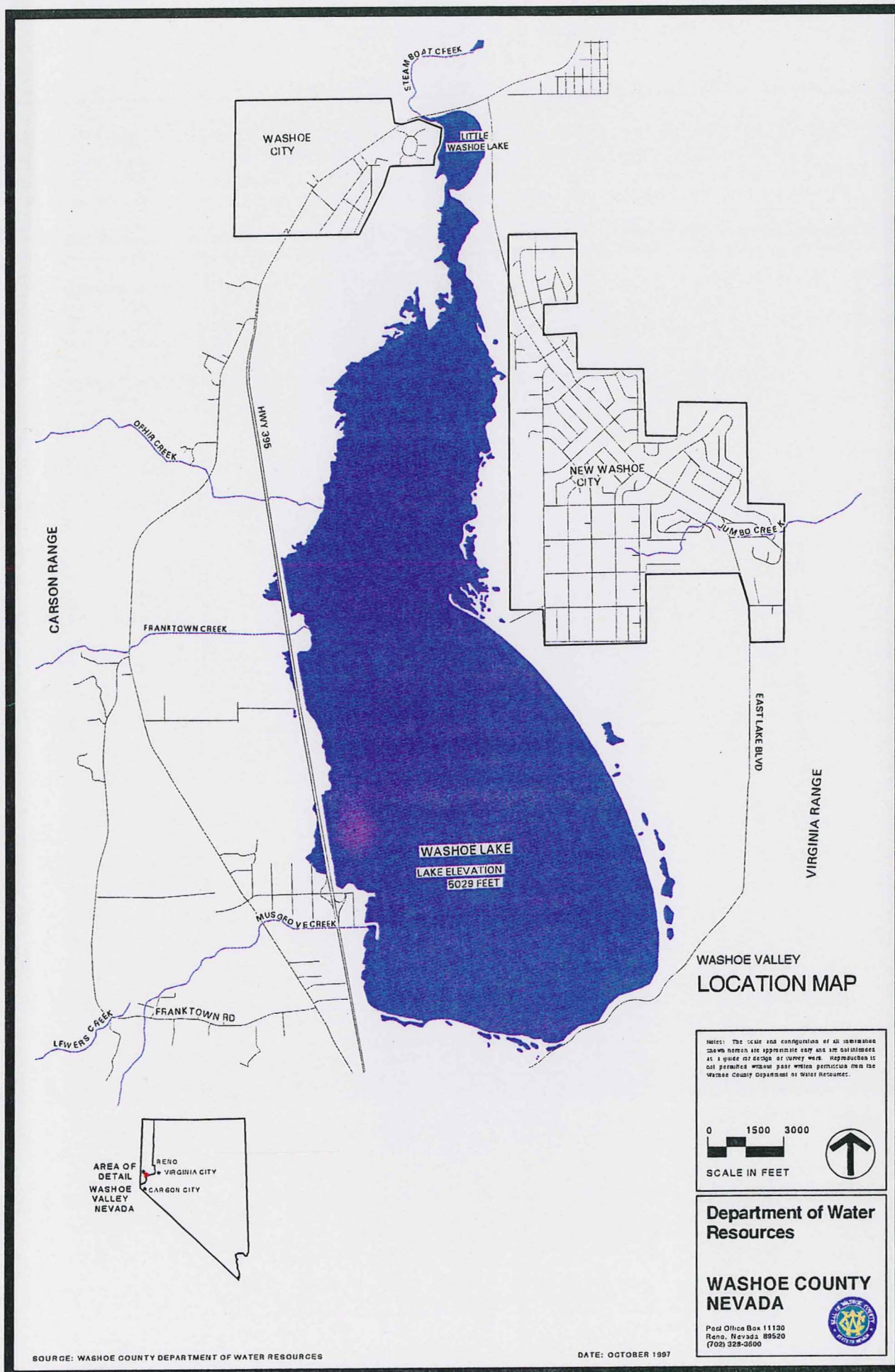
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Figure 1. Location Map of Washoe Valley

the USGS, under contract with Washoe County, conducted another water resource investigation (Arteaga, 1984) which developed a more thorough water budget. Information developed by this investigation included water yield estimates (both ground and surface water resources) specific to sub-basin watersheds, a water well survey, evaporation estimates from the average lake surface, and alluvial thickness estimates. Arteaga also performed preliminary ground-water modeling that was not discussed in the text.

The Desert Research Institute (DRI) investigated water quality in the New Washoe City area (Armstrong and Fordham, 1977 and McKay, 1991). The Institute analyzed the chemical constituents iron, fluoride and nitrate that were elevated in the ground water drinking supply of this area as there are primary and secondary health effects from these constituents. Fluoride (primary) and iron and manganese (secondary) occur naturally in this area, but nitrate (primary) occurrence is frequently a result of the presence of septic tanks.

Ronald Peterson completed two ground-water flow models of Washoe Valley (Peterson, 1993, and Peterson, and others, 1994). The first modeling effort (Peterson's master's thesis) was to show that geophysical data could be used as a basis for estimating aquifer transmissivity. Peterson carried that work further with DRI under contract with Washoe County to more accurately model Washoe Valley. This work culminated in a steady state model that provided the basis of this current study.

Karl Kanbergs, a Washoe County graduate student intern, is currently evaluating the ground-water resources specific to New Washoe City. His work further details the geologic structure and geochemical anomalies found in this area. One concern is the documentation of a thermal plume of ground water found in the extreme southern portion of New Washoe City. The hydraulic aspects of his work are included herein.

Ground-water level surveys in Washoe Valley have been surveyed 1965-66 by Rush (Rush, 1967), 1981-82 by Washoe County and the USGS (Arteaga, 1984) and in 1994 and 1997 by the Washoe County Utility Services Division. The Washoe County Utility Services Division collected stream-flow measurements for 18 months from 1983 to 1984 and that the USGS has been measuring the lake level since 1963.

GEOLOGIC SETTING

Washoe Valley is a structural depression or graben with a north-south oriented axis. This depression is a result of regional extension of the Basin and Range physiographic province (Fenneman, 1931) and uplift from the Sierra Nevada Batholith. As a result, two mountain ranges have formed, the Virginia Range on the east and

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southeast and the Carson Range on the west. The Carson Range is comprised of granodiorite. The Virginia Range is comprised of granodiorite, metasediments, and volcanics of primarily andesitic composition (Tabor and Trexler, 1977). Please refer to figure 2.

The drainage area for Washoe Valley is 81 mi^2 (210 km^2) and the valley floor comprises 28 mi^2 (72 km^2) in area. The basin floor is relatively flat lying with alluvial fans emanating from most of the canyons. Elevations of these alluvial fans slope downwards from 5,200 ft (1,585 m) at both east and west margins to 5,020 ft (1530 m) at the lake. It has been estimated through gravity surveys that the basin is as much as 1,000 ft deep (Peterson, 1993), mostly in its western. The valley lithology primarily consists of sediments derived from the granodiorite on the west and a mixture of volcanics, metasediments and granodiorite on the east, north and south margins. Geophysical surveys have located a volcanic ridge in the southeast beneath Washoe Lake (Peterson, 1993). This volcanic ridge is buried beneath approximately 200 ft of sediments and has formed what can best be described as a "buried sub-basin". Please refer to figure 3. Sediments are generally coarsest along the western margins and in the north central portion of the basin. Sediments are finest in the east and southeast, and near the northern margins (Dighem, 1994).

GEOPHYSICAL SURVEYS

Several geophysical surveys have been conducted. These include gravity and seismic data (Tabor, and others, 1983), gravity and electromagnetic data (Peterson, 1993), and an airborne survey collecting magnetic and electromagnetic data (Dighem, 1994). Of particular importance to this study is the airborne survey. In 1994, Washoe County contracted with Dighem Airborne Processing, Inc. to conduct an airborne geophysical survey of Washoe Valley. The survey included Total Field Magnetics and three frequencies of Electromagnetics (56,000, 7,200 and 900 Herz). The results of that survey were used to determine the gross geologic structure and lithology of aquifer materials in Washoe Valley.

Total Field Magnetics
Total field magnetics is a wavelength measurement of the magnetic signature of crustal rocks or, in other words, the measurement of the concentration of the mineral magnetite in various lithologies. The unit of measurement is nanoteslas (NT). This potential field measurement is used to describe subsurface rock units. When used in conjunction with gravity measurements and other physical parameter measurements (such as density and magnetic susceptibility), total field magnetics can be modeled two-dimensionally to give a geologic, cross sectional description of the earth's upper crust. Rock units rich in magnetite, such as basalt, will have a much higher signature than rock units deficient in magnetite, such as alluvium or granite. This investigation did not involve the exact modeling of this potential field data. None the less, the geologic subsurface structure can still be described given other existing data.

Figure 4 is a total field magnetic contour map of Washoe Valley has been simplified for illustration. Most striking is the anomalously high magnetics in the northern portion of the study area. The area of high magnetics (>51800 NT), shown in purple, represents near-surface or surface andesite of the Kate Peak formation. Conversely, the area of anomalously low magnetics (<51200 NT), shown in dark blue in the extreme southwest, represents granodiorite; perhaps strongly weathered. In the central portion of the map, the magnetics shown in dark gray to dark green (51200 to 51400 NT) represent thick alluvial deposits, which have been documented in other geophysical studies

WASHOE VALLEY
GEOLOGY

QUATERNARY

UNDIFFERENTIATED QUATERNARY SEDIMENTS
Lake, alluvial, alluvial fan, talus and playa deposits.

LANDSLIDE DEPOSITS
Coarse mixtures of basalt, tuff, diatomite
and tuffaceous sediments.

PRE-LAKE LAHONTAN DEPOSITS
Terrace, alluvial fan, and pediment gravels. These gravels are
deeply weathered, highly dissected, faulted and tilted gravels.

BASALT AND ANDESITE FLOWS
Flows of olivine basalt and hornblende andesite of
Pleistocene age.

TERTIARY

RHYOLITE
Intrusive plugs, protrusive domes, and flows of rhyolite glass.
with phenocrysts of plagioclase, biotite, and alkali feldspar.

BASALT AND BASALTIC ANDESITE
Basalt, basaltic andesite, and pyroxene andesite flows.
Unit overlies and intertongues with Tertiary sedimentary rocks.

FLUVIATILE AND LACUSTRINE SEDIMENTARY ROCKS
Diatomite, arkose, volcanic sediments, conglomerate, breccia, silicic
vitric tuff, basalt lapilla tuff, and undifferentiated basaltic flows.

KATE PEAK FORMATION
Flows, breccias, volcanic conglomerates, and associated intrusives of
pyroxene andesite to myodacite. Includes intercalated sediments.

GRANITIC ROCKS
Intrusive masses of quartz monzonite, granodiorite, and quartz diorite
porphyry. These rocks are usually propylitically altered and locally
exhibit argillic and quartz-sericite-pyrite alteration phases.

PYRAMID SEQUENCE
Basalt, andesite, and dacite flows, flow breccias, tuffs and associated
intrusives. Lenses of silicic waterlain tuff, diatomite, shale and sandstone.

ALTA FORMATION
Pyroxene and hornblende andesite flows, breccias and pyroclastics.
Commonly propylitized and locally bleached.

HARTFORD HILL RHYOLITE
Predominantly ash-flow tuffs ranging in composition from rhyolite to quartz
lalite. Includes some ash-fall tuff and lenses of clastic sediments.

SOUTH WILLOW FORMATION
Basalt, andesite, and dacite flows, mudflow breccia and associated intrusive
phases. Dark colored porphyritic rocks with plagioclase phenocrysts.

PAH RAH FORMATION
Propylitized pyroxene andesite mudflow breccia with occasional clasts
of Mesozoic granitic and metamorphic rocks.

CRETACEOUS

INTRUSIVE ROCKS
Undifferentiated Plutonic rocks ranging from gabbro to granite. Mostly
granodiorite and quartz monzonite with included pegmatite-aplite dikes.

TRIASSIC AND JURASSIC

METAMORPHIC ROCKS
Undifferentiated metavolcanic and metasedimentary rocks.

WATER BODIES

SOURCE: WASHOE COUNTY DEPARTMENT OF WATER RESOURCES

DATE: OCTOBER 1997

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0   2000   4000

SCALE IN FEET

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NEVADA**

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Figure 2. Geologic Map of Washoe Valley
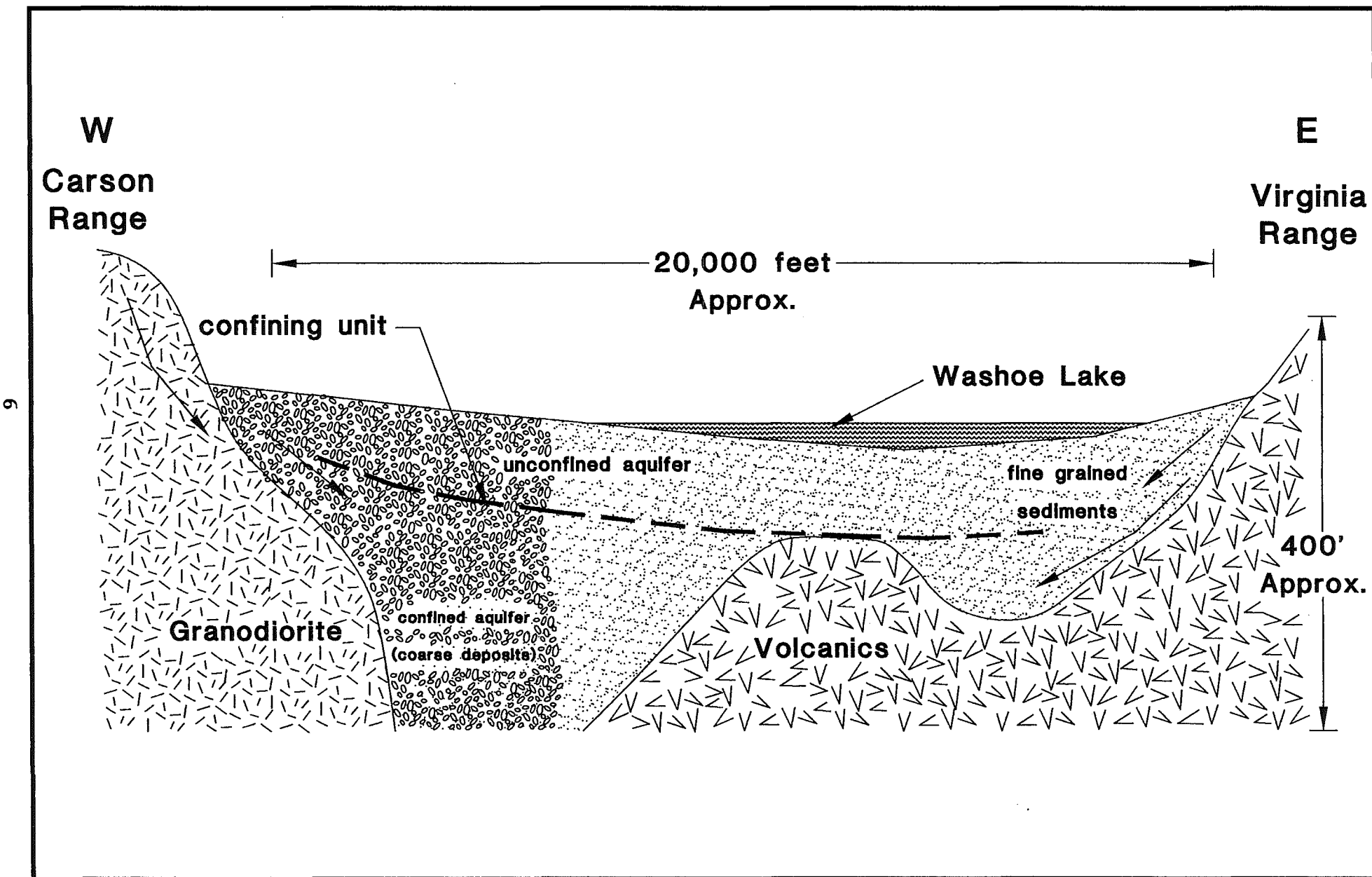
Figure 3. Generalized Geologic Cross Section of Washoe Valley
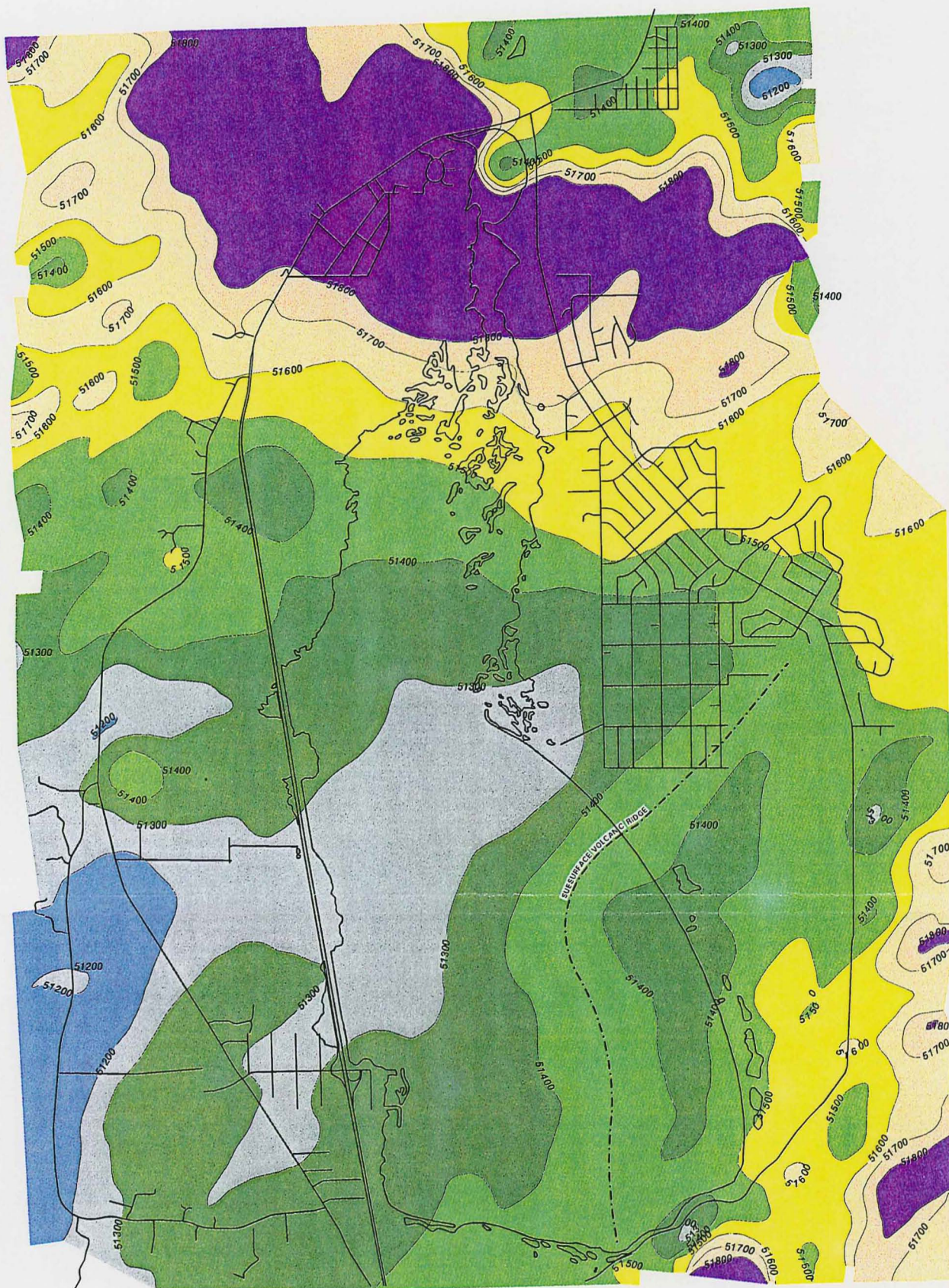
WASHOE VALLEY
TOTAL FIELD MAGNETICS

CONTOURS IN NANOTESLAS

Legend	
> 51800	51400 - 51500
51700 - 51800	51300 - 51400
51600 - 51700	51200 - 51300
51500 - 51600	< 51200

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SCALE IN FEET

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SOURCE: DIGHEM

DATE: OCTOBER 1997

Figure 4. Total Field Magnetics of Washoe Valley

(Peterson, 1993). In the lower central area a somewhat linear feature shown in green (51400 to 51500 NT) is interpreted as a near surface volcanic ridge (Peterson, 1993). To the east of this ridge are dark green and green (51300 to 51500 NT) areas indicating alluvial deposits. Hydrothermally altered volcanic areas are inferred in the extreme northwest and southeast. Faulted areas have not been investigated.

Electrical Resistivity

Electrical resistivity methods have been used in hydrogeologic investigations for over 50 years. The method relies on the fact that certain earth materials are good conductors of electricity while other are not. For example, clays are very good conductors, especially if they are saturated. Poor conductors would be competent rock such as granite or unsaturated gravels. Studies have shown that electrical conductivity of earth material can be directly related to hydraulic conductivity, the measurement of the ability of water to move through earth material (Erdelyi and Galfi, 1988; Keys, 1989; Repsold, 1989).

Electromagnetic frequencies are used to induce low voltage current into the ground. This current creates a secondary electromagnetic field, which then is measured with a receiver coil. The strength of this signal is a function of the resistivity or conversely, the conductivity of the particularly earth material or geoelectric layer. The resistivity values, measured in ohm meters (ohm.m), typically range from 1 to 1,000 ohm.m. Lithologies with resistivities of 10 ohm.m or less usually represent saturated clays while units of greater than 200 represent hard, competent rock. The depth of penetration of the currents is a function of the resistivity of the material such that in highly conductive material the penetration is less than in resistive material. Additionally, by using progressively smaller frequencies, an increase in the depths of electrical current

penetration will occur such that the investigator can view resistivity at different depths at different frequency bands.

Figure 5 is a contour map of electrical resistivity of Washoe Valley from the 900 Hz frequency (deepest penetration). The figure depicts resistivities of lithologic material from the surface to depths of about 200 to 400 ft. The largest feature is the 10 to 40 ohm.m material (red to dark tan) that dominates the eastern portion of the valley. This is interpreted as fine-grained alluvium; silty sands, silts and clays. These materials are inferred to be at least 200 ft thick. The 60 to 100 ohm.m material (yellow) is inferred to be sands and gravels which dominate the central and southwest portion of the valley floor. Material mapped at or above 200 ohm.m probably represents hard competent rock. One feature of note is a linear feature, trending east-west, that emanates from the Franktown Creek Canyon. This feature has a signature of 100 to 200 ohm.m (green) and most likely represents coarse gravel. Another feature of note is the <10 ohm.m (dark red) circular area beneath southwestern New Washoe City. This was thought to represent a small geothermal area as elevated ground water temperatures have recently been measured in this area (McKay, personal communication). Further work by Kanbergs indicates that this signature more accurately represents relatively thick and saturated clayey alluvium.

Figure 6 is a map display of total dissolved solids (TDS) based on a geochemistry survey of water wells conducted in spring 1994 (Washoe County, 1994). This map can be used with figure 5 to determine whether any electrical resistivity anomalies can be attributed to the electrical conductance of the ambient ground water. Figure 6 indicates that, of those 45 wells sampled, TDS ranges from approximately 50 to 250 ppm with one value of 439 ppm. This range is generally below the level needed to affect electrical conductance (Hem, 1970).

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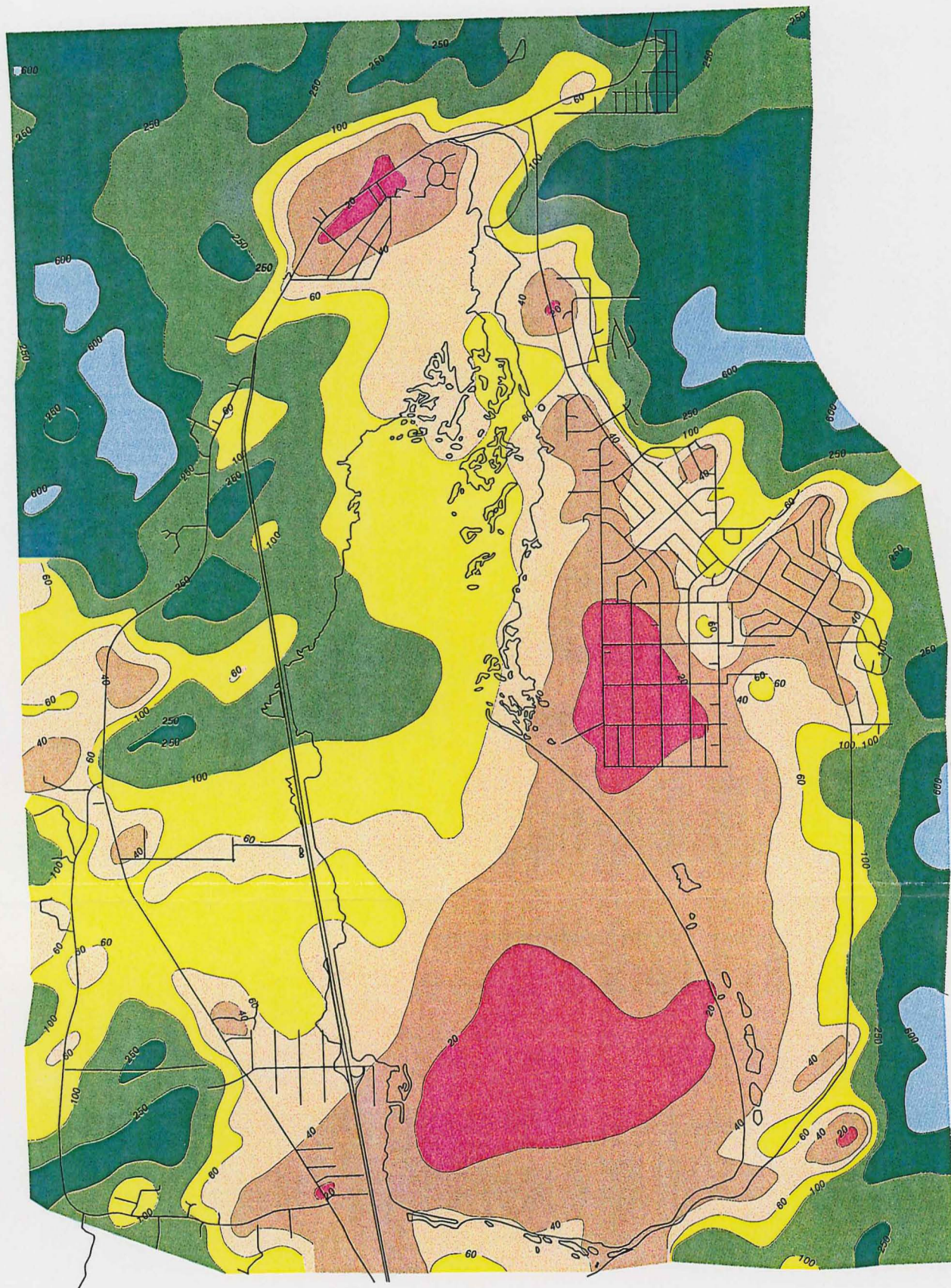
WASHOE VALLEY
RESISTIVITY - 900 HZ COPLANER

CONTOURS IN OHM.METERS
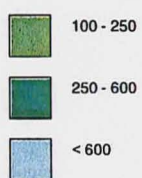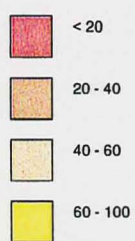
■ < 20		■ 100 - 250	
■ 20 - 40		■ 250 - 600	
■ 40 - 60		■ < 600	
■ 60 - 100			
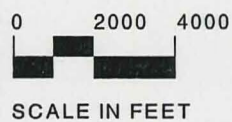
SOURCE: DIGHEM

DATE: OCTOBER 1997

Figure 5   Electrical Resistivity Map of Washoe Valley
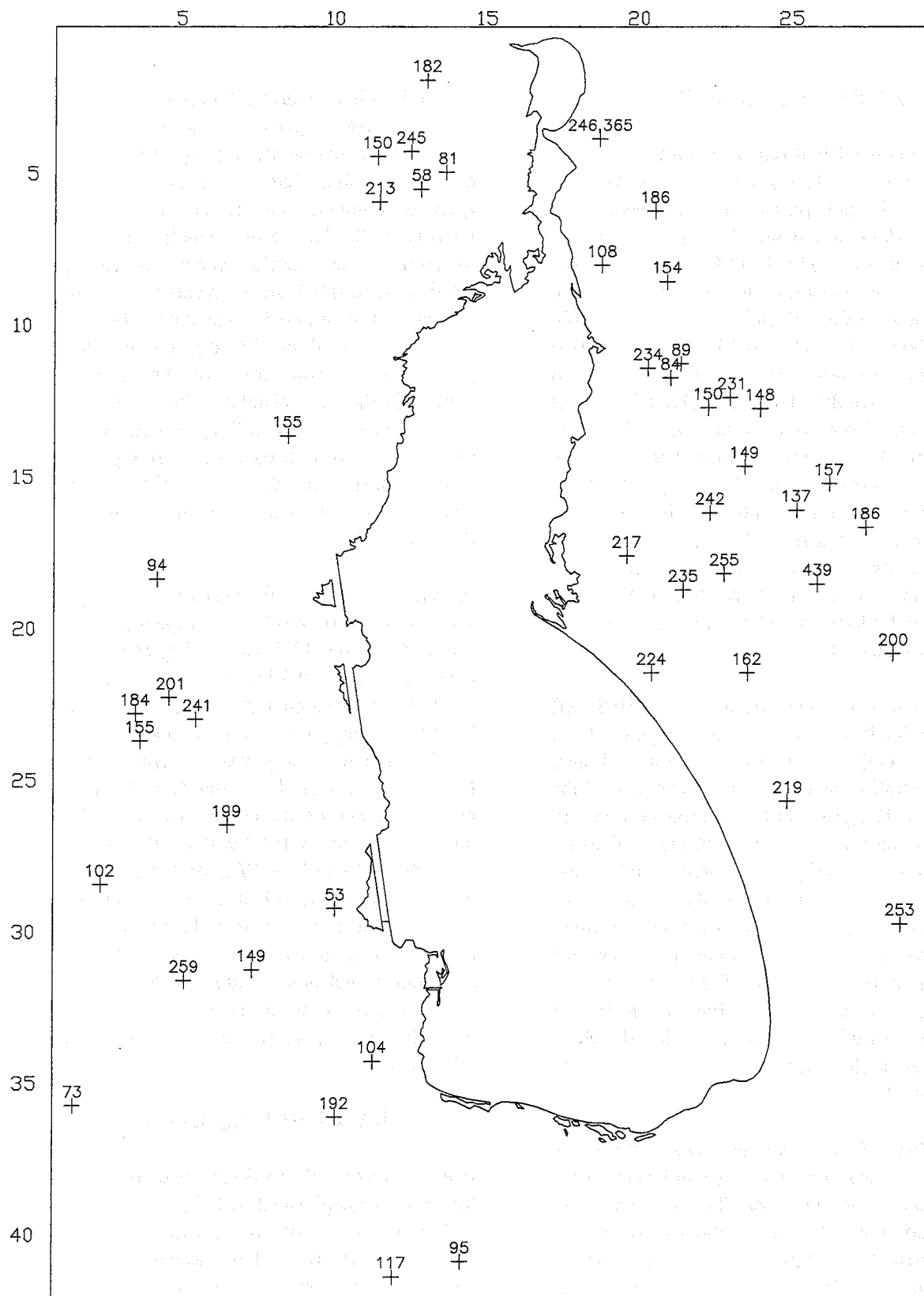
FIGURE 6
LOCATION MAP OF WATER QUALITY, 1994 STUDY, WASHOE VALLEY
(AS TOTAL DISSOLVED SOLIDS IN PARTS PER MILLION)

SCALE: 1" = 5000'
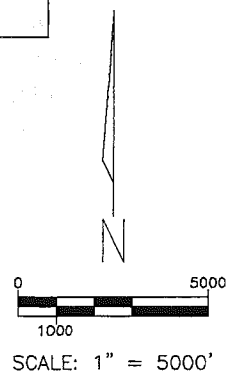
HYDROLOGIC SETTING

The dominant hydrologic feature of Washoe Valley is the broad and shallow Washoe Lake which occupies about 25 per cent of the valley floor or 8.6 mi^2 (22.3 km^2) at a lake elevation of 5,027 ft (1,941 m). During floods and moderate water years the lake enlarges northward and connects with Little Washoe Lake. The land between these two features usually remains as wetlands and provides wildlife habitat. The lake is fed primarily from streams emanating from the Carson Range; Ophir, Franktown, Lewers and Musgrove creeks. However, valley floor irrigation practices rely heavily on these streams. The lake is drained by Steamboat Creek that flows northward from Little Washoe Lake, out of Washoe Valley, and eventually to the Truckee River, 15 miles (24 km) to the north.

Precipitation ranges from 20 in. (50.8 cm) along the base of the Carson Range to 10 in. (25.4 cm) along the Virginia Range. Precipitation in the higher elevations of the Carson Range nears 60 in. (152 cm) and 24 in. (61 cm) in the Virginia Range (Klieforth, and others, 1983). The winter and spring mountain front provides the majority of runoff to the lake. A dominate weather feature of Washoe Valley is wind; the duration and intensity of wind in Washoe Valley are anomalously high compared to other nearby basins of western Nevada which increases the rate of ET (ET) normally expected.

Washoe Valley can be characterized as having two different groundwater flow regimes. On the west, the lake, abundant streams emanating from the Carson Range and irrigation practices have saturated nearly all the valley floor such that ground water is at or near land surface and artesian or flowing wells are common. On the east, the land rises more abruptly from the lake area and the amount of surface water from streams, and consequent lack of irrigation,

coupled with low precipitation produces an area relatively poor in ground water resources. Additionally, the aquifer material east of Washoe Lake is commonly fine-grained alluvium or fractured rock in contrast with the western side's coarse to medium grained, granitic sands and gravels. Aquifer materials beneath Washoe Lake are primarily fine grained immediately beneath the lake (0-30 ft or 0-9 m), remain fine-grained in the southern area, but become coarser in the north (Dighem, 1994). On the western side of the valley, ground water moves from west to east, discharging at or near the lake. On the eastern side, moves from east to west and discharges at or near the lake.

A small geothermal system discharges ground water of moderate temperatures on the western side of Washoe Valley at Bowers Mansion Park. Additionally, a few domestic water wells in southwest New Washoe City have had rising ground-water temperatures in the last ten to twenty years. This rise in temperature is most likely due to water level declines caused by the capture of the colder, ambient ground water by the 1,000 or so domestic wells in New Washoe City. It may also be the result of a small geothermal system with ground-water discharges that now rise closer to the surface. Hydrothermal alteration of volcanics is most likely cause of elevated concentrations of iron, manganese and fluoride in New Washoe City and Washoe City.

BASIN FILL AQUIFER

Aquifer thickness' are determined from drill logs and/or geophysical techniques. Washoe Valley, has more than a thousand wells, but most are relatively shallow and concentrated. Therefore, this study relied primarily on geophysics in determining aquifer thickness and areal extent: works from Tabor and Ellen, from Peterson, and interpretations from the Dighem data. Figure 7 shows alluvial thickness for portions of

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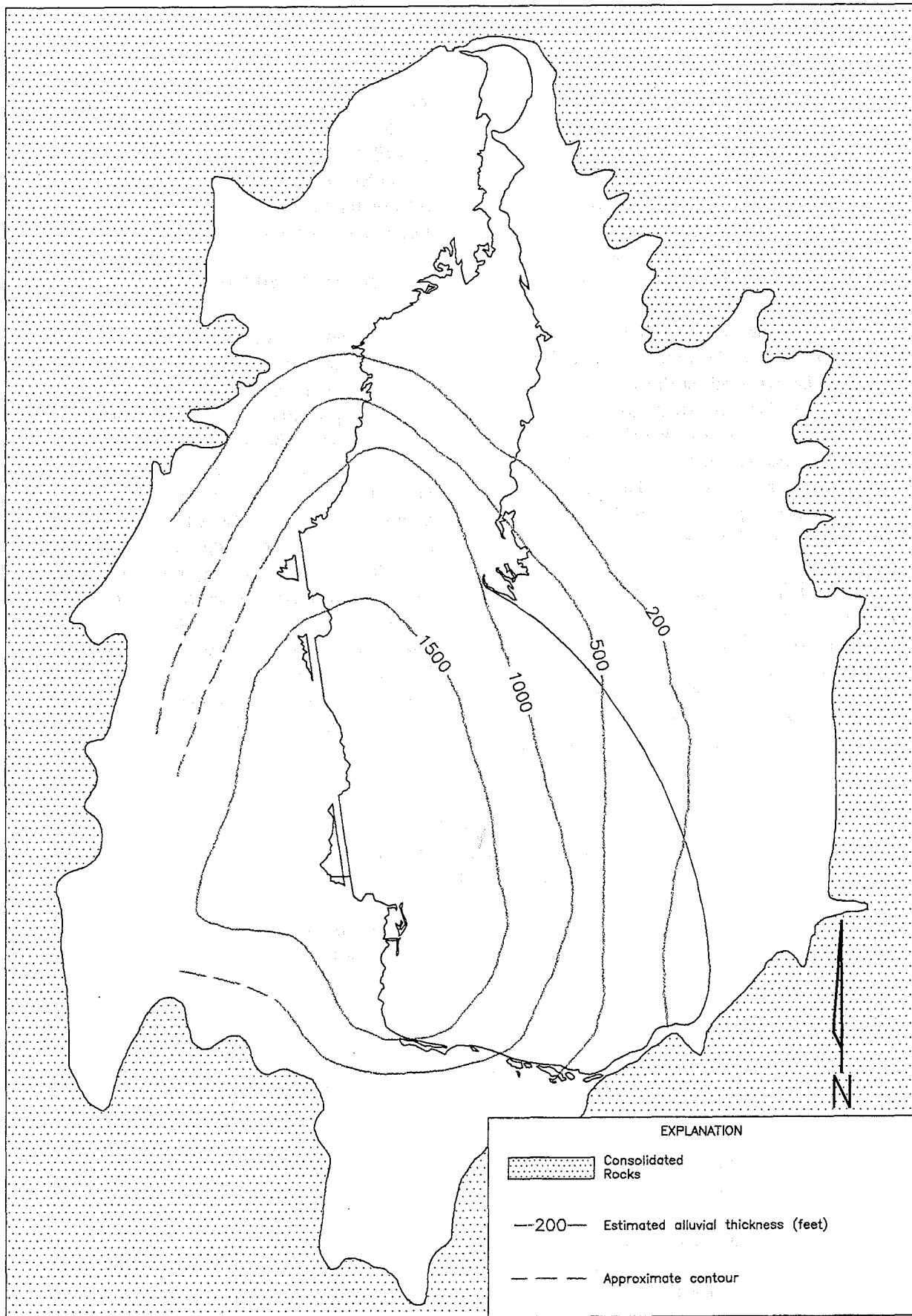
FIGURE 7
ALLUVIAL THICKNESS MAP FOR WASHOE VALLEY

EXPLANATION

Consolidated
Rocks

—200— Estimated alluvial thickness (feet)

— — — Approximate contour

SCALE: 1" = 5000'

Washoe Valley based on geophysical and well log interpretations by Peterson (1993, 1994). It indicates that the deepest alluvial deposits are in the south central portion of the valley and that the alluvium thins to approximately 200 ft (61 m) in the northern and eastern portions of the basin. In the northern portion of the valley, the total field magnetics data indicate that the Kate Peak formation (andesites) is relatively shallow and is inferred to be approximately 200 ft (61 m) below land surface. The upper portions of this formation are most likely well fractured and weathered and can be treated as a porous medium, albeit with a low hydraulic conductivity. This has been documented in a production well constructed west of Washoe City (Widmer, 1994b).

Transmissivities of the alluvial basin are the products of thickness and hydraulic conductivity. Accurate values for these parameters are typically derived from pumping tests and few tests have been performed in Washoe Valley. However, there are examples of water production from

wells in the valley that suggest hydraulic conductivities may range from 1 to 15 ft per day (0.3-4.6 m/d) or greater. In this study, estimates for hydraulic conductivity are mostly based on the Dighem data, further discussed in the model simulation section.

GROUND WATER BUDGET

Water budget components describe the quantity and movement of surface and ground waters within the area of study, including precipitation, well pumpage, ET and any interbasin inflows or outflow from the study area. These quantities vary from year to year and estimates of these components are usually within an order of magnitude. A water budget can provide the basis for the understanding, or the conceptual model, of the ground water flow system. For purposes of this current study, Arteaga's 1984 (his table 3) report provided a hydrologic budget that is used as a starting point to develop ground-water budget quantities and is depicted in table 1.

Table 1
Hydrologic budget for conditions as of 1980
(from Arteaga and Nichols, 1984)

Budget Item	Estimated Quantity (acre-ft/year)
INFLOW	
Water yield	26,000
Precipitation	22,900
Imported surface water	4,000
Total inflow (rounded)	53,000
OUTFLOW	
Lake surface evaporation	23,000
Evapotranspiration	27,300
Stream outflow	2,300
Exported surface water	700
Consumptive use of domestic pumpage	100
Total outflow (rounded)	53,000

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This table shows the total water budget of 53,000 acre-feet (65 hm³) estimated for 1980 in Washoe Valley of which 26,000 acre-feet (32 hm³) is water yield. Arteaga and Nichols discuss the term "water yield" as essentially the ground and surface water that emanates at canyon mouths from upland watersheds to the valley floors. These waters are derived from precipitation, largely mountain front. In a particular watershed, if the surface water component is known (as estimated from a stream gaging station at the canyon mouth) the ground-water component can be determined as the volume difference between the water yield and surface water values. Precipitation is that upon the valley floor. The imported surface water is an out-of-basin creek diversion into Washoe Valley (Galena Creek). Stream outflow is Steamboat Creek and the exported surface water is a creek diversion to Carson City and Virginia City.

Natural Ground Water Recharge from Precipitation

Within the watersheds, snowmelt dominates the process of ground-water recharge. Since most of the snowpack is found in the mountains, most of the natural ground-water recharge occurs above the valley floor. This is particularly true in the Virginia Range. Basinwide, the majority of recharge occurs in the Carson Range and can be considered a component of Arteaga's estimated water yield. Therefore, an adjustment to the water yield was made in order to estimate the ground-water component. This was done by assuming that 25 per cent of the water yield figure constituted the ground-water component (and further adjusting it through computer modeling methods). This initial value was 6,500 acre-feet (8 hm³). In this report the ground-water component of the water yield is termed mountain front recharge from the mountain block to the valley floor.

In terms of magnitude, recharge on the valley floor from the mountain front or winter rains

occurs primarily along the eastern mountain front of the Carson Range, though it is recognized that lesser amounts do occur throughout the valley. From the precipitation record it is estimated that 75 per cent of the annual precipitation occurs during the winter. During that period an amount of precipitation satisfies soil moisture deficits, runoff and evaporation (a small amount of evaporation occurs relative to summer evaporation). The residual contributes to recharge. Generally, precipitation rates decrease from west to east in Washoe Valley due to orographic and rain shadow effects. Precipitation records are sparse for Washoe Valley. One long-term station (1968 to present) exists along Franktown Road on the west side. To estimate precipitation on the east side of the valley, a long term station on the east side of the South Truckee Meadows was used (Olson, 1994). Based on these two precipitation records, linearized precipitation rates for the entire valley were made (Peterson, 1994): 23 in. (58.4 cm) on the westside decreasing to 11 in. (28 cm) on the eastside of the valley.

To account for valley-floor recharge from precipitation, the Maxey-Eakin method (Maxey and Eakin, 1949) was applied. This method, whereby recharge to the ground water system is a function of elevation and precipitation, was developed for reconnaisance estimates of ground-water recharge for areas in southeastern Nevada. This methodology can be used as a first estimate of recharge in western Nevada and can give good approximations in some basins in southern Washoe County (Berger, and others, 1996). The method assumes that a percentage of the precipitation becomes ground-water recharge as shown in table 2. Applying this methodology, recharge values of 7 to 2 in. (18 to 5 cm) were applied linearly from the Carson Range front (Franktown Road) to the western edge of Washoe Lake, based upon the precipitation record for Washoe Valley. This resulted in approximately 2,400 acre-feet (3 hm³) of

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ground-water recharge over the entire western basin exclusive of the lake. Records indicate that most of this precipitation occurs in the winter. Because of the relatively smaller amount of precipitation on the eastern alluvial side of the basin, no recharge was recognized in this area.

Table 2
Maxey-Eakin Recharge Method

Precipitation (inches)	Recharge (percent)
10-12	3
12-16	7
16-20	15
> 20	25

Recharge from Irrigation

Flood irrigation is the primary application method of irrigation, at least on the western side of the valley. In his 1967 report, Rush estimates that in 1965, irrigated lands accounted for 3,600 acres (1,458 hectares) on the western side. It is recognized that as much as 25 per cent of these waters can percolate below the root zone and recharge the ground water system (Handman, 1990), however, this may be more a rule of thumb assumption than what actually occurs. Given several conversations with local irrigators, it is assumed, in this investigation, that most irrigated lands receive 2.5 acre-feet per acre of water, of which 25 per cent (0.6 acre-feet) percolates below the root zone. This is approximately what Rush reported. The total application rate may be the water right adjudication that ranges up to 4.5 acre-feet per acre, but it is assumed that excess water, over and above the 2.5 acre-feet application, runs off to be used on other lands or re-enters ditches and streams (Guitjens, and others, 1978). If 3,600 acres (1,458 hectares) are irrigated in this fashion (Rush, 1967), approximately 2,200 acre-feet (2.7 hm^3) per year recharges the ground water system from these assumed irrigation practices.

Evapotranspiration

This dynamic process is difficult to estimate as so many variables are involved. Different plant types consume different rates of water and weather influences the availability of water. Since the dominant force in ET is wind (Brutsaert, 1991), and Washoe Valley has this resource in abundance, one would expect higher ET rates than in other western Nevada basins. However, measurement studies need to be undertaken in order to define rates for Washoe Valley.

It is assumed that some volume of ground-water discharges to Washoe Lake and evaporates. Evaporation from Washoe Lake and peripheral wetlands, as compared to Lake Tahoe or Pyramid Lake, should be greater in that Washoe Lake is shallow, therefore warmer, and that the frequency of wind action is probably greater. Wind is the major driving action of ET processes. And because Washoe Valley has anomalously high winds, evaporation rates should be higher than other nearby valleys, perhaps by 10 per cent. Records from Washoe County's weather station in the South Truckee Meadows indicate that pan evaporation was 57 in. in 1987 (Water Research and Development, 1988). Using this as an approximation, the evaporation rate off Washoe Lake may approach 60 in. (152 cm). With an average lake elevation of 5,027 ft (1,533 m), there is a surface area of 5,500 acres (2,228 hectares) according to Rush (1972). Given a range of evaporation rates from 50 to 60 in. (127 to 152 cm), evaporation from Washoe Lake water could range from 22,900 to 27,500 acre-feet per year (28.2 to 33.9 hm^3). This value is only partially satisfied from ground-water discharge, the major component being surface water flowing to the lake.

Records at the CDB weather station indicate that alfalfa fields evapotranspire an average of 44 in. (112 cm) of water per year (Water Research and Development, 1987). Phreatophytes (plants with the root zone

immersed in water much of the year) are indigenous to the wetlands near the lake. These plants are assumed to evapotranspire at rates between the range of alfalfa (at least 44 in. or 112 cm) and an open water body (60 in. or 152 cm), or at an estimated rate of 48-52 in (122-132 cm). Pasture crops such as grass is assumed to evapotranspire at a rate of 24 in. (61 cm) per year. Finally, The eastern side of Washoe Valley is naturally vegetated with different sages, rabbitbrush, greasewood and other similar plant types. For this study, these plants are estimated to transpire at 10 in. (25.4 cm) per year (Nichols, 1994).

The estimate of Et from ground water is a formidable problem to solve as precipitation is directly involved in the total ET process. Compounding this is that some areas are also irrigated. A simplified way is to estimate potential ET, using rates described above, and subtract the precipitation from this in order to derive ET discharge from ground water. In irrigated areas this approach becomes one more of academics than of practical usage. In areas where precipitation matches estimated ET, such as east Washoe Valley, it is assumed that little or no ET occurs from the ground water system. However simplified, a cursory attempt is made in table 3 to determine ET from the ground water system in order to complete a ground-water budget. This table shows the water deficit (in column ET-Precip) in terms of ET needs not satisfied from precipitation

and irrigation. This volume of 6,930 acre-feet (8.5 hm³) is assumed to be from ground-water discharge.

Based upon these assumptions, it is apparent that the phreatophytic lands are the major dischargers of ground water with respect to other vegetation types in Washoe Valley. The area figures were derived from Rush's report, corrections to and estimates from his figure 7 and ET rates as discussed above. This figure also indicates that significant ground-water recharge occurs from irrigation practices. Note that the precipitation column includes irrigation on cropland and pasture.

Pumpage
Rush estimated that during 1965, 1,000 AF (1.2 hm³) of consumptive ground-water pumpage occurred for irrigation and domestic needs (see Rush, 1967, page 24). Generally, irrigation in Washoe Valley relies on surface waters such that pumping only supports irrigation needs during below average water years. This means that most of the ground-water rights are secondary to surface waters rights. This process has continued with time as more irrigators have been permitted with secondary ground-water rights. From the State Engineer's Hydrographic Basin Summary for ground water usage (1983), it is estimated that 6,660 acre-feet (8.2 hm³) per year of irrigation rights were permitted of which 3,570 acre-feet (4.4 hm³) are secondary.

Table 3
Estimated ET from the Ground Water System
(acre-ft/year)

Vegetation Type	Area (acres)	Precip (ft)	ET Rate (ft/year)	ET-Precip (ft/yr)	GW ET (AF/yr)
forested area	1000	2.0	2.0	0	0
cropland (w/irrigation)	3500	4.2	3.7	-0.5	0
pasture (w/irrigation)	1300	2.7	2.0	-0.7	0
phreatophyte zone (west)	1500	1.5	4.2	2.7	4050
phreatophyte zone (east)	900	1.0	4.2	3.2	2880
east Washoe above lake	2800	0.8	0.8	0.0	0
Total	11,700				6,930

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Ground-Water Budget Summary

To better understand the ground-water flow system and to visualize a conceptual model, a ground-water budget, based on 1965 conditions, is presented in table 4. This budget is a cursory estimate and any of the components could be off by 50 per cent. The 3,170 acre-feet (3.9 hm^3) component of discharge to Washoe Lake and wetlands is estimated by difference, but is reasonable given that the estimated evaporation from the lake ranges from 22,900 to 27,500 acre-feet (28 to 33.9 hm^3). The budget was used as a starting point for the steady state modeling that represents conditions as of 1965.

SIMULATION OF GROUND-WATER FLOW

Conceptual Model

Conceptually, modeling the ground-water flow system of Washoe Valley is rather straightforward. Most ground water occurs as recharge from the mountain blocks and moves towards the lake. Irrigation practices in the summer and precipitation in winter adds to the ground-water system. Discharge of ground water occurs in the form of ET at the periphery of the lake, at the wetlands, and at near shore croplands; some ground-water pumpage; and direct discharge to the lake.

Washoe Lake is thought to have formed after volcanic flows essentially dammed the northern end of the valley. As a result, this basin is normally fully saturated with ground water such that a portion of surface water runoff is actually rejected ground water recharge. This surface water ends up in the lake. The lake level should also be thought of as a reflection of the water table. During drought, the lake stage responds as input from annual runoff decreases, but ground-water levels still appear to remain high and discharge to the lake continues. The question arises as to whether Washoe Lake discharges to ground water aquifers. This would occur only where significant ground-water pumpage is near the lake, which is the case in New Washoe City (see figure 8).

This current study assumes that there is a dynamic interaction in that water can move into or out of the lake. As stated, the lake is supported by surface water from streams and irrigation, precipitation and most likely ground water discharges. There is also a discharge from the lake in the form of Steamboat creek, evaporation and perhaps discharges back to the ground-water system. Herein lies the difficulty in the modeling process: how to treat the lake numerically as it not only represents the ground water system, but is also controlled by surface water runoff.

Table 4
Estimated Ground-Water Budget (1965)
(acre-ft/yr)

Component	Rate
Mountain Front Recharge	6,500
Valley Precipitation Recharge	2,400
Irrigation Recharge	2,200
Evapotranspiration	-6,930
Discharge to lake and wetlands (estimated by difference)	-3,170
Pumpage	-1,000
Balance +/-	0

PHREATOPHYTE AREA

WETLANDS AREA

NORMAL LAKE
AREA BOUNDARY

LAND SURFACE

▽ WATER SURFACE
ELEV=5027'

WATER TABLE

LAKE BED

DIRECTION OF
GROUNDWATER
FLOW, TYPICAL

A

18

LAND SURFACE

LAKE AREA
DURING DROUGHT

▽ WATER SURFACE
ELEV=5022'

WATER TABLE

LAKE BED

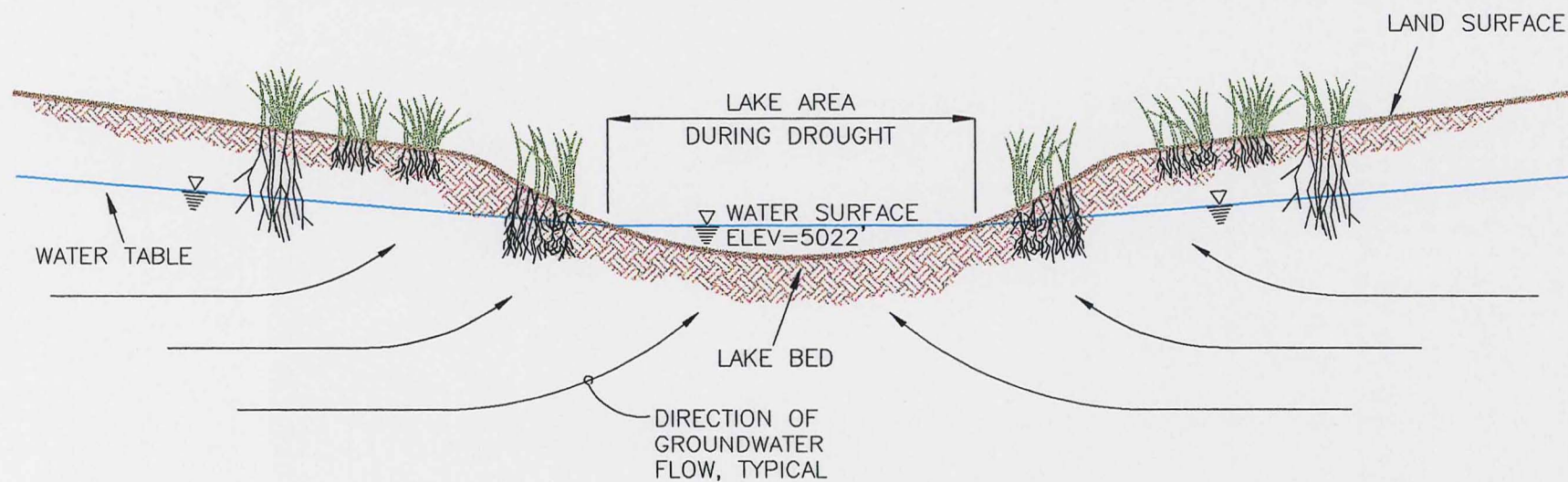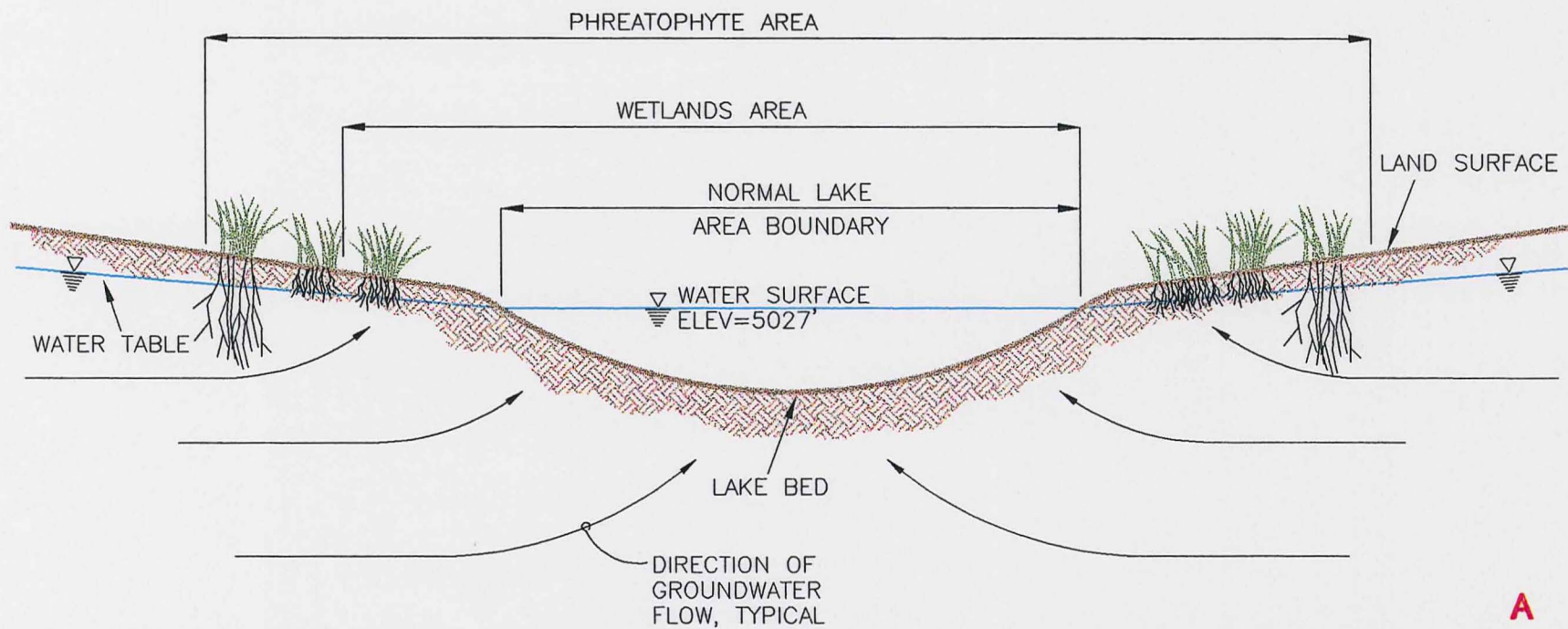DIRECTION OF
GROUNDWATER
FLOW, TYPICAL

B

FIGURE 8
AQUIFER/LAKE DISCHARGE FLUX RELATIONSHIP
NOT TO SCALE (VERTICAL EXAGGERATION)

Mathematical Model

The mathematical model used to analyze the ground-water flow system in Washoe Valley is the USGS's modular, three-dimensional model, **MODFLOW** (McDonald and Harbaugh, 1988). MODFLOW has been used successfully in ground-water modeling problems for the last 15 years. It is recognized as an industry standard. This model, through finite difference techniques, solves the Laplacian equation for ground-water movement

$$\partial/\partial x(K_{xx}\partial h/\partial x) + \partial/\partial y(K_{yy}\partial h/\partial y) + \partial/\partial z(K_{zz}\partial h/\partial z) - W = S_s\partial h/\partial t,$$

where K_{xx}, K_{yy} are the hydraulic conductivities in the principal horizontal directions, in length per unit time; K_{zz} is t he hydraulic conductivity in the vertical direction, in length per unit time; h is hydraulic head, in length; W is the volumetric flux of recharge or discharge per unit volume (source or sink terms), in 1/time; S_s is specific storage, in 1/length; t is time; and x, y, z are Cartesian coordinates aligned along the major axes of hydraulic conductivity.

According to Thomas (and others 1989), this model will solve the ground-water flow problem (the distribution of head and the mass balance) given the following information;

1) hydraulic properties,
2) the shape and physical boundaries,
3) the flow conditions at the boundaries, and
4) the initial conditions of the ground – water flow system and water levels.

The three main limitations that constrain the model results (Harrill, 1982) are;

1) model simplifications of the physical complexities of the flow system,

2) the lack of data or distribution of field data, and
3) the nonuniqueness of ground-water modeling.

In other words, the validity of the results is dependent upon the sufficiency of data and the correct conceptual understanding of the physical system as well as the proficiency of the modeler. For more information, the reader is directed to any number of ground-water modeling texts such as Anderson and Woessner's APPLIED GROUNDWATER MODELING, Academic Press, Inc., 1992.

Model Grid Configuration

Model Area

The model peripheral boundaries were established at alluvial/mountain block interfaces (see figure 9). Along the western front, alluvial material is abruptly interfaced with granodiorite. Along the eastern, southern and northern boundaries the alluvial deposits adjoin mostly volcanic units and lesser metasediments and granodiorite units. In keeping with Peterson's models, the grid cells are kept constant at 1,000 ft (304.8 m) per side. There are 1,218 cells of which 918 are active (75 per cent). The active cells represent 33 mi^2 (85.5 m^2) of Washoe Valley. The lower left cell center has State Plane coordinates 141152 (northing) and 1628613 (easting). Inactive cells generally represent the mountain block areas. However, peripheral active cells do represent fractured rock in some areas.

Model Layers

The model has two layers (see figure 9), the first simulating unconfined conditions, the lake, areas dominated by ET and domestic well pumpage. The second layer represents the deeper flow system within the alluvial aquifer. There are equal numbers of active cells in both layers. Layer 1 extends from land surface to a base elevation of 4,920 ft (1,500 m) above mean sea level throughout the modeled area making for easier computa-
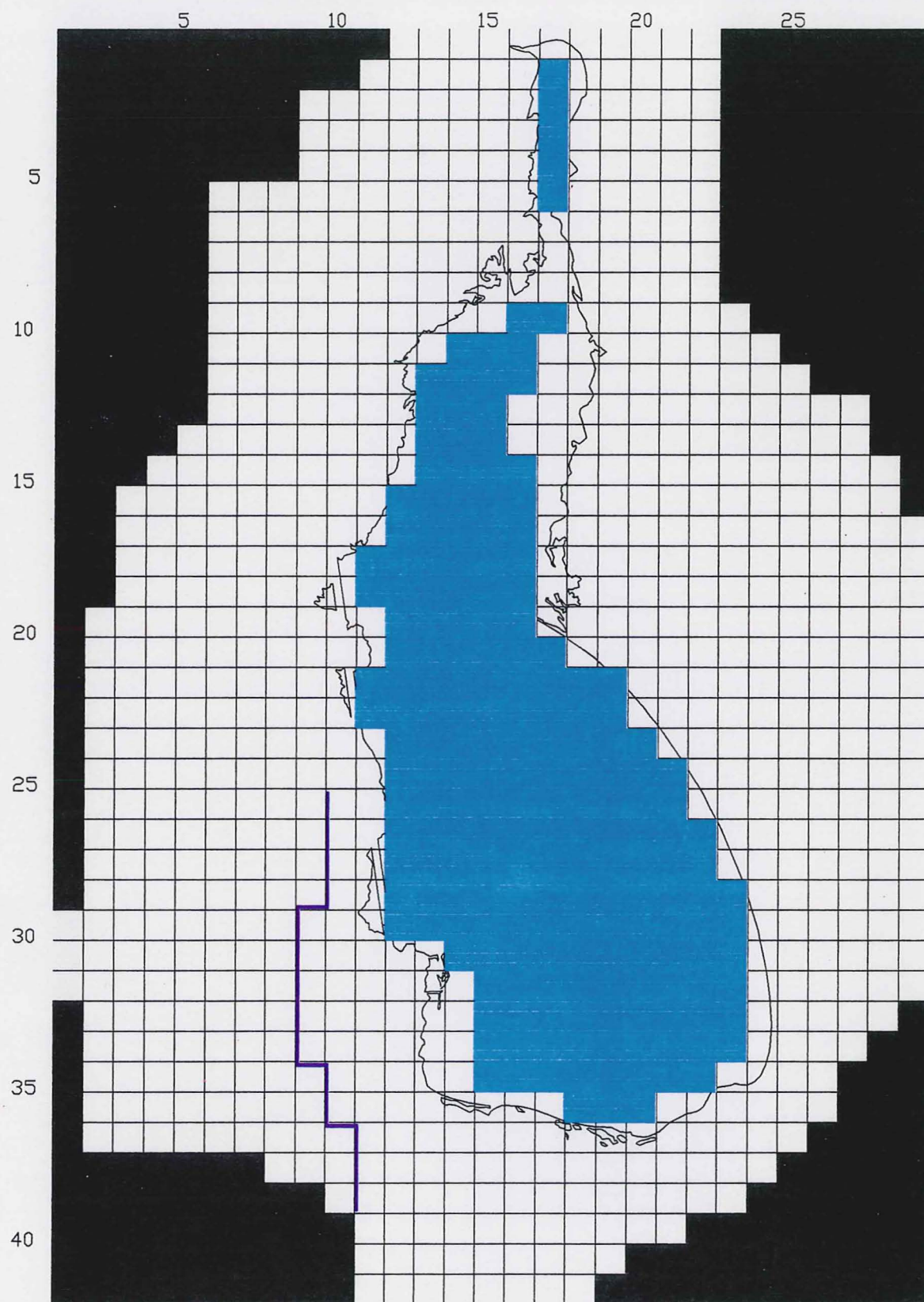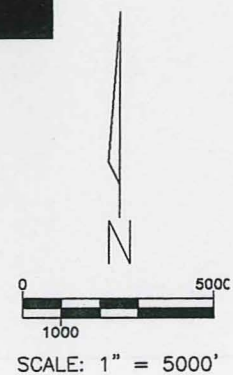
FIGURE 9
MODEL GRID CELLS AND BOUNDARIES

LEGEND

GENERAL HEAD BOUNDARY

INACTIVE CELL

FAULT STRUCTURE

20

SCALE: 1" = 5000'

tions. Review of well drilling logs suggests that a semi-impermeable layer exists approximately 100 ft (30.5 m) below the valley floor (elevation 4,920 ft or 1,500 m amsl) throughout much of the model area (Peterson, 1994), however there is insufficient evidence to suggest that it is basin wide. Therefore, this model does not recognize this clay layer explicitly, but rather implied it in the assignment of vertical conductance. All layers contain representations of fractured rock material at the model boundaries. The thickness of layer 1 increases towards the basin margins--from 100 ft (30m) thick at the lake to its maximum of 250 ft (76m) at the margins. Layer 2 has an upper elevation boundary at the 4,920 ft (1,500 m) level and a thickness that varies from 900 ft (274 m) at the valley center, thinning to 250 ft (76m) at the margins. This layer also thins to about 250 ft (76m) thick northward from the central portion of the basin. The bottom of layer 2 corresponds to the approximate depth to granitic bedrock.

Treatment of the Lake

With MODFLOW, the lake can be treated as a sink (or drain), as a fixed head (constant source or sink of water), or as an ET surface. Actually, the lake should be treated by all three methods simultaneously depending on the lake level as it is always in a constant state of flux. This investigation treated the lake in two ways. First as a general head boundary that could be adjusted semi-annually based on USGS records of lake-stage. While this is somewhat satisfactory when the lake is mostly full, it fails to satisfy when the lake is dry or nearly dry. A second method is to replace the general head cells with an ET surface as the lake dries. Both concepts where applied and will be reviewed in the "Transient Model" section. The steady state model used a general head boundary for the lake based on the assumption that over the long term, an average lake level is maintained.

Steady State Model
Boundary and Initial Conditions

No flow boundaries (inactive cells) were placed at the model perimeter to represent mountain block areas of the Carson and Virginia Ranges (see figure 9). These boundaries were adjusted frequently and resulted in a larger, active cell model than previous efforts. An effort was made to include rock aquifer units where well data or other evidence existed.

Figure 9 shows the cells representing Washoe Lake during average water years such as during 1965 (Rush, 1967). The General Head Boundary (GHB) is used in the steady state model whereby the lake has a prescribed head elevation of 5,027 ft (1,533 m). After reviewing the records, this elevation is estimated as the average lake level during Rush's investigation (Rush, 1967). This value also appears appropriate after reviewing USGS records of the lake level taken from 1963 to 1997. The GHB maintains this head such that water can move freely between the lake and the unconfined aquifer, depending on the gradient. This type of boundary makes use of a conductance term, though not physically based, and can be thought of as an estimation of the permeability of (or leakance through) the lake bed sediments (McDonald and Harbaugh, 1988). The conductance is calculated as the product of the vertical hydraulic conductivity and the cell area divided by the thickness of the lake bed sediments per cell. The lake bed sediments are assumed to be silty clay such that the vertical permeability was estimated as 0.1 ft/day (0.03 m/day). The value of conductance was calculated at 10,000 ft^2/day (930 m^2/day) with the thickness of the conductant material estimated at 10 ft (3m).

A water well survey conducted by Rush (1967) measured water levels. These water levels serve to represent the steady state conditions of the water table surface, (layer 1) in Washoe Valley. The lake level also

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serves as a potentiometric surface. Because of the scarcity of water level data representing layer 2, detailed calibration attempts on layer 2 water levels were not made. It must be kept in mind that land surface elevation estimates were accurate to within 20 ft (6 m), or more, which also represents the accuracy of the water table elevations of that time.

Hydraulic Properties

The aquifer material simulated in this investigation is segregated into two types, alluvium and fractured rock. Fractured rock is highly anisotropic and usually has poorly known hydraulic properties. In this investigation an attempt was made to include fractured-rock aquifers, as they are prevalent, especially on the eastern side of Washoe Valley. From work completed in areas of southern Washoe County, fractured rock aquifers can conduct water in the range of 0.1 to 2 ft/day (0.03-0.6 m/day). Fractured rock aquifers in Washoe Valley can be subdivided into hard, competent granodiorite and metavolcanics or well-fractured and altered volcanics. The altered volcanics can be relatively permeable compared to the granodiorites. This study treats the fractured and altered volcanics as low-permeable alluvial deposits because sufficient evidence indicates that they behave

as a porous medium continuum (various pumping tests conducted by Washoe County). Hydraulic conductivity was initially determined by interpreting the electromagnetic data as described in the "Geophysical Survey" section. This interpretation was cursory because it was dependent on borehole geophysical data and pumping test data that is currently lacking. Electrical resistivity was related to hydraulic conductivity as shown in table 5.

This interpretation was the result of incomplete studies conducted in the South Truckee Meadows comparing geophysical data with borehole lithologic logs and aquifer parameter estimation techniques. These values compare well with published data (Walton, 1984). The areal extent of these resistivities (or hydraulic conductivities) is well mapped in the Dighem data (see figure 5). Through the calibration process, conductivity was adjusted. Layers one and two are shown in figures 10 and 11, respectively. Comparing these with figure 5 shows good agreement. The 56,000 Hz and the 7,200 Hz data were used for layer 1 and the 7,200 Hz and the 900 Hz data were used for layer 2. The maximum reliable depth of geophysical penetration was approximately 400 ft (122 m) where resistivities are

Table 5

Electrical Resistivity to Hydraulic Conductivity Conversions

Porous Media	Resistivity (Ohm-m)	K_{hor} (ft/day)	K_{vert} (ft/day)
clay	10	<1	0.05
mostly clay	<20	1-2	0.05-0.1
mostly silty	20-40	2-6	0.2-0.6
mostly sands	40-80	3-15	0.3-1.5
sandy gravel	60-100	5-25	0.5-2.5
gravel	80-120	10-50	1.0-3.0
altered volcanics	80-150	1-2	0.05
fractured rock	>150	0.25-0.50	0.0025

22
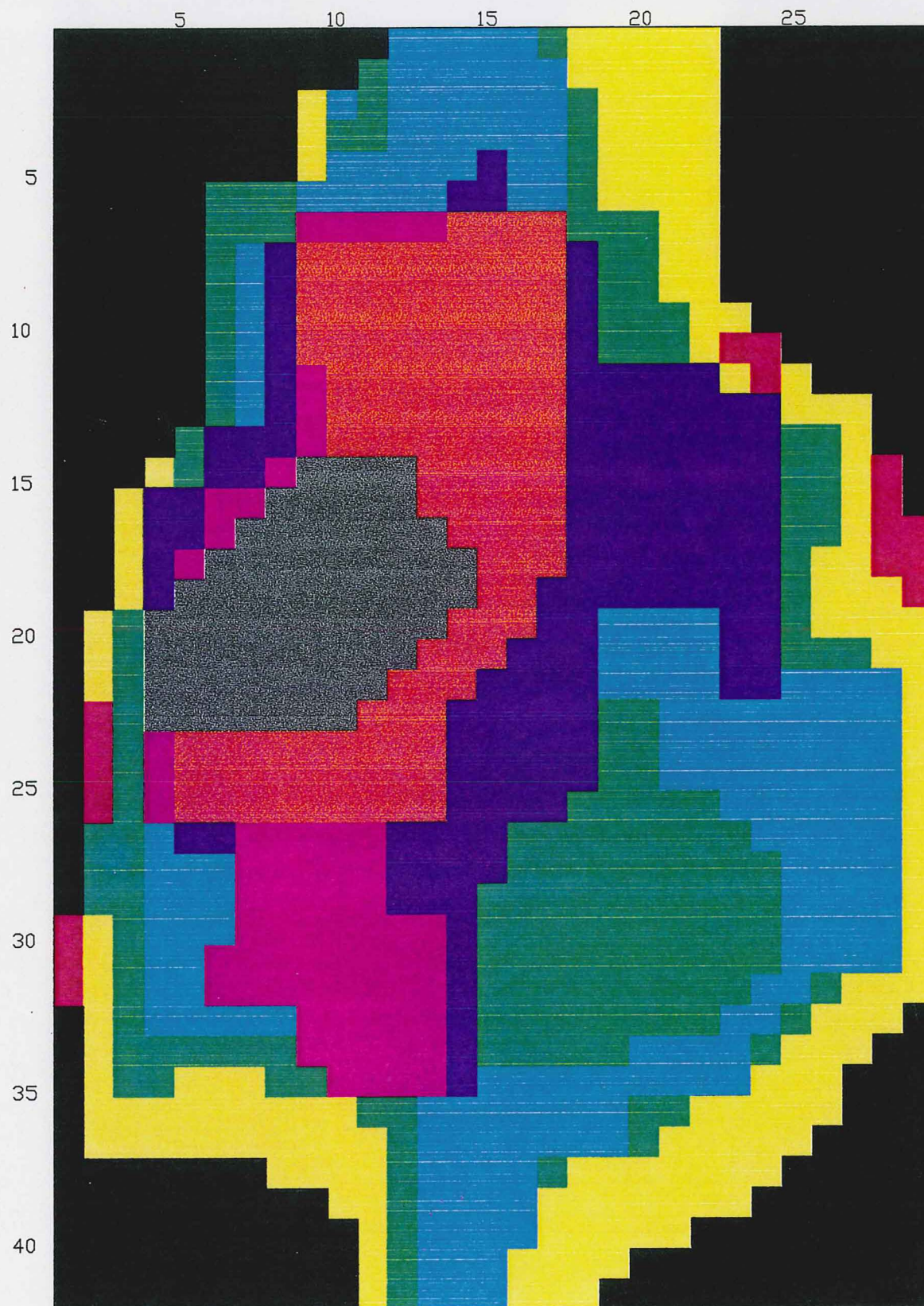
FIGURE 10
CALIBRATED HYDRAULIC CONDUCTIVITY FOR LAYER 1

LEGEND

0.25	2	7	
0.5	3	15	
1	5	23	

VALUES INDICATED ARE FT./DAY

SCALE: 1" = 5000'
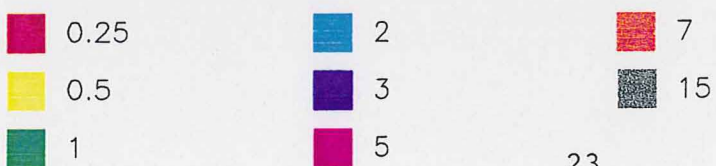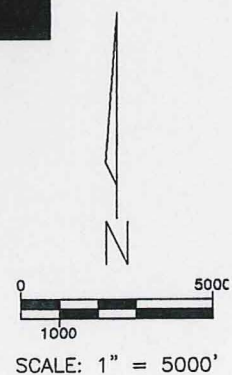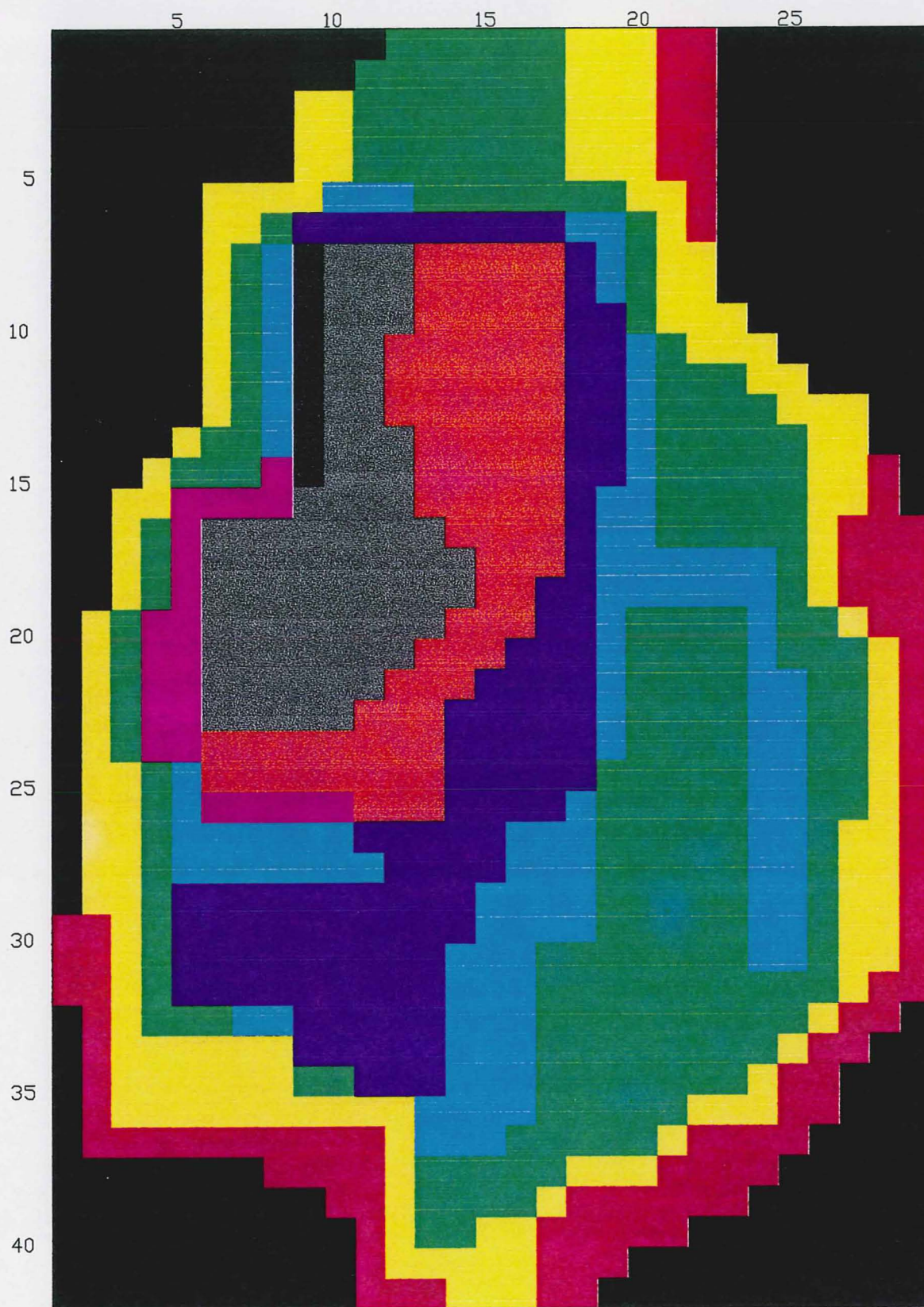
FIGURE 11
CALIBRATED HYDRAULIC CONDUCTIVITY FOR LAYER 2

LEGEND

🟥 0.25	🟦 2	🟥 7				
🟨 0.5	🟪 3	⬛ 10				
🟩 1	🟪 5	▦ 15				

VALUES INDICATED ARE FT./DAY

24

SCALE: 1" = 5000'
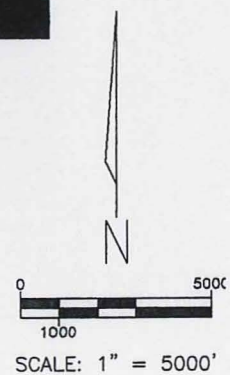
>80 ohm.m. Where resistivities are <40 ohm.m, penetration was ≤200 ft (61 m).

Leakance, Storativity and Impermeable Boundaries

MODFLOW requires that vertical conductance be calculated for each cell between layers. This was done by assigning a value of approximately 10 per cent of the horizontal hydraulic conductivity as the vertical hydraulic conductivity (see table 4) and then dividing this value by the layer midpoint distances (McDonald and Harbaugh, 1988). The areal distributions are shown in figure 12. Storage values were based on a literature review, modeling efforts in other basins of Washoe County and the geophysical data (Dighem, 1994). Layer 1 is unconfined. The specific yield values range from 0.01 for fractured rock to 0.15 for sands and gravels. It is assumed that layer 2 is confined and storativity values range from 10^{-5} to 10^{-6}. Figures 13 and 14 illustrate the values for layers one and two, respectively.

A question arises about the validity of using specific yield values for layer 1 beneath the general head boundary. These specific yield values range from 0.10 to 0.15. With these specific yield values, changes in storage within these cells will buffer the interaction between the lake and the aquifer. If storativity values were used, ranging from 0.001 to 0.0001, the physical effects of the lake-aquifer interaction might be better realized. To test for this sensitivity, storativity values were used beneath the general head boundary. There was essentially no change in the results.

There is evidence from previous geologic mapping (Trexler, 1977) that a near surface fault may impact ground-water movement in the southwest of Washoe Valley. This fault follows a northward trend from the Carson Range into the valley floor (columns 9 and 10). Flowing wells are recognized west of this fault trace. During the calibration process, this area was sensitive to mountain front recharge rates applied at the model boundaries. The use of MODFLOW's Horizontal Flow Barrier package to simulate the assumed impermeable nature of the fault helped to desensitize this area (see figure 9). The Horizontal Flow Barrier is a low conductance value applied to individual cell walls resulting in reduced flux from one cell to the next.

Recharge

A major source of ground-water recharge to Washoe Valley occurs within the Carson mountain block largely from snow-melt processes. As discussed previously, this recharge and stream-flow enters the valley at the mountain front (see the explanation of water yield in the GROUND-WATER BUDGET section). The ground water that flows into the alluvial system is simulated in the flow model by the use of wells at these boundaries. Figure 15 shows the location of these "mountain front" wells. Mountain front wells were included in both layers in order to facilitate model stability at these boundaries, however, there is some question about the physical reality of this practice. These fluxes were initially derived from Arteaga's efforts (Arteaga, 1982) and were later adjusted during the calibration effort. Arteaga derived water yield fluxes for each sub-basin within the Carson and Virginia Ranges. An initial value of 25 per cent of the water yield was used for the mountain front wells, located at and near the respective canyon mouths of individual drainages.

Recharge wells were also located within layer 2 and beneath New Washoe City. This flux into the model domain is the result of an ongoing study by Washoe County (Kanbergs, 1997) and is discussed below. McKay provides evidence for a small geothermal plume in the extreme south end of New Washoe City (McKay, 1989). This was noted in the airborne geophysical survey, though not displayed in figure 5, as a low resistivity unit (< 10 ohm.m). Recently, there Was a substantial increase in the water
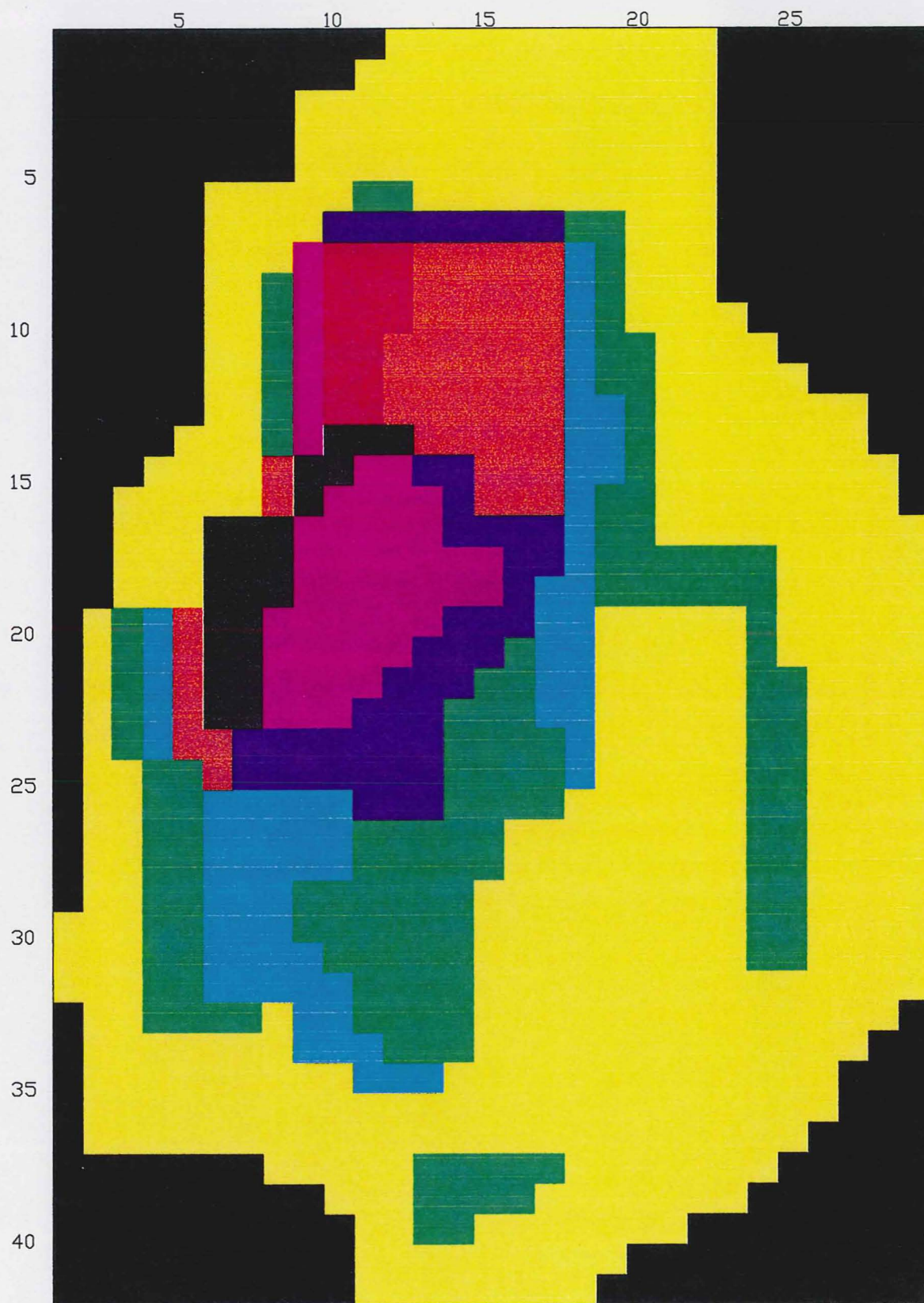
FIGURE 12
VERTICAL CONDUCTANCE

LEGEND

0.0002		0.0025		
0.0004		0.0035		
0.0005		0.0044		
0.001		0.006		

VALUES INDICATED ARE FT./DAY

26

SCALE: 1" = 5000'
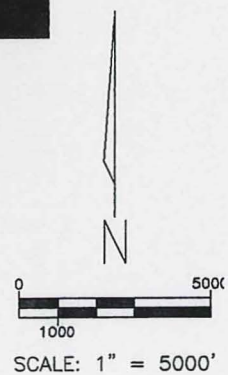
FIGURE 13
SPECIFIC YIELD VALUES FOR LAYER 1

LEGEND

- 0.05
- 0.10
- 0.15
- 0.20
- 0.25

SCALE: 1" = 5000'

27
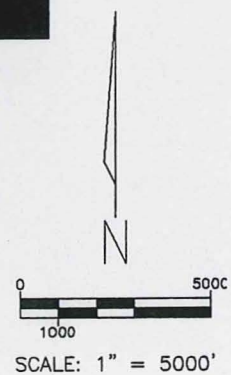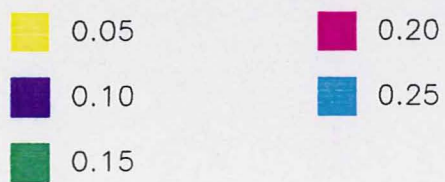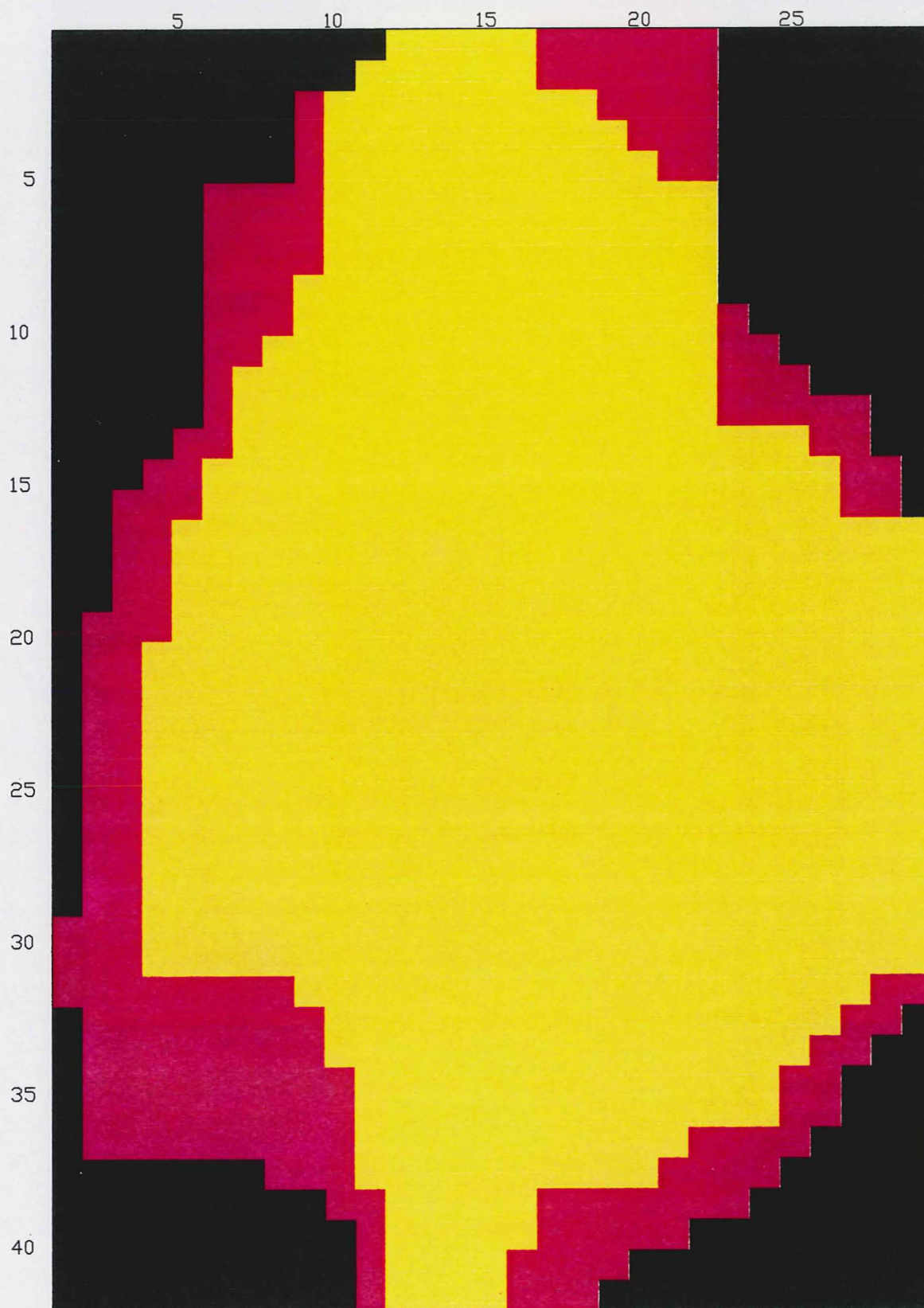
FIGURE 14
STORATIVITY FOR LAYER 2

LEGEND

10^{-6}

10^{-5}

INACTIVE CELL

28

N

SCALE: 1" = 5000'
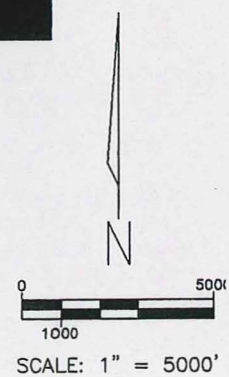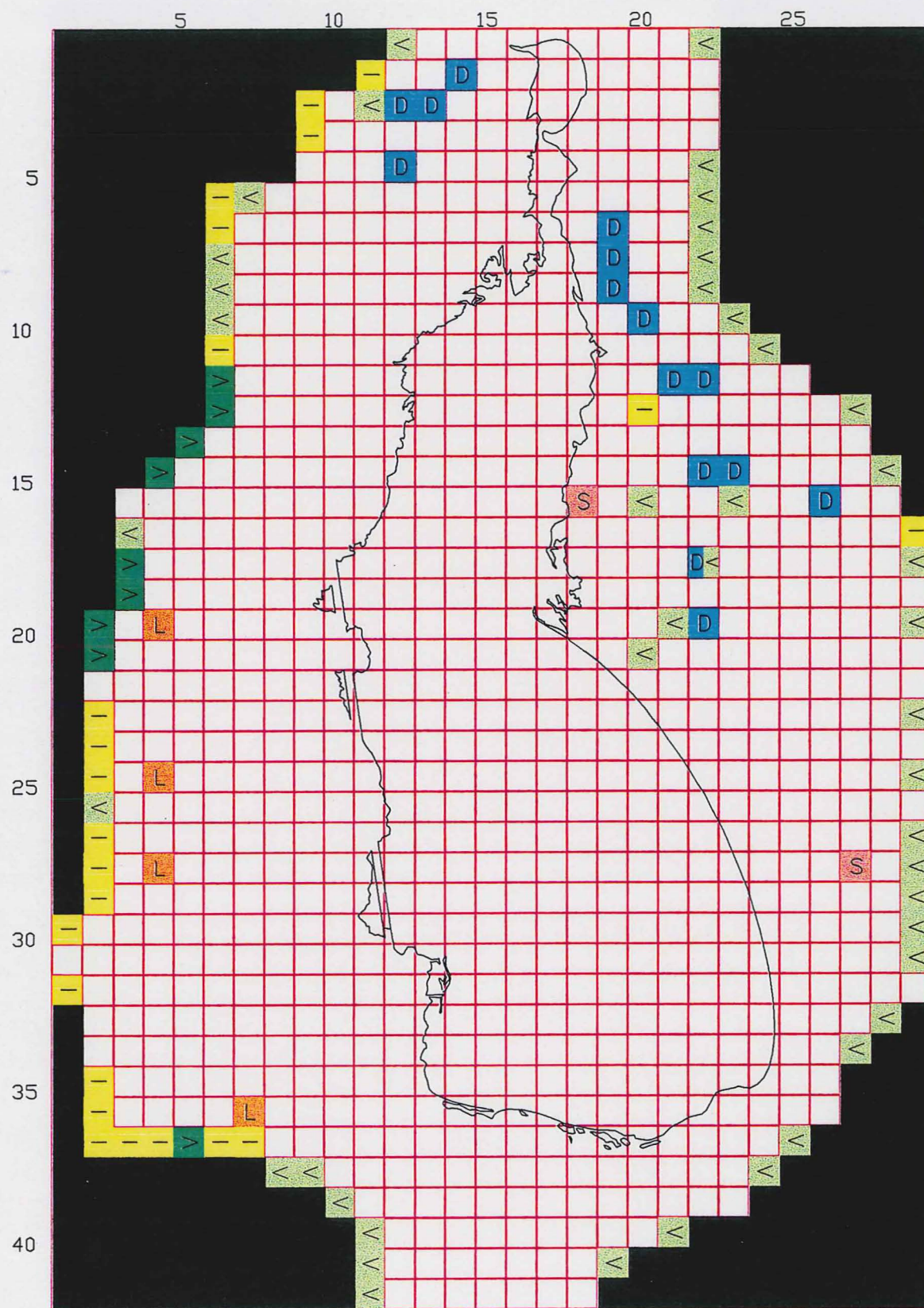
FIGURE 15
STEADY STATE WELL LOCATIONS

MOUNTAIN FRONT RECHARGE WELLS

<	< 10,000
−	10,000−20,000
>	> 20,000

VALUES INDICATED ARE CU.FT./DAY

DISCHARGE WELLS

D	DOMESTIC
S	SMALL IRRIGATION
L	LARGE IRRIGATION

SCALE: 1" = 5000'

29
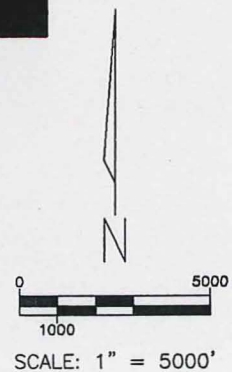
temperature of a residential well (McKay, 1994). This increase may have resulted from the drought in that a reduced flux in cold water would allow the greater migration and upwelling of hot water.

Kanbergs is investigating this small geothermal plume. His work will delineate the plume's extent, chemistry and source. His work will also further detail the hydrogeology of the New Washoe City area, resulting in a refined ground water flow model for the east Washoe Valley. To date it is recognized, albeit through calibration efforts, that upwelling of ground water is occurring in the New Washoe City area along fault structures (Kanbergs, 1997). As a result, recharge wells were included in this current study based on Kanbergs' investigation.

As was discussed in the "GROUND-WATER BUDGET" section, recharge from precipitation on the valley floor occurs mainly on the western side of Washoe Valley and during the winter. Using the Maxey-Eakin method, estimates for the different areas for Washoe Valley are listed in table 6. This table shows the percentage of precipitation that contributes to ground-water recharge. Because forested areas are located near model boundaries where recharge is simulated using wells, it was assumed that the proportion of precipitation that contributes to recharge in the forested area is lumped in with simulated recharge through wells at the model boundaries. At the irrigated lands, 0.6 ft (0.18 m) of precipitation contributes to recharge, 0.4 ft (0.12 m) and 0.2 ft (0.06 m) of precipitation contributes to recharge in the western and eastern phreatic areas, respectively. It is assumed that no precipitation recharges to the eastern unconsolidated areas because of small precipitation amounts, a relatively, deep water-table and soil moisture deficits. No precipitation can be applied to the lake because the lake is being treated as a prescribed head in the sense of a general head

boundary. It is further assumed that summer precipitation does not contribute to recharge because the precipitation rates are small and ET rates are large.

Areas of irrigation are based on Rush (Rush 1967, figure 7) as shown in figure 16. It is assumed that current irrigation practices are the same as during Rush's investigation. Discussions with a local irrigator (Ed Evans, 1994) indicate that flood irrigation prevails and that application rates are approximately 2.5 acre-feet/acre/season, on average. It is assumed then, that 25 per cent of this application rate percolates below the root zone and provides secondary recharge to the ground water system or approximately seven in (18 cm). Figure 17 shows the rate of recharge to areas receiving irrigation and precipitation.

Discharge
Evapotranspiration is estimated by vegetation type as illustrated in the Rush report. Rates were developed based on data from the CDB Weather Station located in the South Truckee Meadows. Rates were subjectively increased 10 per cent because of the anomalously high winds associated with Washoe Valley, wind being the dominate driving force in ET processes. Given the previous discussion in the "GROUND-WATER BUDGET" section, ET rates (per year) used were as follows: 4.5 ft (1.37 m) on the western phreatic areas bounding the lake, 3.8 ft (1.16 m) on irrigated areas, 2.3 ft (0.7 m) for phreatophytic areas at the eastern shore and 1.1 ft (0.33 m) for the unconsolidated areas of eastern Washoe Valley (see figure 18). ET rates for the forested areas are omitted because these areas are in cells represented as mountain front recharge boundaries and the ET is implied in these cells. Extinction depths were set at 7 ft (2.1 m) for all areas except for the eastern uplands of Washoe Lake, set at 25 ft (7.6 m).

30
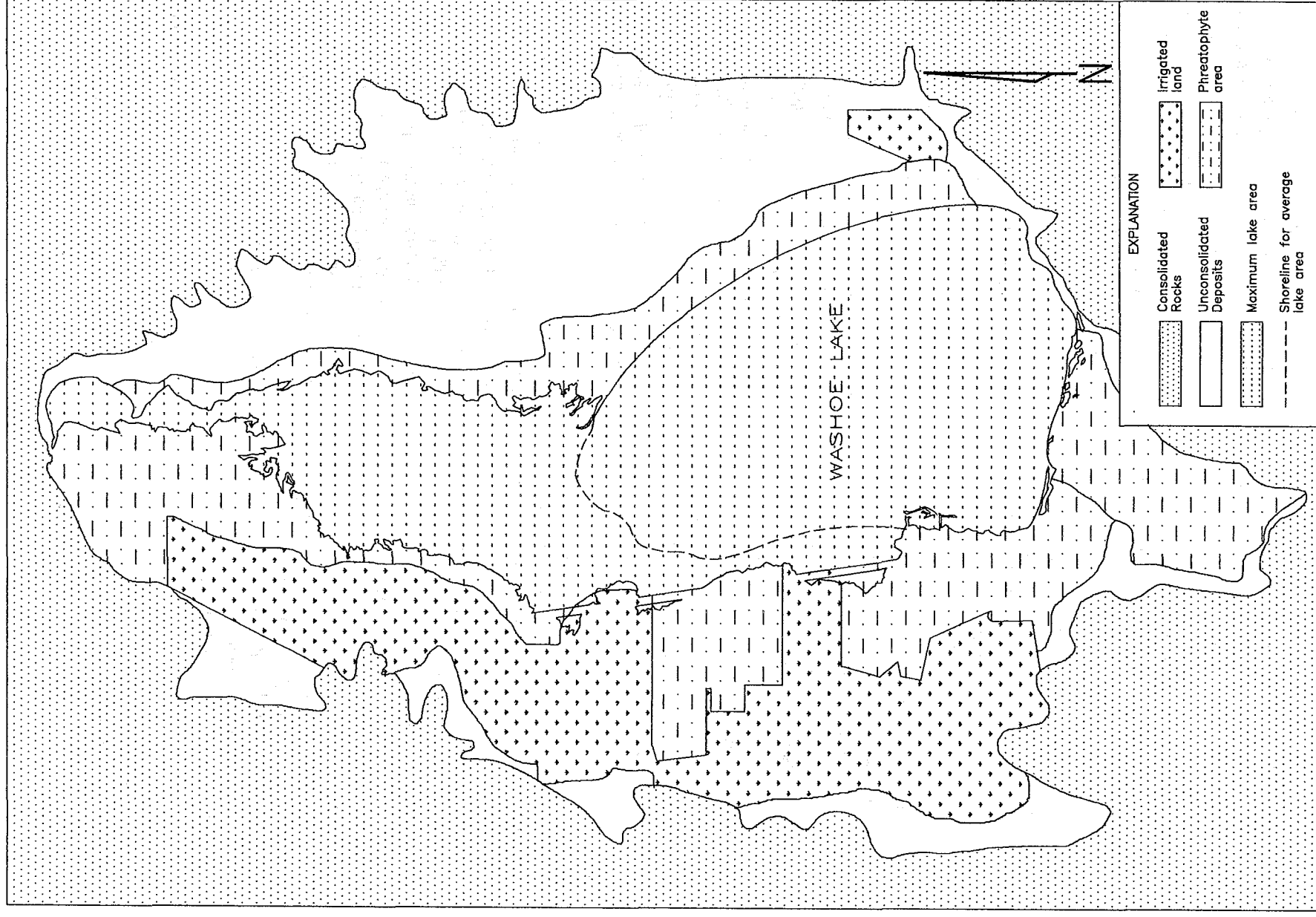
FIGURE 16 – 1965 IRRIGATED AREAS

(According to Rush, 1967)

WASHOE LAKE

EXPLANATION

Consolidated Rocks

Unconsolidated Deposits

Maximum lake area

Shoreline for average lake area

Irrigated land

Phreatophyte area

SCALE: 1" = 5000'

31
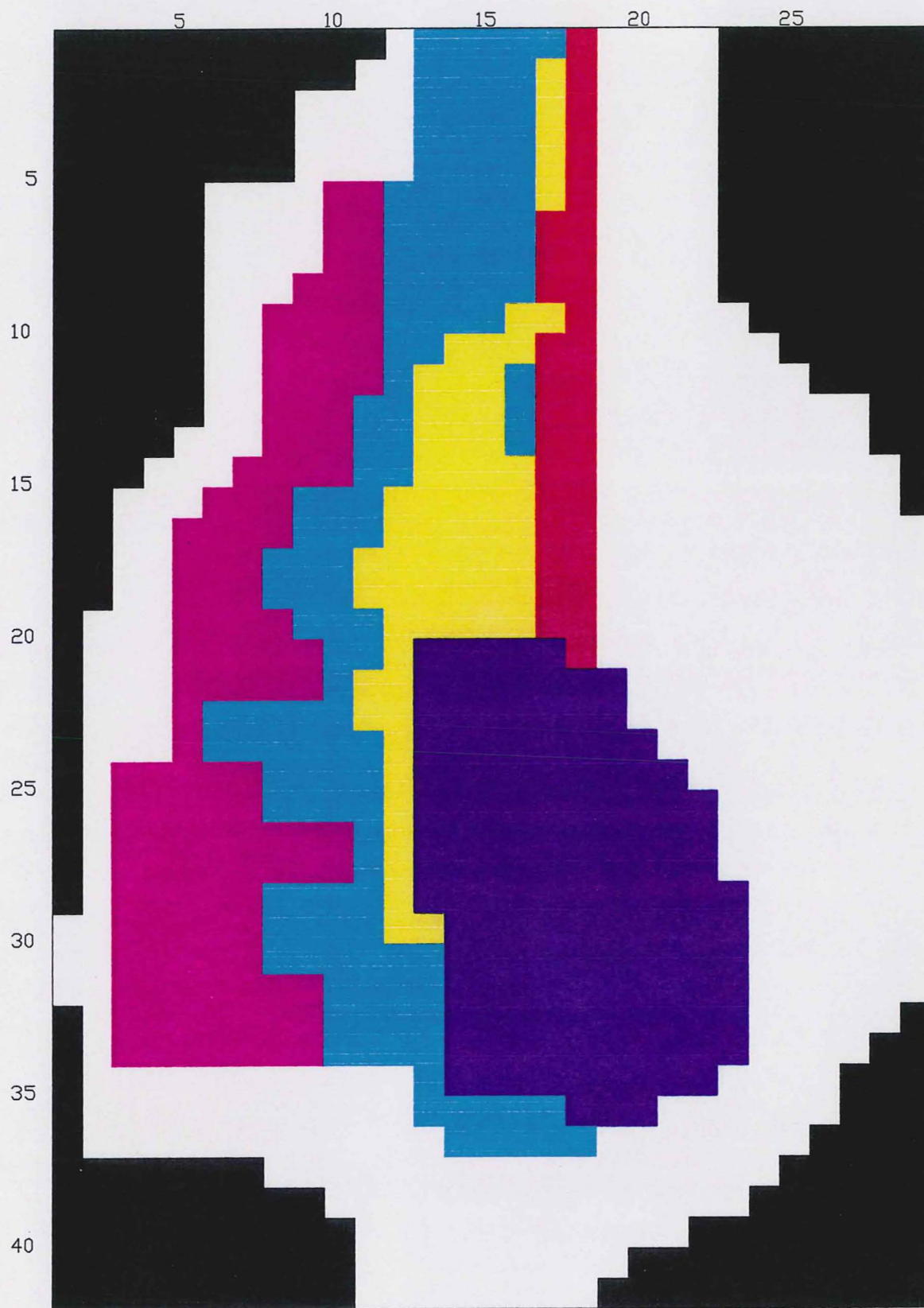
FIGURE 17
VALLEY FLOOR RECHARGE FROM
IRRIGATION AND PRECIPITATION

LEGEND

■ 0.0005	■ Wetlands (General Head Boundary)
■ 0.0031	■ Lake (General Head Boundary)
■ 0.0011	

SCALE: 1″ = 5000′
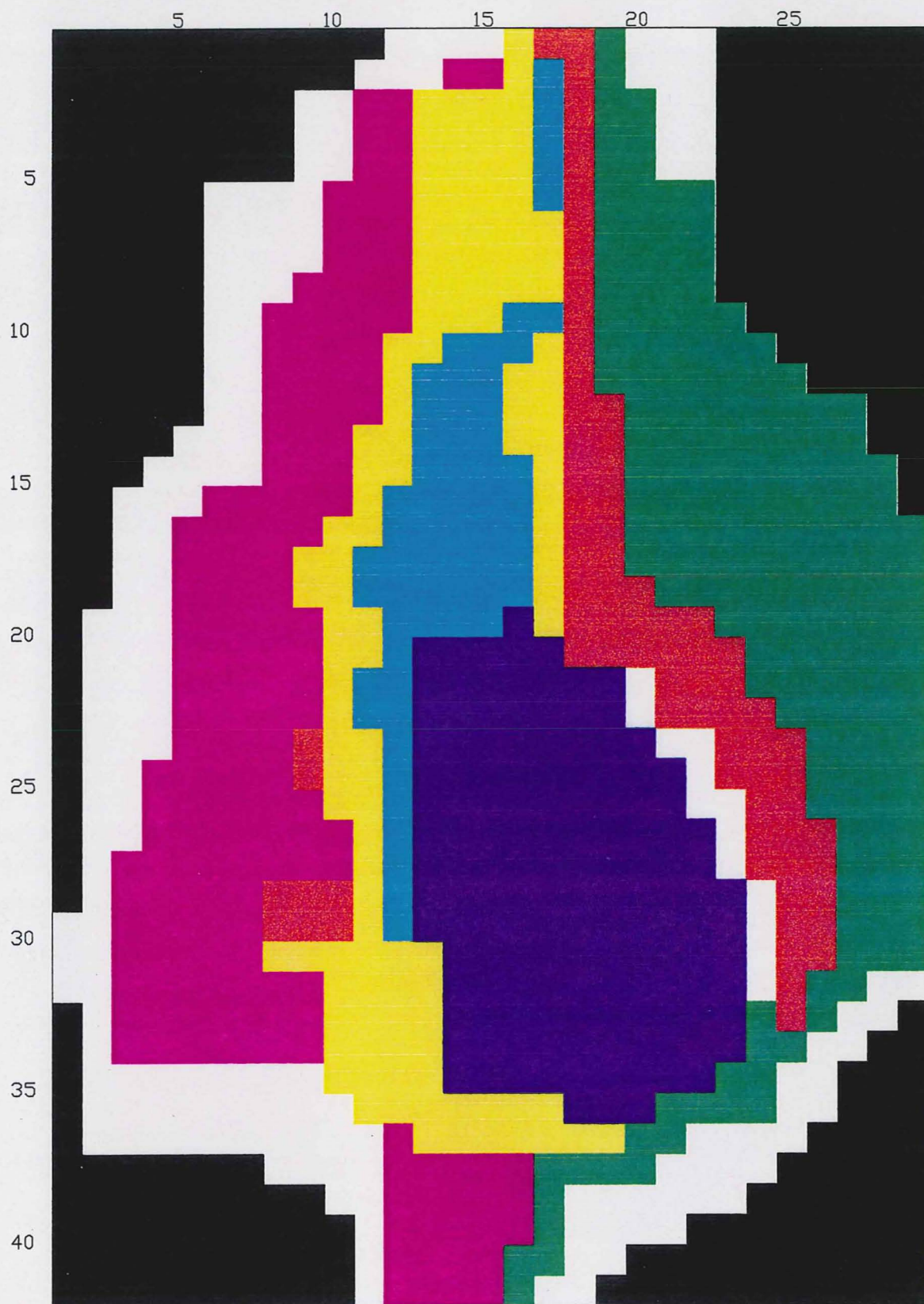
FIGURE 18
EVAPOTRANSPİRATION ZONES

LEGEND

■ 0.003	■ 0.0123	■ Inactive Cell
■ 0.0063	■ General Head Boundary	
■ 0.0101	■ General Head Boundary	
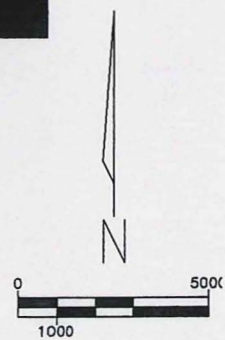
Irrigation and domestic pumpage occurs within the model area. Prior to 1965 (steady state conditions), irrigation dominated the annual pumpage and Rush estimated this at 800 acre-feet per year (1 hm³), however pumping records are very poor. Because pumping wells are used only when surface water is unavailable for irrigation (late summer), full utilization of the ground-water rights probably did not occur each year. It is unknown how Rush derived his estimates. Estimates for this model were set at 1,000 acre-feet 1.23 hm³) based on State Engineer records. Domestic pumpage primarily occurred in the New Washoe City and

Washoe City areas. Rush estimated the total domestic pumpage, including livestock watering, at 200 acre-feet (0.25 hm³) per year. See figure 15 for well locations. For the model, only the areas of concentrated domestic pumpage (87 acre-feet/yr or 0.11 hm³/yr) were considered. Irrigation pumpage was located in layer 2 while domestic pumpage was located in layer 1. Pumping wells are included in the steady state model under the assumption that the effects of this pumping were totally offset by a reduction in discharge or by the inducement of additional recharge.

Table 6
Applied Precipitation Recharge Rates (ft per year)

Land Type	Annual Precip	Recharge	Percent of Precip
Forested Lands	2.0	0.0	0
Western Irrigated Lands	1.7	0.6	35
Western Phreatic Lands	1.5	0.4	27
Eastern Phreatic Lands	1.0	0.2	20
Eastern Unconsolidated Lands	0.8	0.0	0

Calibration Results

Calibration was accomplished by adjusting mountain front recharge, hydraulic conductivity and/or irrigation pumping (preferentially in that order) such that simulated heads matched measured heads. The biggest constraint on the calibration process is the uncertainty in water level elevations measured in 1965. Rush estimated these elevations from USGS, 15 minute topographic maps such that the elevation accuracy was probably within 10 to 20 ft (3-6m). An effort was made to more accurately estimate these elevations from 7.5 minute, quad sheets. Other constraints were the lack of accurate data on irrigation pumping and mountain front recharge. However, these constraints are common with most any ground-water resource modeling effort.

The calibration process was considered complete when the following were achieved:

1) simulated heads were generally within 10 ft (3m) of measured heads,
2) the ratio of mean absolute residual to the range of measured head was less than or equal to 5 per cent,
3) vertical hydraulic conductivity gradients were consistent with the conceptual model,
4) the mass balance had an error of less than 0.1 per cent and,
5) the mass balance was reasonable compared to the ground-water budget derived above.

Figure 19 shows a map of the target wells used in the calibration process. The value next to the well is the difference in calculated
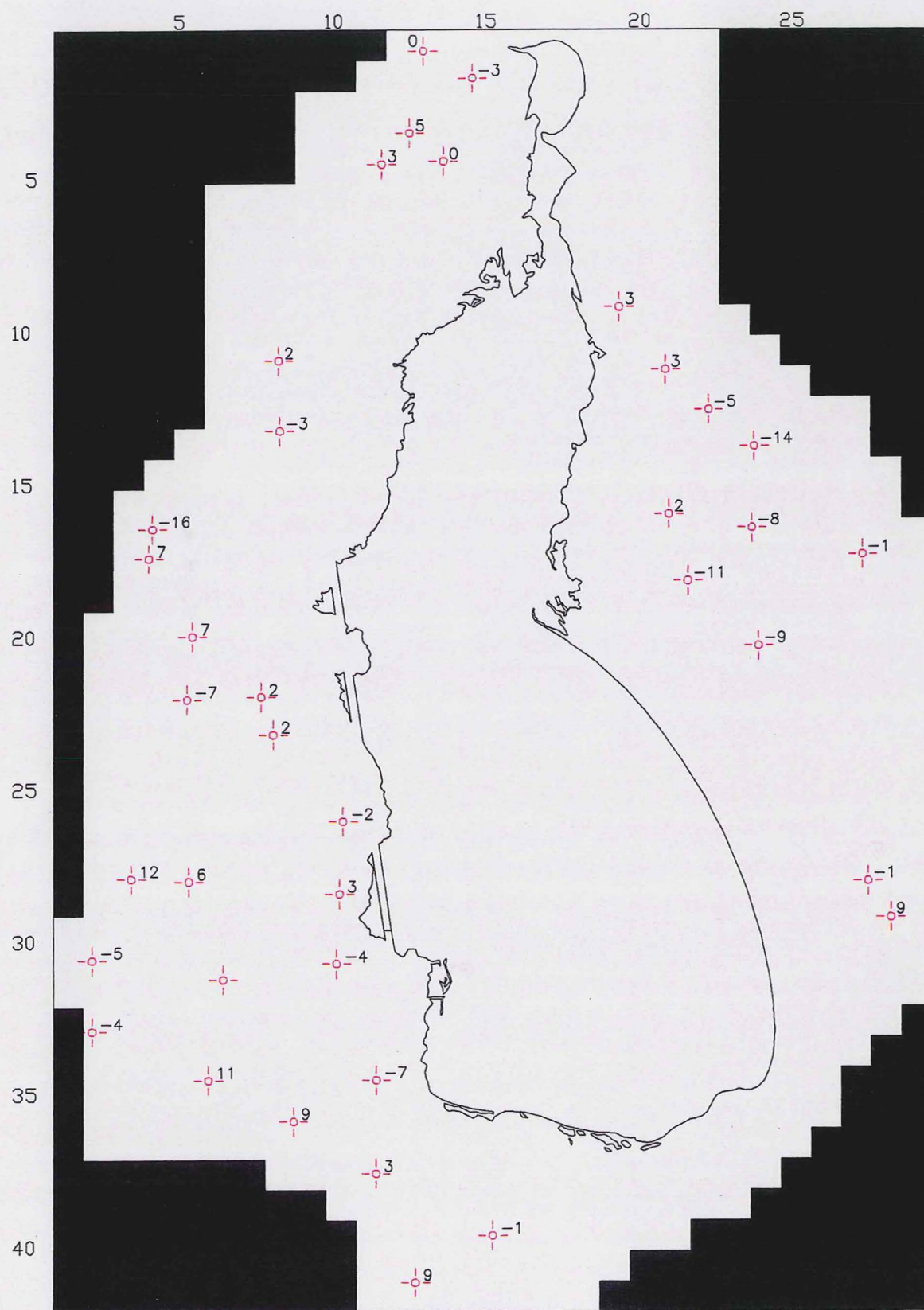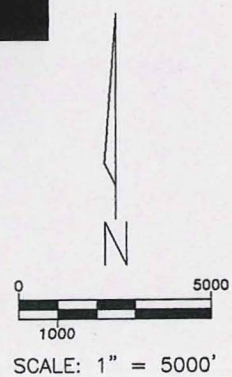
FIGURE 19
CALCULATED RESIDUAL HEADS, STEADY STATE

LEGEND

MEASURED MINUS COMPUTED HEADS

35

SCALE: 1" = 5000'

head vs. measured head. A negative value represents a calculated head higher than the measured head. Target wells with calculated heads off by more than 10 ft (3m) are mostly related to fractured aquifers. The mean absolute residual of 38 target wells is 6.9 ft (2.1m) with the highest residual 12 ft (3.6m) and the lowest -16 ft (4.9m). The standard deviation is 6.9 ft (2.1m) and the ratio of the absolute residual mean to the range in measured values is 4 per cent. Figure 20 is a

graph of the measured heads to the calculated heads and shows relatively good correlation.

Table 7 shows the steady state mass balance. Wells represent either mountain front recharge (+) or pumpage (-), recharge is precipitation and irrigation on the valley floor, ET is evapotranspiration exclusive of the lake, and head dependent boundaries represent the interaction between the lake and the ground-water system, or discharge to the lake.

Table 7
Steady State Mass Balance

FLUX	INFLOW	OUTFLOW
Wells	6,762	-1,043
Recharge	4,490	
Evapotranspiration		-7,022
Head Dep. Bndry	167	-3,352
Total	11,419	-11,417

Figure 20. Graph of Model vs. Observed Heads, Steady State

36
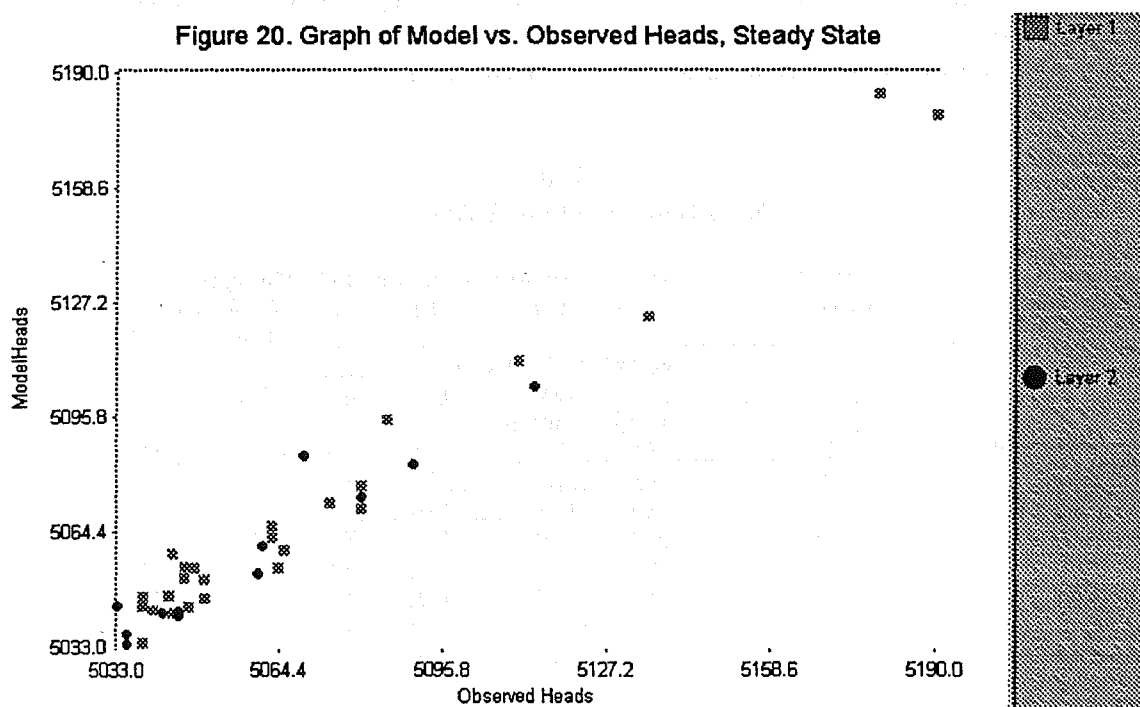
This compares with the water balance as discussed above (page 17). The flux to the lake (3,352 acre-feet or 4.1 hm^3 per year) represents approximately 7 in. (18 cm) per year of discharge per square foot of average lake-area. In terms of evaporation processes on the lake, the simulated flux to the lake represents 17 per cent of the total evaporation on the lake as estimated by Arteaga and Nichols (1984). This mass balance coincides with the values estimated in table 4.

Sensitivity Analysis

Five parameters were adjusted and compared to head dependent boundaries in order to determine the sensitivity of the model. Parameters adjusted were horizontal and vertical hydraulic conductivity, recharge (valley floor), ET maximum rate and ET extinction depth. Parameters were adjusted by 25 per cent and in some cases by a factor of 2. Model runs were then compared to the steady state model values for fluxes to the ET surface and to the lake. Table 8 shows the results of the sensitivity analysis. Increasing the horizontal hydraulic conductivity results in a 14 per cent decrease in ET and a 10 per cent increase in discharge

to the lake. Decreasing the horizontal conductivity increases the ET flux by 4 per cent and decreases the flux to the lake by 16 per cent. Increasing the vertical hydraulic conductivity by 100 per cent decreases the ET flux by 9 per cent and decreases the vertical hydraulic conductivity by 50 per cent. Decreasing the vertical hydraulic conductivity by 25 per cent decreases the ET flux by 2 per cent and decreases the flux to the lake by 15 per cent. Increasing the valley floor recharge by 25 per cent increases the amount of flux to the ET surface (5 per cent) and the lake (9 per cent). Decreasing the amount of recharge decreases the amount of flux to the ET surface (18 per cent) and to the lake (11 per cent). Increasing the rate of ET by 25 per cent increases the flux to the ET surface (2 per cent) and decreases the flux to the lake (18 per cent). Decreasing the rate of ET decreases the amount of flux to the ET surface (17 per cent) and increases the amount of flux to the lake (24 per cent). Increasing the ET extinction depth by 100 per cent increases the flux to the ET surface (6 per cent) and decreases the flux to the lake (49 per cent). Finally, decreasing the ET extinction depth by 50 per cent decreases the flux to the ET surface (26 per cent) and increases the flux to the lake (17 per cent).

Table 8
Results of Sensitivity Analysis

Parameter Varied	Percent Change	abs. res. mean	Min. Res (ft)	Max. Res. (ft)	Std. Dev.	Flux at head dpndnt bndry ET Srfc (AF/yr)	Flux to Lake (AF/yr)
		Steady State Calibration					
		5.6	-16.0	12.0	6.9	7022	3352
		Sensitivity analysis					
Horz. Hydr. cond.	+25	7.1	-8.8	24.4	7.9	6038	3700
all layers	-25	7.1	-27.6	4.6	8.0	7276	2465
Vert. Hydr. cond .	x 2	5.5	-15.7	13.4	6.8	6388	3350
all layers	x 0.5	6.2	-15.0	19.5	7.7	6900	2837
Recharge	+25	5.5	-17.3	9.9	6.8	7365	3499
(valley floor)	-25	5.8	-15.2	15.6	7.2	5792	2824
ET Rate	+25	5.6	-15.8	12.6	6.9	7135	2608
(max)	-25	5.6	-17.0	10.8	6.9	5838	3936
ET Ext.	x 2	6.7	-12.7	16.5	7.1	8205	1556
(depth)	x 0.5	9.2	-17.6	47	13.7	5186	3718

Results and Discussion

The steady state model indicates that the total ground-water flux is 11,418 acre-feet/yr (14 hm³/yr). Mountain front recharge accounts for 6,760 acre-feet (8.3 hm³) of which 5,740 acre-feet (7.1 hm³) is generated on the west side of the valley and 1,020 acre-feet (1.25 hm³) is generated on the east side from the Virginia Range. Previous investigators have approximated these same values. There is some indication, from a previous model and from sensitivity analysis, that recharge on the west side may be greater than this current estimation of 5,740 acre-feet (1,750 m). The majority of mountain front recharge from the Virginia Range is generated in the Jumbo Creek drainage area. Irrigation practices add significant recharge to the western side of the valley as well as winter precipitation. This is estimated at 4,490 acre-feet/yr (5.5 hm³/yr). Discharge to the lake and associated wetlands is also a major source of ground-water outflow, estimated at 3,352 acre-feet (4.1 hm³). Evapotranspiration accounts for 7,022 acre-feet (8.7 hm³) of ground-water discharge, primarily west of the lake. Figure 21 shows the potentiometric surface at 20-foot contours. This indicates that ground-water movement is toward the lake. Gradients also appear to closely follow the land surface topography. Figure 22 shows the layer 2 potentiometric surface. Figure 23 shows velocity vectors generalizing the direction of flow to the lake.

Transient Model

Transient modeling, in this study, is an attempt to verify the steady state model by imposing natural and man-made stresses on the model and comparing calculated heads to measured heads within a particular time series. The stresses represent time dependent physical processes such as fluctuating lake levels and mountain front and valley floor recharge, annual pumping and volumetric ET rates. The transient run begins in 1965 where steady state conditions are assumed and stops in 1997. Measured water well levels from 1981, 1994 and 1997 surveys were used in the transient run as calibration targets in order to test the steady state model's conceptual accuracy. Only the 1994 and 1997 water well surveys measured the same wells at approximately the same time of the year. In 1981, the survey was conducted over one year. This 31-year period was subdivided into 63 stress periods of 6 months each. Ten time steps per stress period were used with 1.4 days as the first time step and 1.4 as the time step multiplier.

Historical Precipitation

The Regional Climate Center at the Desert Research Institute in Reno, Nevada, provided precipitation data from three long-term gages. These were the Carson City (at the Carson City Airport, 3 miles (4.8 km) south of Washoe valley), Cliff Ranch (at the north end of Franktown Road) and Little Washoe Valley (2 miles or 3.2 km west of the valley proper in the Carson Range) gage. Average precipitation for Washoe Valley was estimated from these data. Yearly percentages of normal were made based upon the Carson City record, minor adjustments being made. These percentages were then used to adjust the amount of mountain front recharge that occurred for that year in the model. Recharge on the valley floor was not adjusted because the combination of precipitation and irrigation was assumed to remain mostly constant regardless of the change in precipitation. This assumption is based on the premise that if winter precipitation is below normal, above normal irrigation will occur for any one year and vice versa. Over the long term, this would tend to average the amount of recharge on the valley floor. Additionally, the valley floor precipitation recharge is based upon the Maxey-Eakin method, which by itself, is a long-term averaging process.

Historical Lake Level

The USGS has maintained records on the level of Washoe Lake since 1963. Figure 24

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FIGURE 21
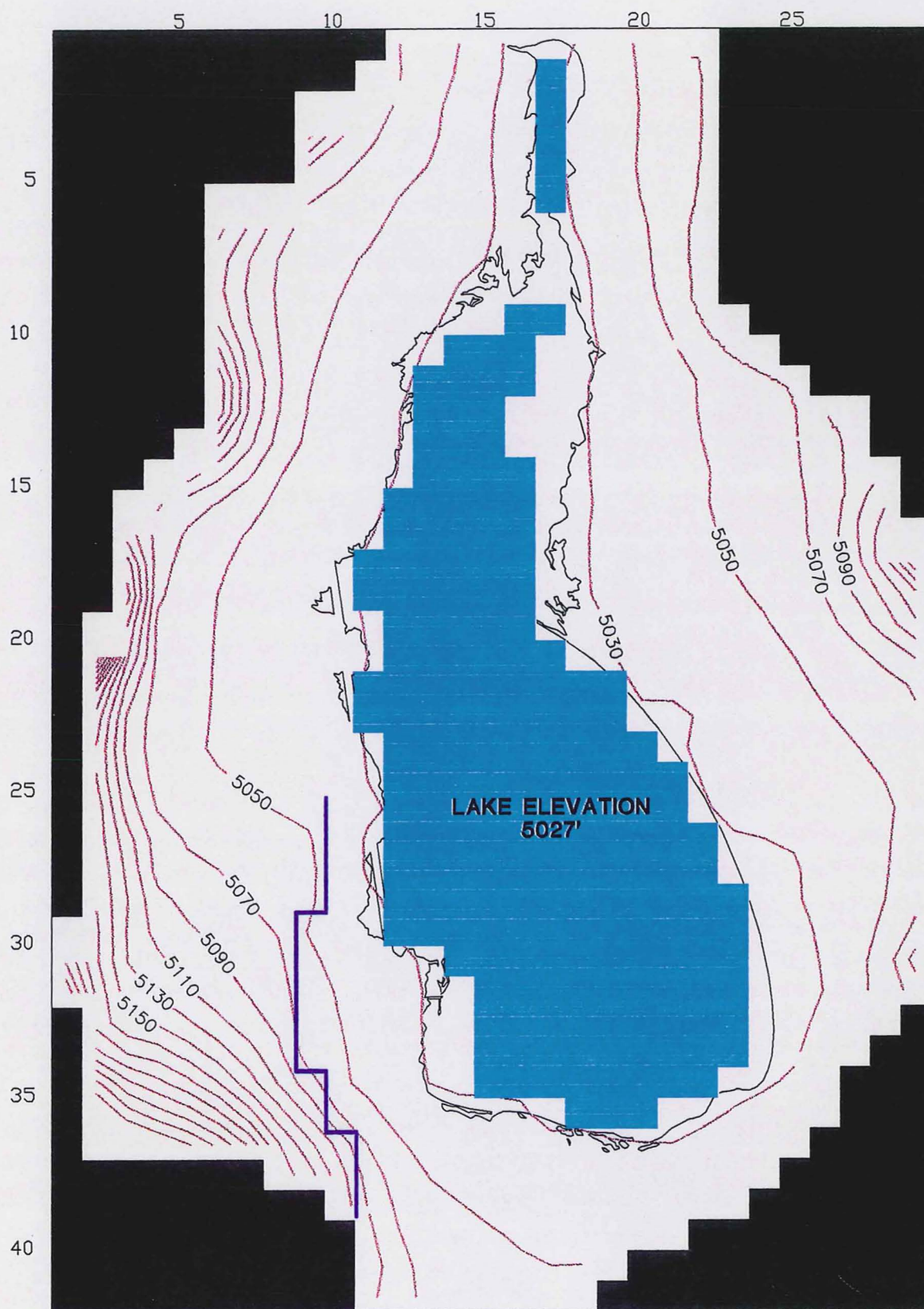STEADY STATE POTENTIOMETRIC MAP FOR LAYER1

CONTOUR INTERVAL = 20'

LEGEND

General Head Boundary

—5090— Simulated Hydraulic Head contour
(feet above mean sea level)

— Fault Structure

SCALE: 1" = 5000'
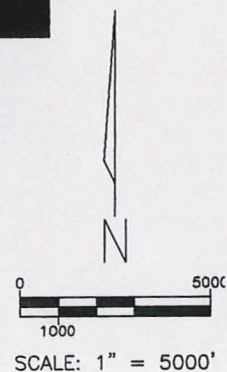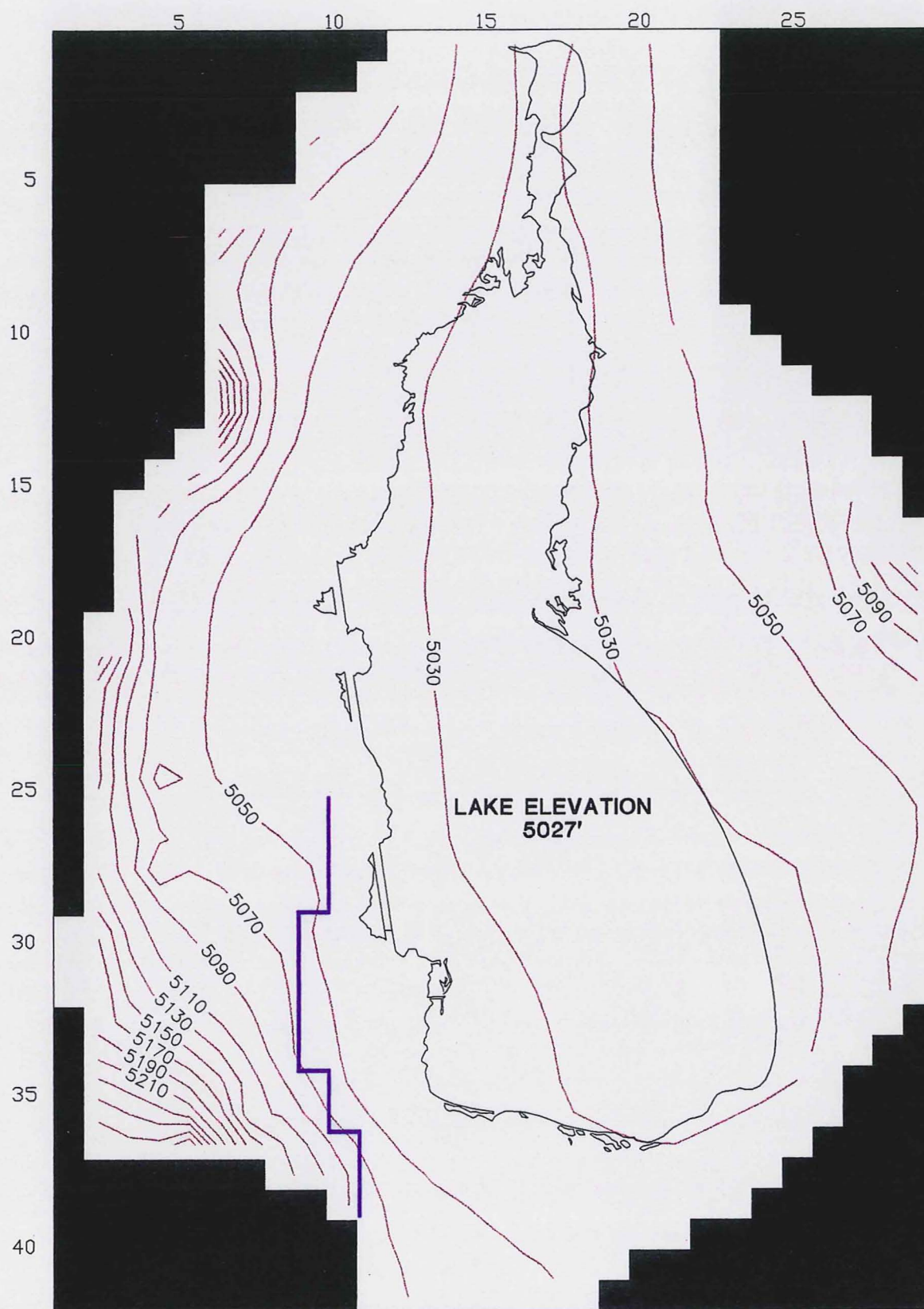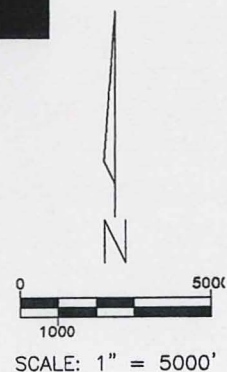
FIGURE 22
STEADY STATE POTENTIOMETRIC MAP FOR LAYER 2

CONTOUR INTERVAL = 20'

LEGEND

—5130— Simulated Hydraulic Head contour
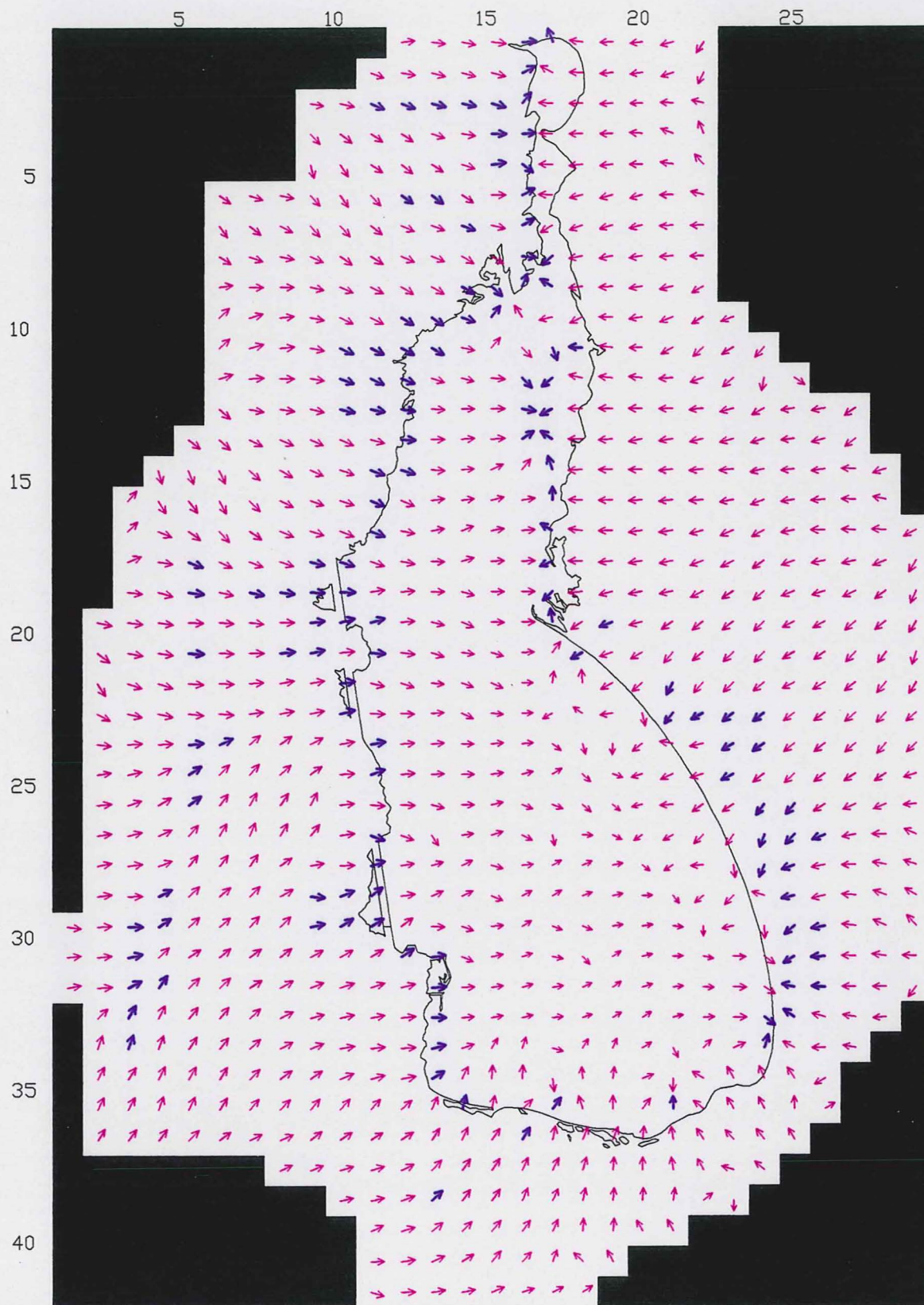(feet above mean sea level)

—— Fault Structure

SCALE: 1" = 5000'

40

FIGURE 23
ESTIMATED DIRECTION OF GROUND WATER FLOW, 1965
(LAYER 1)

LEGEND:

→ DOWNWARD/HORIZONTAL FLOW

→ UPWARD FLOW

41

SCALE: 1" = 5000'
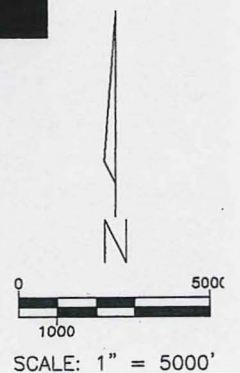
Figure 24. Washoe Lake Historical Elevation (feet)
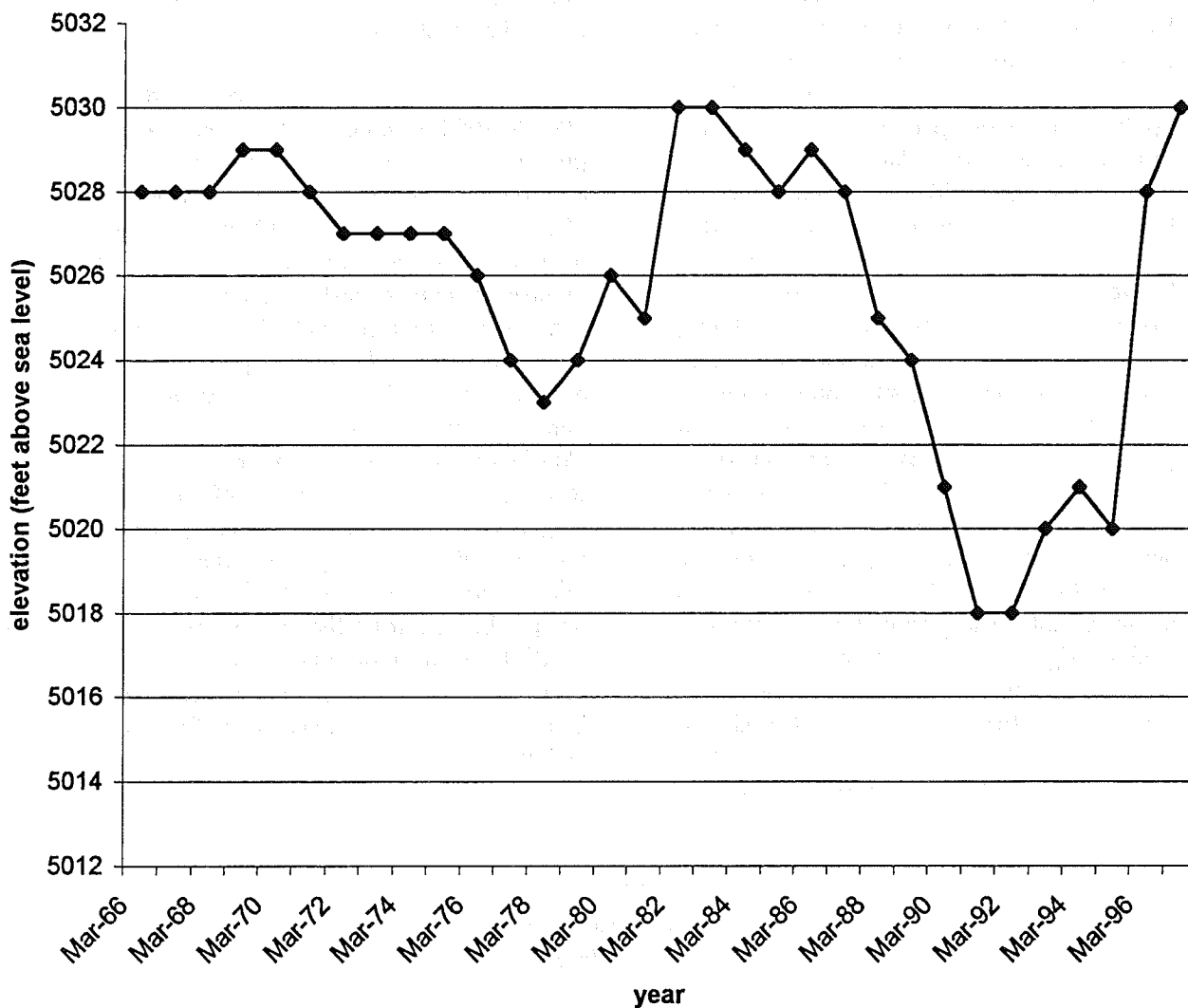
is a graph showing the lake level changes since 1965. For the transient modeling, the average lake level for each six-month stress period was calculated. These values were then used for the general head boundary for that stress period. During 1991 and 1992 the lake was mostly dry. This caused a conceptual problem in the model for a general head boundary would be inaccurate. Consequently, two models were developed: one with general head boundaries throughout the transient time frame and another with an ET boundary that replaced general head boundaries in time in an attempted to mimic the drying of the lake, the later which met with poor success. For the period when the lake dried up, appropriate lake cells were replaced with an ET boundary.

Historical Pumpage

The State Engineer's Office (Ricci, 1995) assumes that in Washoe Valley, and on a long-term average, only about 50 per cent of the permitted ground-water pumpage occurs. This is because surface water is the primary source of irrigation supply, and ground-water

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pumpage is secondary and therefore not constant from year to year. Irrigation practices during the transient period are based on conversations with local irrigators. During normal years it is assumed that irrigation pumpage primarily occurs from early July to September, with 10 to 14 day cycles at 12 hours per day. For example, someone with a secondary permit for 265 acre-feet/yr (0.3 hm3) and a 1,000 gpm (63 l/sec) well would pump 12 hours per day times 12 days (26.5 acre-feet/cycle or 0.03 hm3/cycle) during the later part of the irrigation season. There are 4 cycles during this period and irrigation is not used during harvest. An irrigator would pump 106 acre-feet (0.13 hm^3) during the season or about 40 per cent of the permitted supplemental right. During dry years, the irrigator might pump 60 per cent of the right and during very wet years perhaps only 30 per cent of the permitted right. The State Engineer's Office assumes that during normal years, Washoe Valley irrigators pump 50 per cent of their secondary right, so this example is pretty close to that. Irrigators on the eastern side of the valley are assumed to pump most of their right. Table 9 shows the estimated average

pumpage for the modeling effort based on assumed irrigation practices and are less that those permitted. These estimates have not been adjusted for recharge due to irrigation (secondary recharge).

Where residential development occurred from 1965 to 1993, estimates were made of annual growth (see table 10). This table was developed from home estimations made for 1965, 1981 and 1994. Interpolation was made between these years, such that annual pumpage was increased in each cell. Checks were made from the actual counts to the model counts. Domestic pumpage was estimate at 0.75 acre-feet (925m^3) of pumpage per domestic well per year. Consideration was given to secondary recharge from septic tank effluent and irrigation. The estimated consumptive use was calculated at .25 acre-feet/yr (308 m^3/yr). For the model, domestic consumptive use per home during the summer was set at 55 ft^3/day (1.6 m^3/day) and consumptive use during the winter was set a zero. Groupings of discharge wells are shown in figures 25 and 26.

Table 9
Estimated Irrigation Pumpage
(acre-feet/yr)

Year	66-69	70-73	74-77	78-81	82-85	86-89	90-93	94-96
	1036	1230	1400	1618	1275	1855	2293	1590

Table 10
Estimated Residential Development
(number of homes)

AREA	1965	1981	1993
New Washoe City	125	725	1175
Washoe City	37	82	150
Bellevue	0	48	95

FIGURE 25
TRANSIENT MODEL WELL LOCATIONS FOR LAYER 1

MOUNTAIN FRONT RECHARGE WELLS

<   < 10,000

−   10,000−20,000

>   > 20,000

DISCHARGE WELLS

D   DOMESTIC

S   SMALL IRRIGATION

L   LARGE IRRIGATION

General Head Boundary

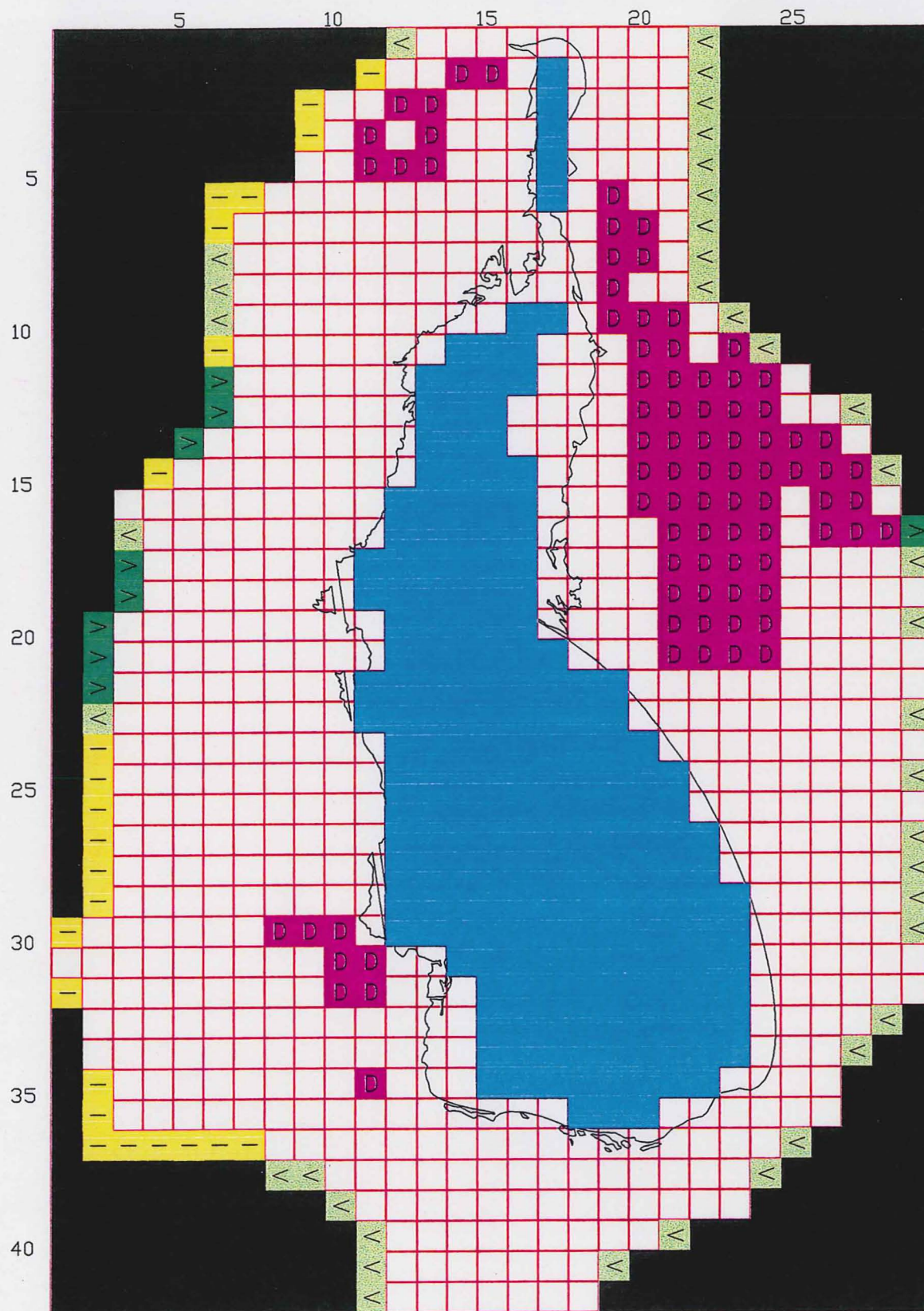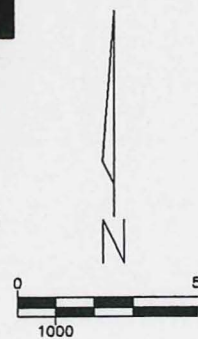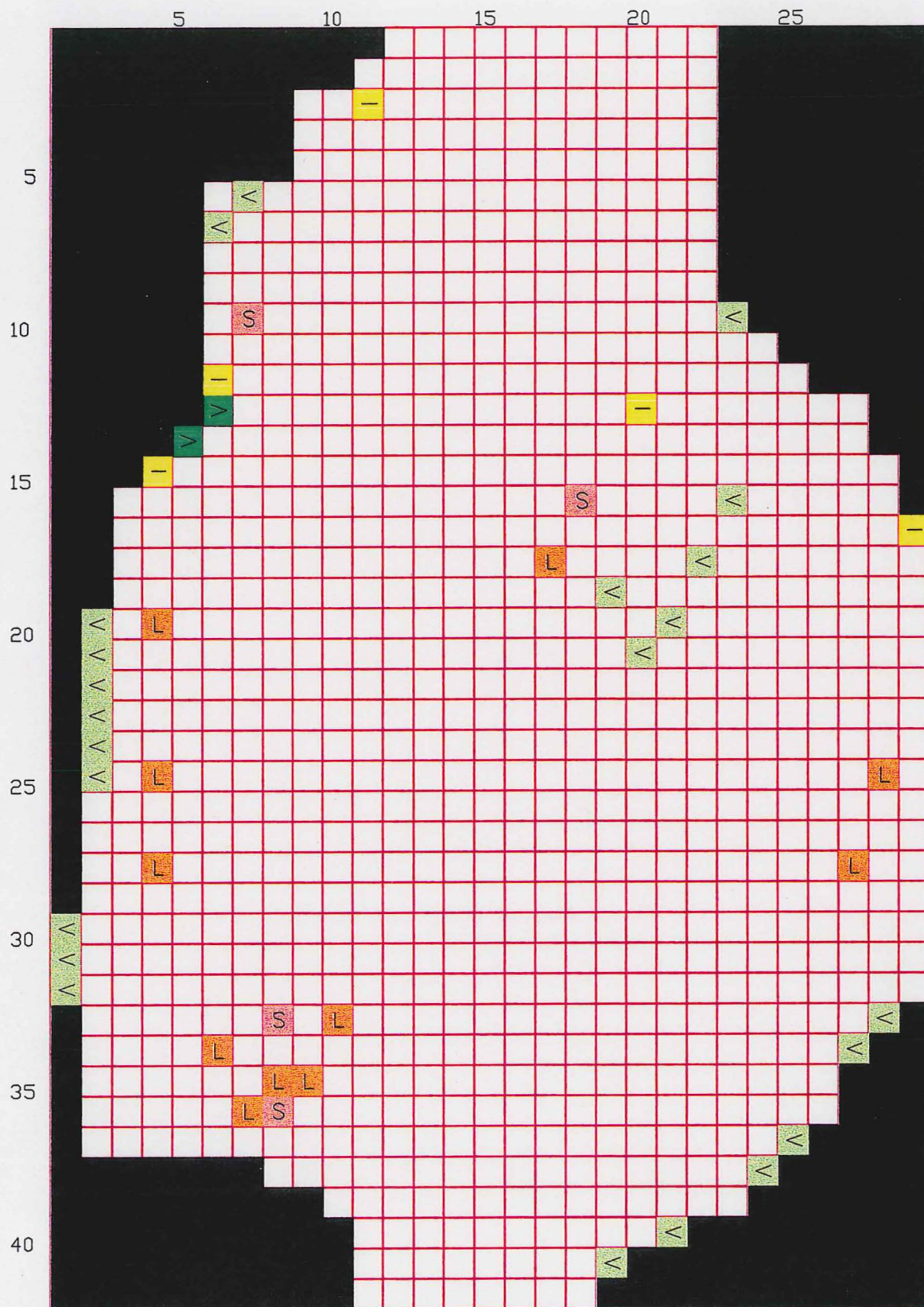N

SCALE: 1" = 500

44

FIGURE 26
TRANSIENT MODEL WELL LOCATIONS FOR LAYER 2

MOUNTAIN FRONT
RECHARGE WELLS

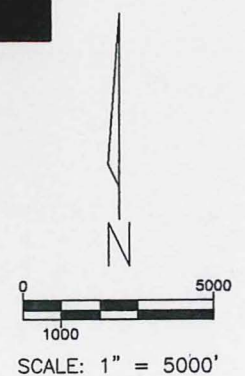<   < 10,000

—   10,000–20,000

>   > 20,000

DISCHARGE
WELLS

S   SMALL IRRIGATION

L   LARGE IRRIGATION

45

SCALE: 1" = 5000'

Appendix 1 lists the values of the three stresses placed on the transient model that changed with time. Note that as the mountain front recharge (RCH WELLS) decreased, there was an increase in irrigation pumpage. No irrigation pumping was simulated for the winter months.

Results and Discussion

Adjustments to the steady state and transient model were made during the transient model calibration process. The biggest adjustment was to the amount of domestic ground-water pumpage. The original estimate, based on total pumpage, was 0.75 acre-feet/yr (925 m³/yr) per residence. This value was reduced to 0.25 acre-feet/yr (308 m³/yr), providing a much better match between the calculated heads and measured heads of domestic wells, particularly for the 1994 survey. This reduction is justified given that it represents the consumptive use portion of ground water pumped or net pumpage. Minor adjustments were made to the amount of mountain front recharge to the system and these adjustments were also made to the steady state model. The calibration process also pointed to a non-linear response in the percentage of precipitation that becomes recharge during extended periods of well above normal precipitation. This can be described as rejected recharge. For this transient model during the period between 1995 and 1997, the mountain front recharge component was adjusted downward from the expected value given the precipitation amounts. This was applied to every mountain front recharge cell in the model.

As stated earlier, two transient model runs were made in an attempt to simulate the lake during the drought period. The first method replaced a general head cell with an ET surface when that particular lake cell went dry in response to the drought. However, this attempt resulted in unsatisfactory head levels in the northern and western lake area. While the target values were reasonably calculated, heads in the "dry lake" area were above ground surface by as much a six feet.

This could be physically explained as ground-water discharge to the lake bed beyond the rate of ET assigned those cells or outflow from the lake to Steamboat Creek. The area in the northern and western lake area is an indication of where the ET effort could not reproduce the dry lake surface and to resolve this, an unrealistic ET rate would have to be assigned those cells. The high heads could also result from computational artifacts between the ground-water level elevations and the "dry lake" heads when the general head boundary is replaced by an ET surface.

The second modeling attempt considered the lake as a general head boundary throughout the transient time frame. This method could be criticized as improper because during the lake's decline unlimited water could be withdrawn from the general head boundary, particularly on the eastern side, although heads were adjusted accordingly. However, this method proved a better fit to observed data.

Overall the transient model shows good calibration with the target wells of 1981, 1994 and 1997. This indicates that the steady state model appears to be a reasonable representation of the ground-water flow system for Washoe Valley. Figures 27, 28 and 29 show the calibrated vs. measured heads for the 1981, 1994 and 1997 surveys, respectively. In comparing the calculated vs. measured heads for the 1981 survey, the absolute residual mean is 5.6 ft (1.7m). The largest differences were 16 ft and -27 ft (4.9 and –8.2 m). For the comparison of the calculated vs. measured heads for the 1994 survey, the absolute residual mean is 4.9 ft (1.5m) with the largest differences being 15 ft and -9 ft (4.6 and –2.7 m). For the 1997 survey, the absolute residual mean was 5.3 ft (1.6 m) with the largest differences

46

FIGURE 27
CALIBRATED RESIDUAL HEADS, 1981

LEGEND

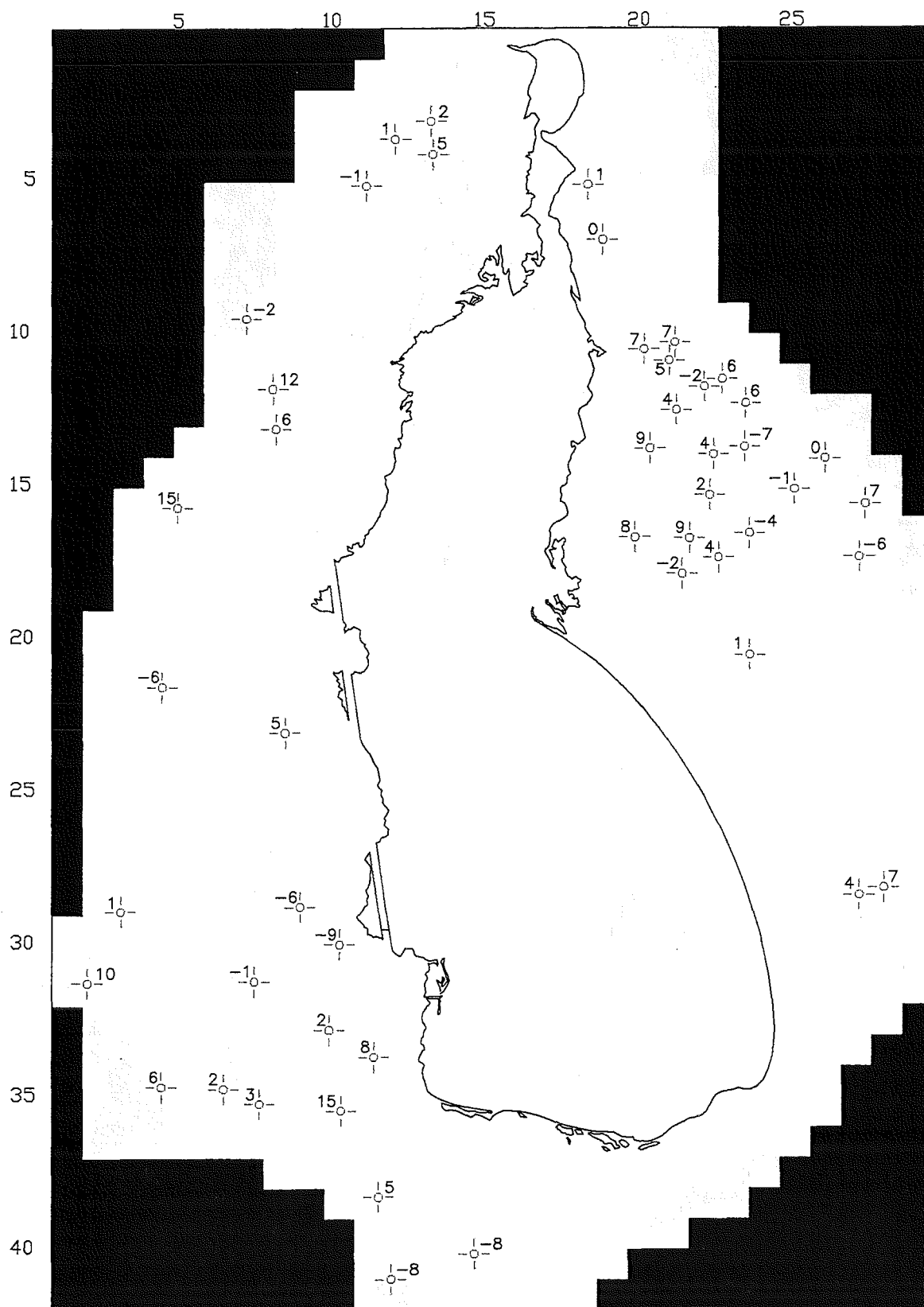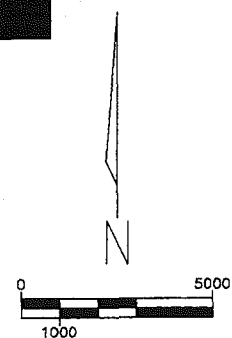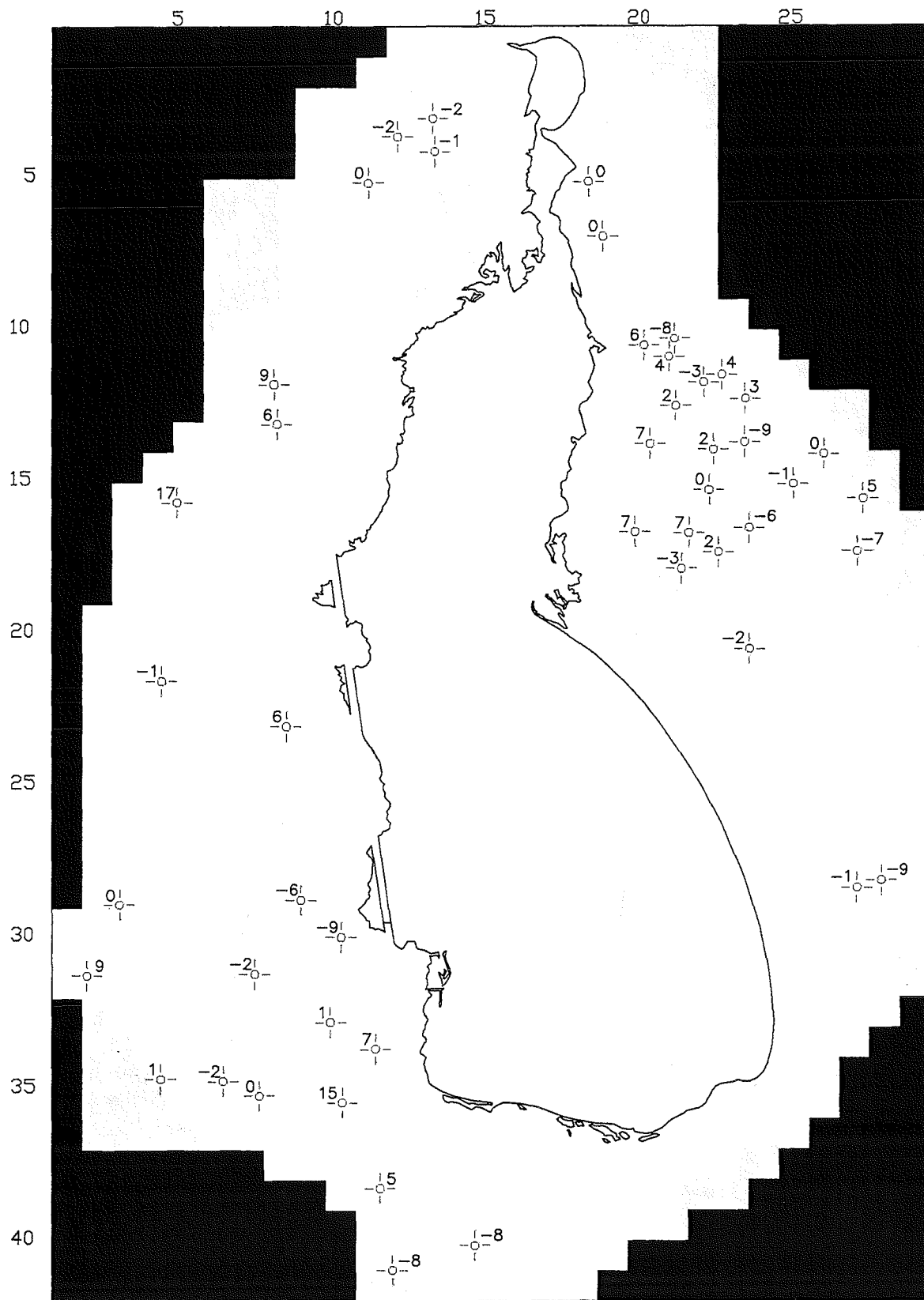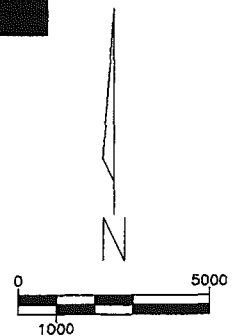$\frac{1}{\circ}$ MEASURED MINUS COMPUTED HEADS

FIGURE 28
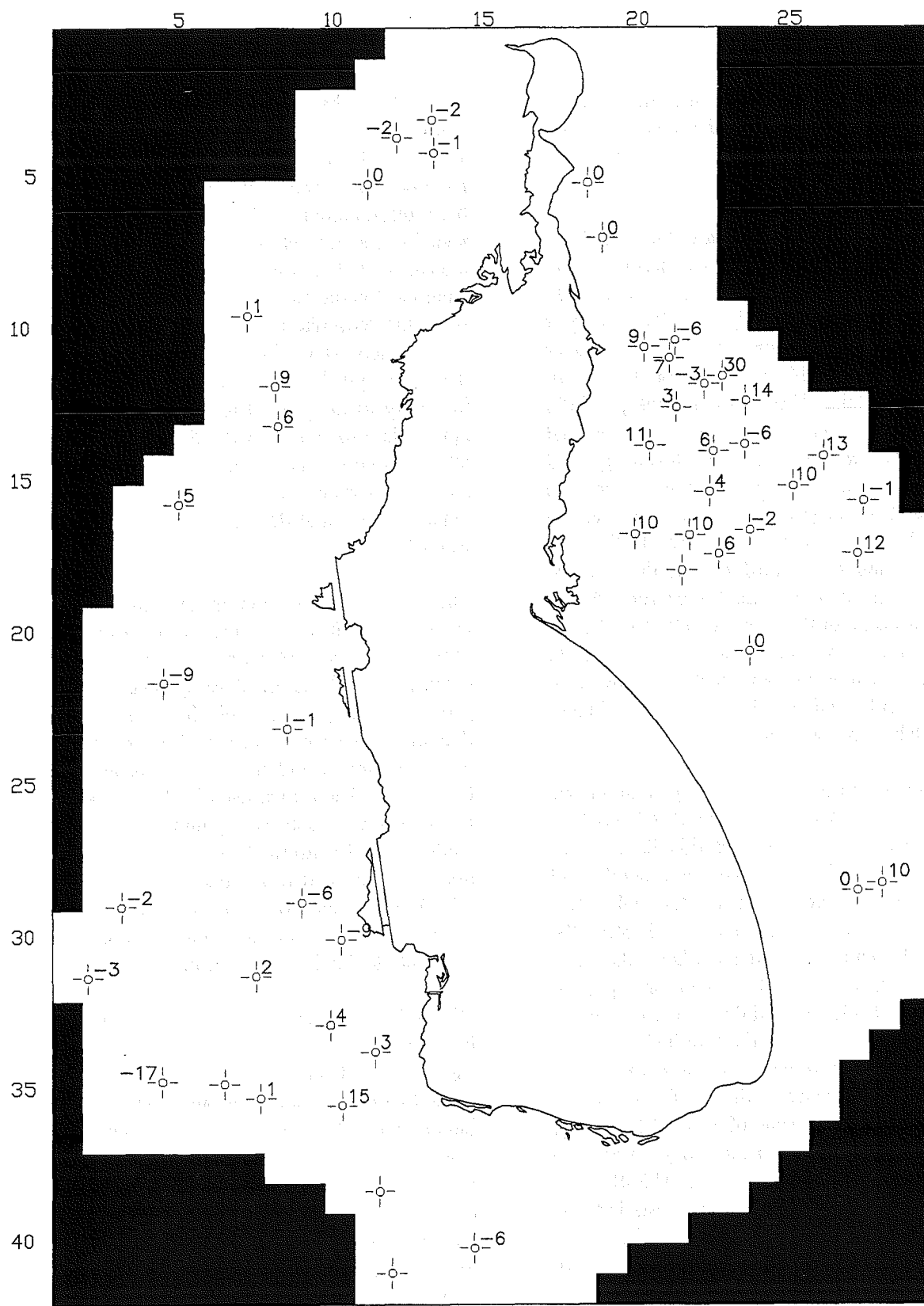CALIBRATED RESIDUAL HEADS, 1994

LEGEND
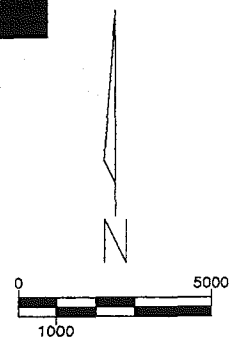
-¦○¦- MEASURED MINUS COMPUTED HEADS

FIGURE 29
CALIBRATED RESIDUAL HEADS, 1997

LEGEND

$-\overset{}{\underset{}{\circ}}-3$ MEASURED MINUS COMPUTED HEADS

-17 ft and 29 ft (-5.2 and 8.8 m). Figures 30, 31 and 32 graph the calculated vs. measured heads for the 1981, 1994 and 1997 surveys, respectively.

Figures 33, 34 and 35 are the simulated potentiometric maps for stress period 31, 57 and 63 (approximately March 1981, 1994 and 1997 respectively). The largest difference in these maps is the migration of the 5,030-ft (1,534-m) contour on the eastern side of the lake. From 1981 to 1994, it shifts eastward. This suggests that domestic and irrigation pumpage was capturing ground water that normally would flow to the lake and that recharge was reduced in response to the drought. From 1994 to 1997, this contour shifts westward, back to the lake due to the increase in snowmelt recharge. At the western edge of the lake, the 5,030-ft (1,534-m) contour also shifts slightly from year to year. On this contour, in the southwest, it consistently indicates heads a few ft higher than lake level elevations.

Figure 36 shows the simulated potentiometric surface (1997) near the lake at 2-ft contour intervals. The purpose of this figure is to assess the validity of using a general head boundary in areas where the lake bed becomes dry. The figure indicates the general head cells, areas where the land surface elevation is less than or equal to 5,021 ft (1,531 m), and the area where model heads are greater than the lake bed elevation. The latter would indicate where the model infers a lake surface during March 1994, given a prescribed head of 5,020 ft (1,531m). This corresponds reasonably well to measured lake levels at the USGS gage (USGS, 1995). The contours also indicate that ground-water movement is still towards the lake and that the general head boundary is not moving water into the ground-water system. Again, while this technique is not physically correct, it still gives reasonable results. Figure 36 also details the influence of irrigation pumpage located in the southeast. One should note that an

assumption has been made about the continued irrigation pumpage and rates from 1965 to 1997. It is possible that the irrigation of any one field or fields may have been discontinuous. Figure 37 shows the velocity vectors estimated for 1994. This indicates that ground-water movement is from the Carson Range, west to the lake and from the Virginia Range, east to the lake. Again, there is no indication that water is being supplied from the general head boundary to the ground water system. It is appropriate to state that the dynamics of the lake itself need to be better understood before an full assessment of this interaction can be made (substantial data collection for a lake water-budget).

Figure 38 indicates the drawdown that is estimated to have occurred from 1965 to 1997. The year 1997 was chosen in order to display the effects of development on the ground-water system. This figure indicates that drawdowns have largely been confined to the southwest and the eastern portions of the valley. The drawdowns in the northeast are a result of domestic pumping. In the southeast and southwest, irrigation pumping may have resulted in approximately 15 and 20 ft (4.6 and 6.1 m) of drawdown, respectively. There are few records to substantiate the drawdown in the southeast.

Discussion of lake and ground water interaction

Figures 39, 40 and 41 were constructed in order to further analyze ground water /lake interactions. The data for these figures were generated from stress period mass balances (see APPENDIX 2) on an annual basis. In these figures, lake level elevations were plotted against ET and the ground-water flux to (discharge) and from (recharge) the lake. Figure 39 plots ET from the modeled area (excluding the lake) against the lake elevation. It is obvious that the two trends match very closely. This indicates the lake matches the water table elevation according to the author's conceptual understanding.

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Figure 30. Graph of Model vs. Observed Heads, 1981
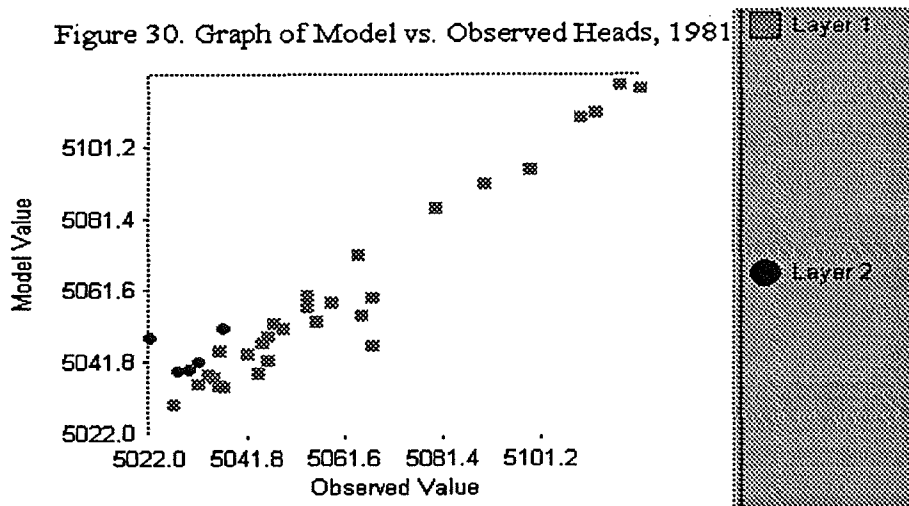
Figure 31. Graph of Model vs. Observed Heads, 1994
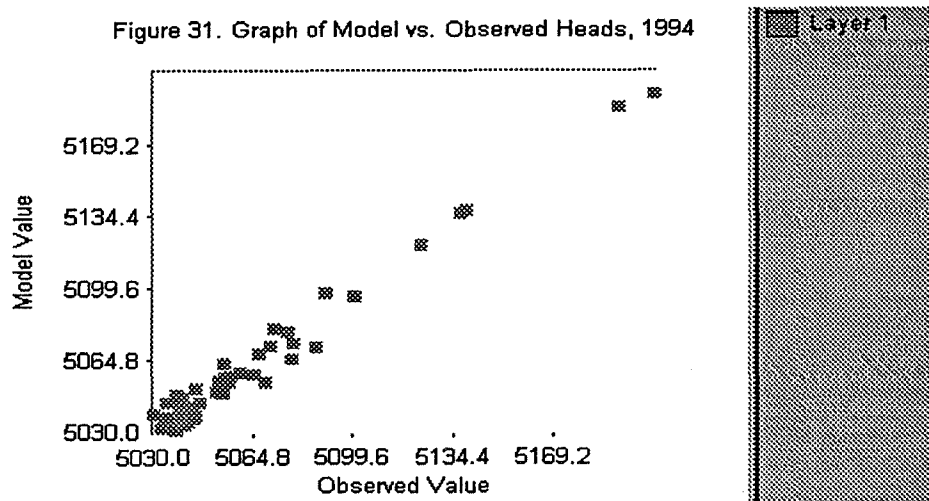
Figure 32. Graph of Model vs. Observed Heads, 1997
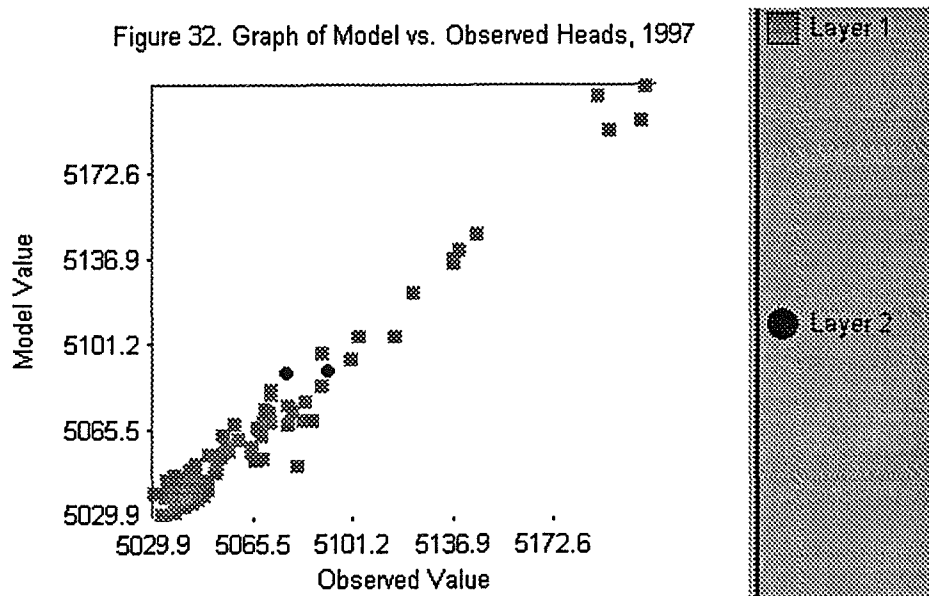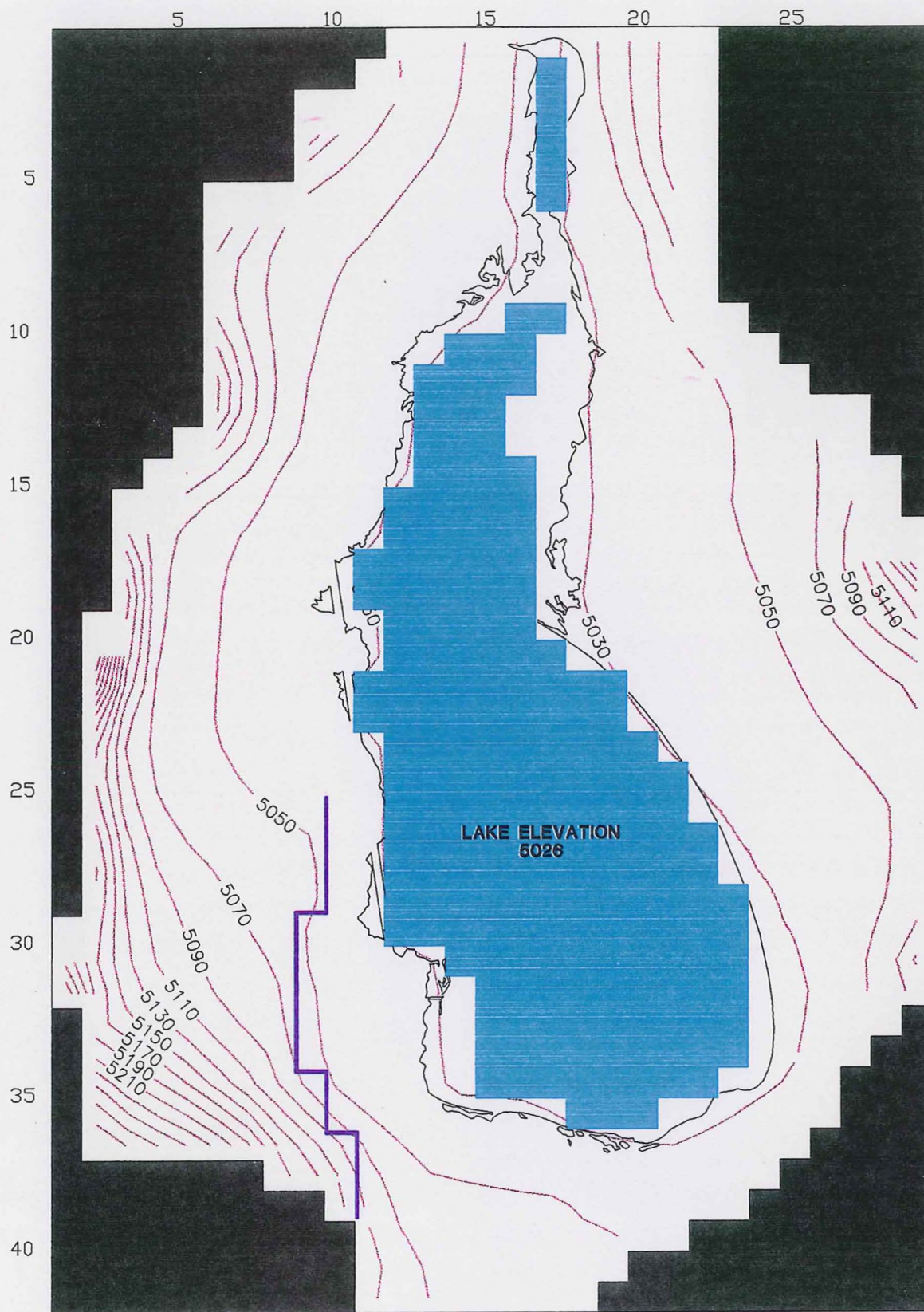
FIGURE 33
POTENTIOMETRIC MAP, 1981, LAYER 1
CONTOUR INTERVAL = 20'

LEGEND

General Head Boundary

—— 5090 —— Simulated Hydraulic Head contour
(feet above mean sea level)

—— Fault Structure

SCALE: 1" = 5000'
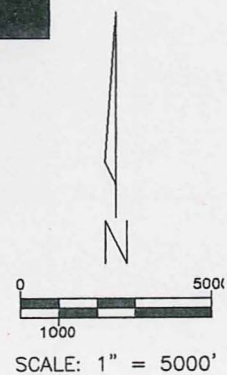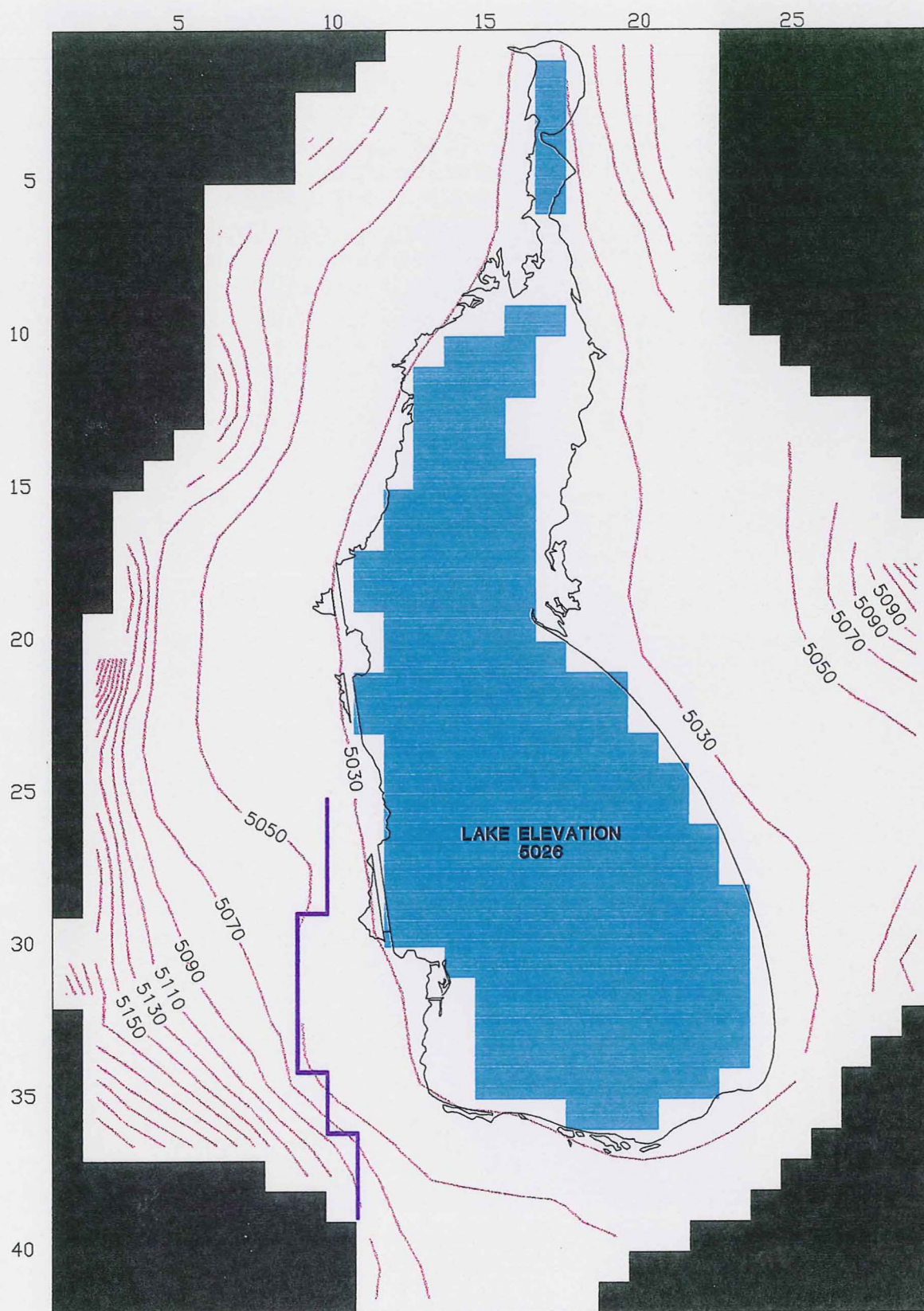
FIGURE 34
POTENTIOMETRIC MAP, 1994, LAYER 1

LEGEND

General Head Boundary

—5090— Simulated Hydraulic Head contour
(feet above mean sea level)

—— Fault Structure

SCALE: 1" = 5000'
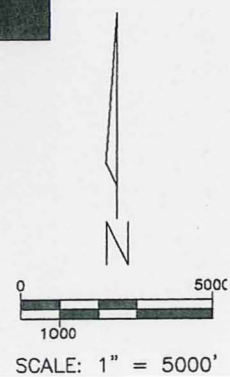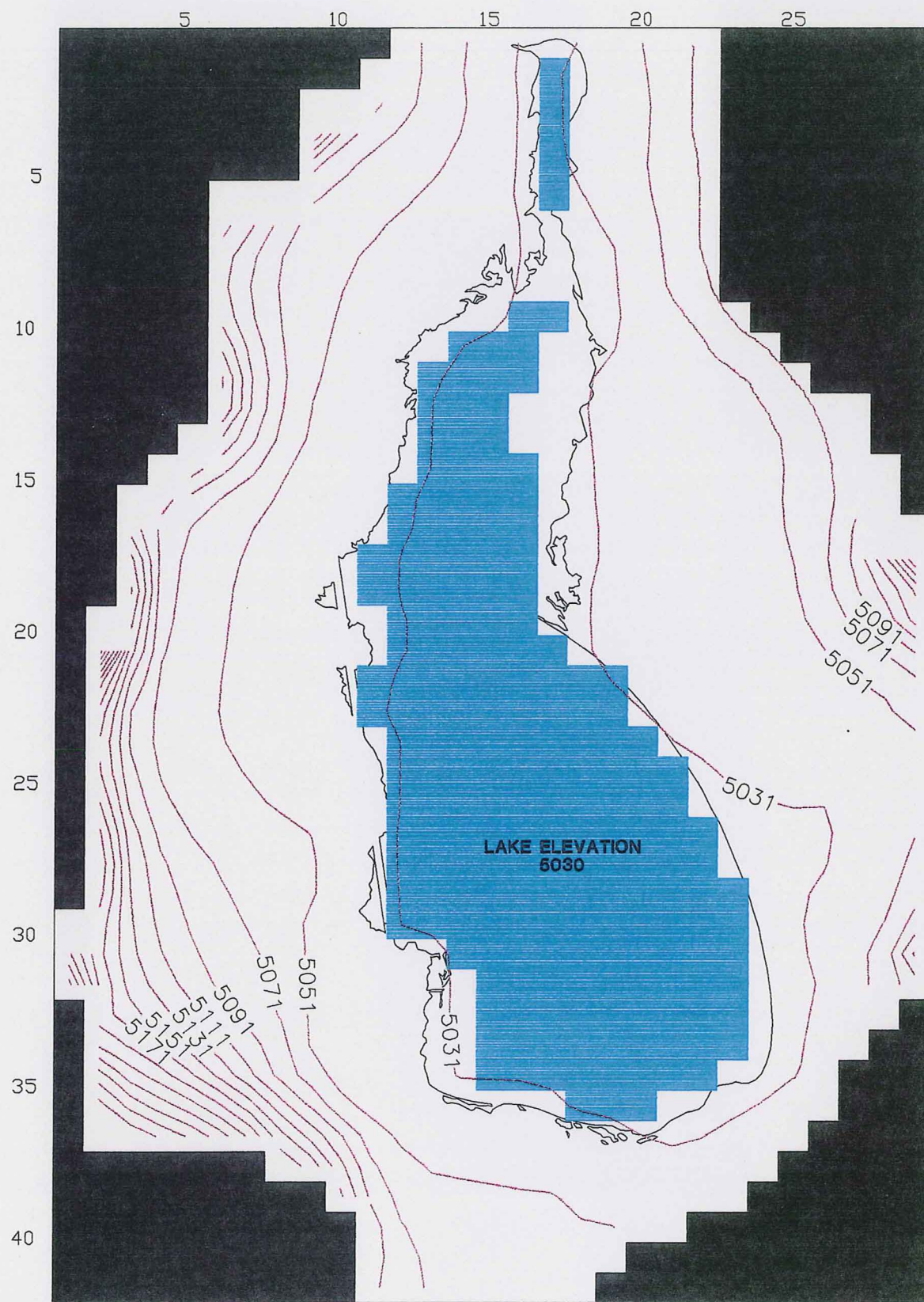
FIGURE 35
POTENTIOMETRIC MAP FOR LAYER 1, 1997
CONTOUR INTERVAL = 20'

LEGEND

General Head Boundary

—— 5130 —— Simulated Hydraulic Head contour
(feet above mean sea level)

SCALE: 1" = 5000'
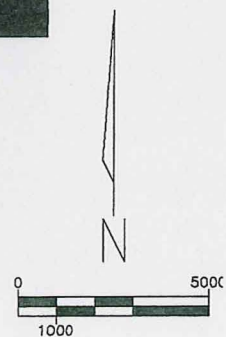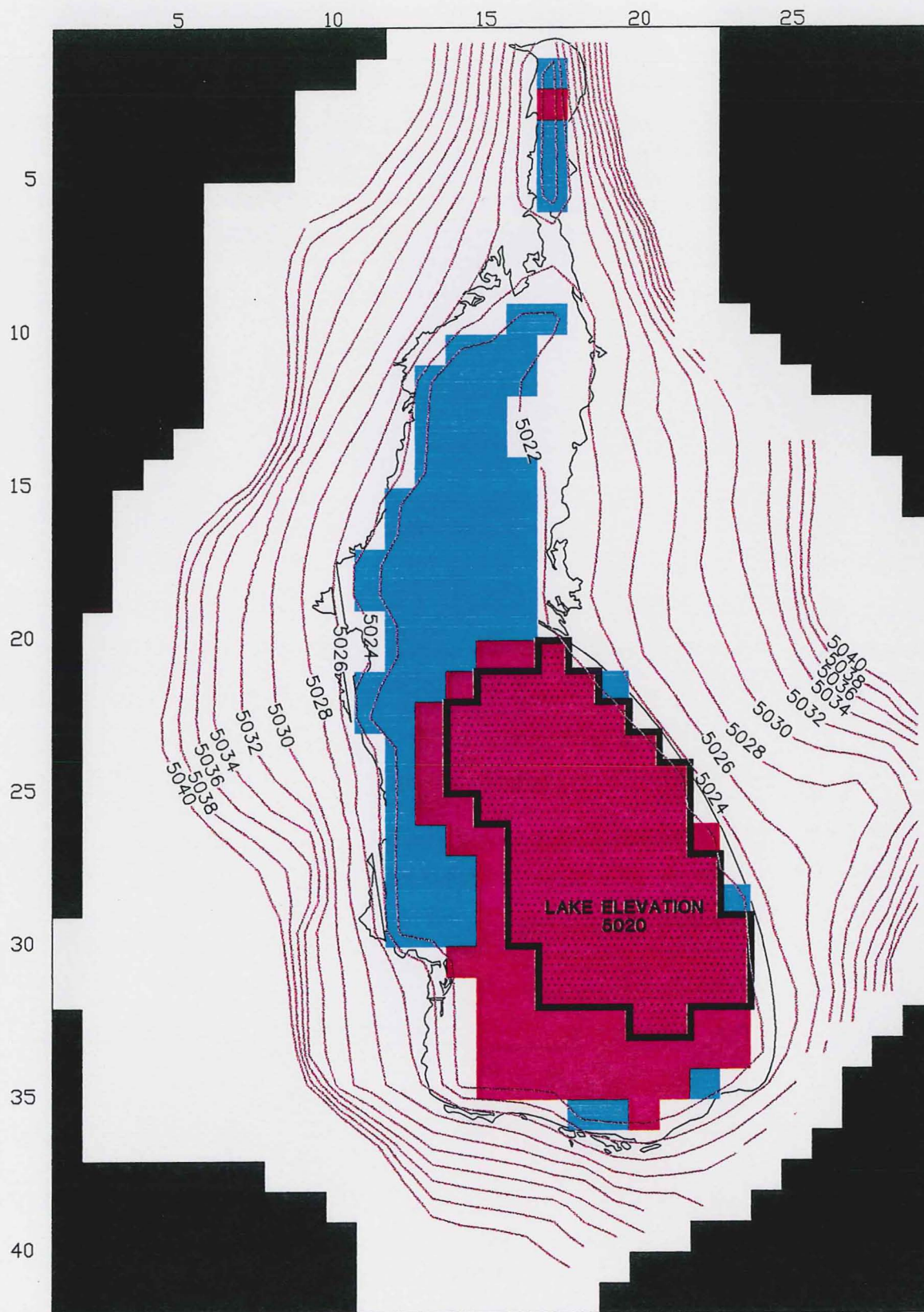
FIGURE 36
POTENTIOMETRIC MAP "NEAR LAKE" FOR 1994
CONTOUR INTERVAL = 2'

LEGEND

LAND SURFACE ELEVATION ≤ 5021'

HYDRAULIC HEAD > LAND SURFACE, MARCH 1994

LAND SURFACE ELEVATION > 5021'

SCALE: 1" = 5000'
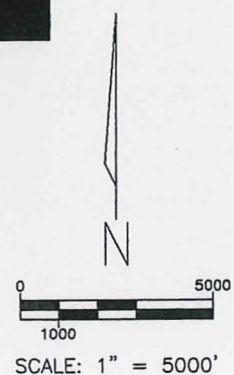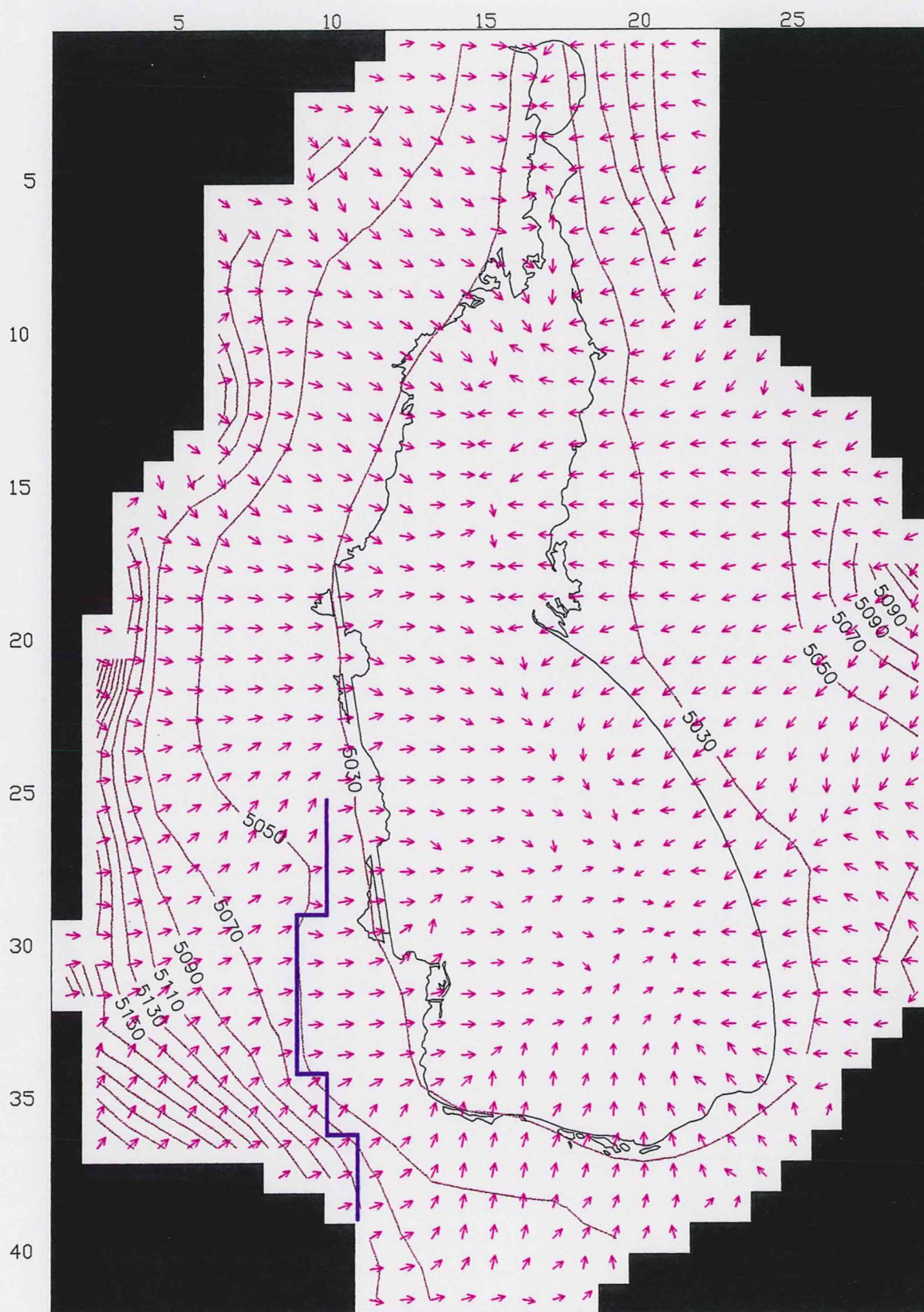
FIGURE 37

ESTIMATED DIRECTION OF GROUND WATER FLOW, 1994, LAYER 1

CONTOUR INTERVAL = 20'

LEGEND

—5090— Simulated Hydraulic Head contour
(feet above mean sea level)

— Fault Structure

Downward/Horizontal Flow

N

SCALE: 1" = 5000'

56
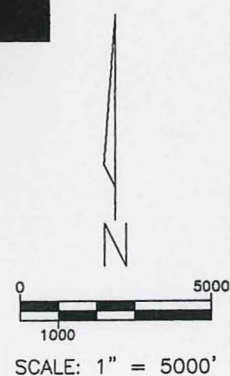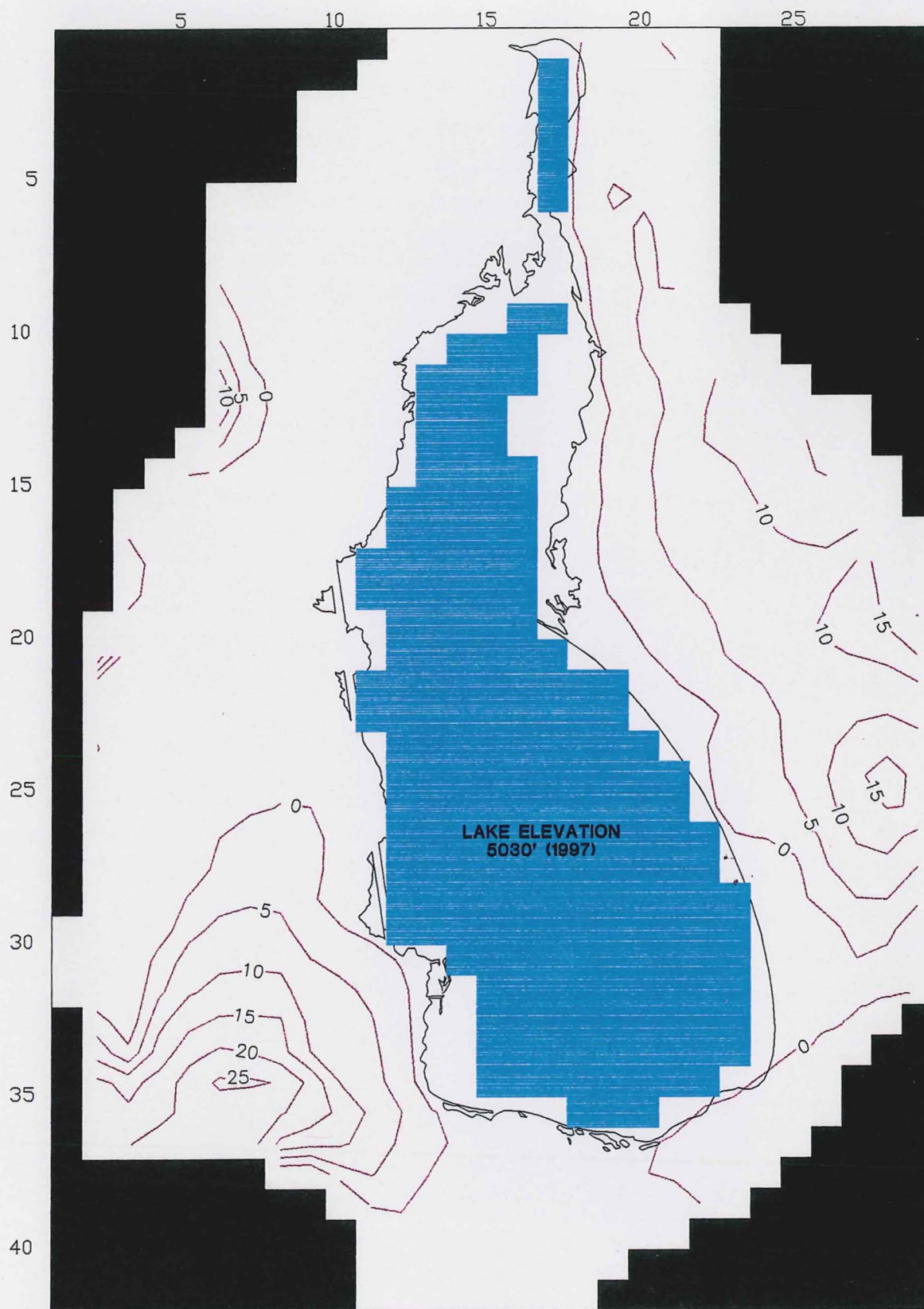
FIGURE 38
ESTIMATED WATER LEVEL DECLINES, 1965-1997
CONTOUR INTERVAL = 5'

LAKE ELEVATION
5030' (1997)

SCALE: 1" = 5000'
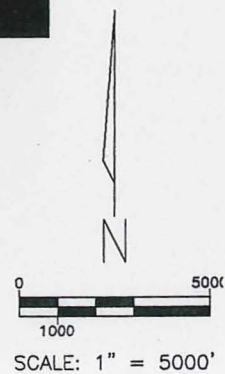
Figure 39. Lake elevation vs. evapotranspiration
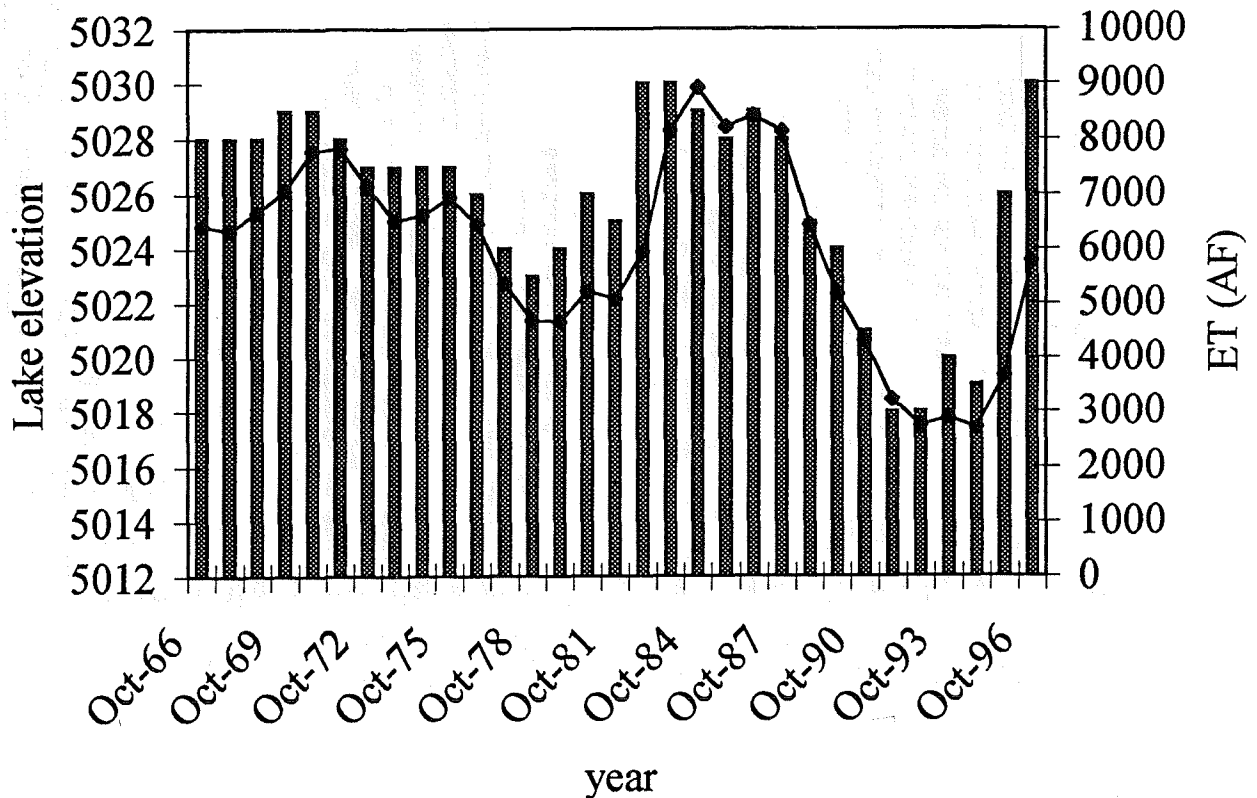
Figure 40 plots the lake elevation against the ground-water flux to the lake. This figure shows that as the lake level rises, the flux to the lake decreases and as the lake level declines; there is a greater flux to the lake. In almost every year ground water is discharging to the lake. This figure also supports the author's conceptual understanding and the use of a general head boundary for the lake. From this figure it should be noted that large changes in the lake level elevation cause a certain amount of instability in the ground water model. This is because simulated ground water levels must numerically react to the difference in the new head prescribed for the lake. Also, ground-water storage contributes to the fluxes at the lake in terms of ET.

This is illustrated in figure 41 where the flux of "surface" water from the GHB to the ground water system is plotted against the lake elevation. It is shown that wherever large head differences occur in the GHB, a relatively large flux of water leaves the GHB or "lake" to the aquifer. However, when lake elevations are low, as in the drought period of 1987 to 1994, or during stable lake elevation periods, the flux is minimal. Comparison of figures 40 and 41 indicate that the general flux is from the aquifer to the lake. The ratio of GHB outflow to inflow ranges from 0 to 156 per cent but key to this is that during drought periods and consequently heavy pumping, there is minor outflow from the GHB.

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Figure 40. Lake elevation vs. Net GW flux to lake
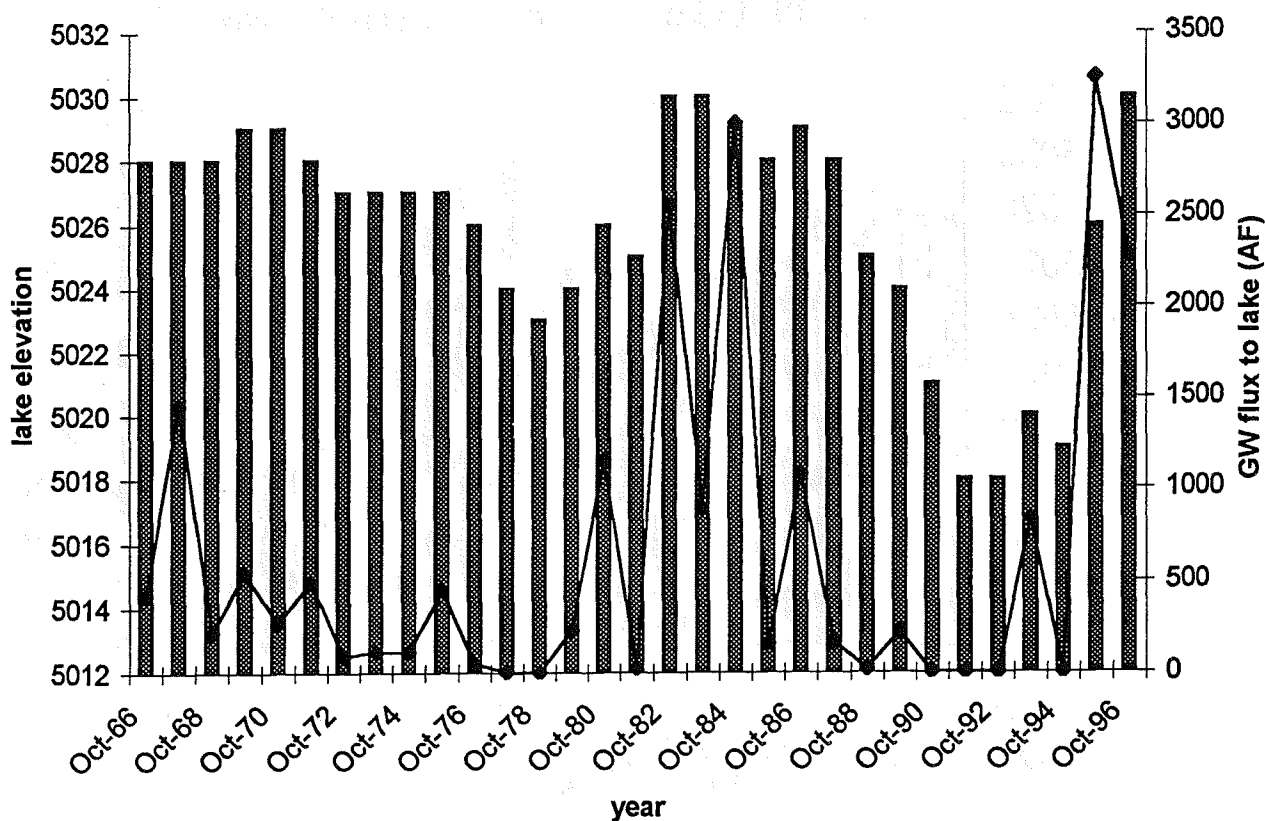
MODEL SCENARIO PREDICTIONS

Introduction

This model was used to determine the effects of two development scenarios on the ground-water system of Washoe Valley. The first scenario attempts to predict the changes in water level elevations given the present day state of development (status quo). The second attempts to predict the changes expected given the full utilization of permitted and certificated ground-water rights. These scenarios assume an average lake level of 5,027 ft (1,533 m), and mountain front recharge as per the steady state model. The starting heads are those of the final heads in stress period 63, March 1997. These scenarios were run for 20 years

and would represent water level conditions in 2017.

Status Quo Scenario

This scenario attempts to indicate what trends to expect in the potentiometric surface given present development (1997). Irrigation pumping on the Lightening W Ranch (southern Franktown Road, southwest Washoe Valley) is assumed to be fully converted to municipal pumping, serving 117 lots and 25 per cent of the irrigation needs of the newly constructed golf course (100 acre-feet or 0.12 hm^3 is pumped annually to augment surface water irrigation). The result of this water use conversion would actually decrease the amount of pumping of previous years. However, this assumption may be

59

Figure 41. GHB outflux vs. lake elevation
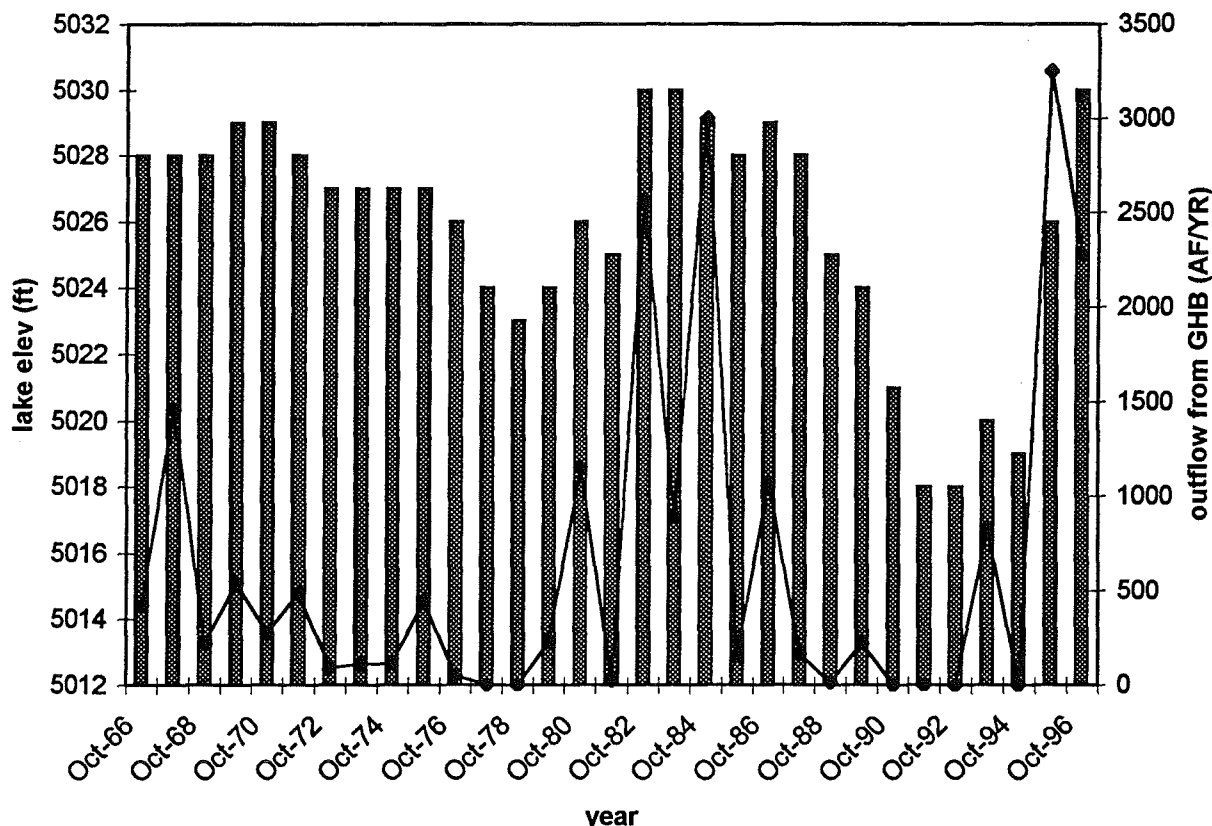
inappropriate. Current and accurate pumping records for wells in this area are necessary for the correct representation. Irrigation pumpage continues at a rate assumed for average conditions.

Figure 42 is a map of the estimated water level changes of layer 1 from 1997 to 2017. Water levels rise as much as 30 ft (9.1 m) in the southwest due to the assumed decrease in pumping. A water level decrease from five to twenty feet (1.5 to 6.1 m) would occur in the southeastern portion of the valley due to both irrigation and domestic pumping. Mass balance calculations indicate that the lake does not support these wells.

Full Pumping Scenario

From figure 42 it is apparent that the current level of development is not overly taxing the

water resources of Washoe Valley. The lake still dominates ground-water conditions. This scenario attempts to predict what ground-water trends might occur if ground-water pumpage equals the total permitted pumpage in the valley, including 50 per cent of the pumping of supplemental rights. This amounts to approximately 4,226 acre-feet (5.2 hm³) of total annual pumpage. Wells are placed at points of diversion as recorded in the State Engineer's Office.

This scenario was run for 20 years with an average lake level of 5,027 ft (1,533 m) and average recharge conditions. Figure 43 is the potentiometric map of layer 1 for this scenario. It indicates two large cones of depression in the southwest and southeast portions of Washoe Valley. There is ground water movement from the lake to these cones of depressions (approximately 300 acre-

FIGURE 42
ESTIMATED WATER LEVEL CHANGES, 1997 TO 2017
CONTOUR INTERVAL = 5'

LEGEND

General Head Boundary

———15——— Simulated Hydraulic Head Drawdown

N

0   5000
1000

SCALE: 1" = 5000'

61

FIGURE 43

POTENTIOMETRIC MAP FOR TOTAL PUMPAGE vs. STATUS QUO SCENARIO

CONTOUR INTERVAL = 20'

LEGEND

■ General Head Boundary

—5010— Simulated Hydraulic Head contour
(feet above mean sea level)

LAKE ELEVATION
5027

SCALE: 1" = 5000'
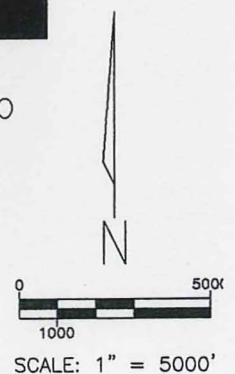
feet/yr or 0.37 hm³/yr). Additionally, depletion of storage occurs (840 acre-feet/yr or 1.04 hm³/yr), and the wells capture ground water that would normally evapotranspire (1820 acre-feet/yr or 2.24 hm³/yr) or flow to the lake (950 acre-feet/yr or 1.17 hm³/yr).

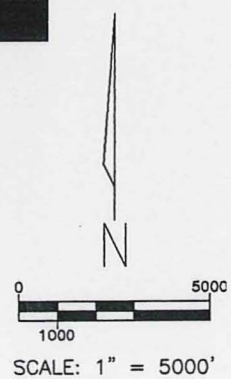Figure 44 is a map of the estimated water level change that might occur based on the sustainable yield scenario rather than the status quo scenario. Most of the valley would realize a small drop in water table elevations, but the changes would occur primarily in the southeast and southwest portions of the valley. Water level declines would also occur in the northwest portion of Washoe Valley by as much as 30 ft (9.1m).

SUMMARY AND CONCLUSIONS

Steady State Mass Balance
The results of the steady state model indicate that in an average water year:

- The alluvial deposits on the western side of Washoe Valley are nearly saturated to their carrying capacity. Consequently, some part of water from snowmelt runoff, precipitation and irrigation is rejected as recharge and runs off to the lake and wetlands.

- Washoe Lake serves as a discharge point for ground water emanating primarily from the west and is approximately 3,350 acre-feet (4.1 hm³);

- Crops and wetlands near Washoe Lake evapotranspire approximately 7,020 acre-feet (8.6 hm³);

- Mountain-front recharge from the Carson Range is approximately 5,800 acre-feet (7.2 hm³), additional recharge occurs through precipitation and irrigation practices in the range of 4,500 acre-feet (5.55 hm³), and mountain-front

recharge on the east side of the basin is approximately 1,000 acre-feet (1.23 hm³); and

- Simulating the hardrock aquifers in the model tended to cause poor calibration of wells located in these aquifers.

Hydraulic properties used in this steady state model were developed from airborne geophysical surveys. The results of the model and its calibration confirm the use of these types of data for hydraulic parameter estimation, especially in Washoe Valley. However, the assignment of numerical values should be tied to borehole geophysics, lithologic logs and aquifer stress tests that would confirm parameter estimation.

Lake Interactions
The true interaction of the lake and the ground water system cannot be simulated with the data at hand nor with the use of fixed heads at the lake. This is not to say that what has been assumed is wrong, just that there is a problem with the verification of it. With this model these interactions can be quantified for various areas of Washoe Lake. However, without field data to support the current assumptions used, it seems inappropriate to put much value into these quantifications. Therefore, while the lake and ground water interactions can be modeled, the options currently available limit the effectiveness of the model.

Transient Model
The transient modeling appears to validate the conceptual understanding of Washoe Valley, the occurrence and movement, and the recharge values; especially the mountain front recharge. The transient modeling was most hampered by the effects of the lake drying during the recent drought. This author would have preferred to treat the lake in a more appropriate manner than with a constant head that changed semi-annually, although an attempt was made to change appropriate cells to ET surfaces. The model

FIGURE 44
ESTIMATED WATER LEVEL CHANGE, TOTAL PUMPAGE vs. STATUS QUO SCENARIO
CONTOUR INTERVAL = 20'

LEGEND

General Head Boundary

—52— Simulated Hydraulic Head Drawdown

SCALE: 1" = 5000'

64
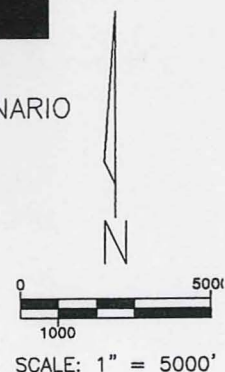
should be used for predicting future scenarios only in a general sense.

The model shows that the lake generally does not augment ground water withdrawn by domestic and irrigation pumpage on the eastern side. The model should better simulate the lake as a boundary before accurate quantification can be made. Additional eastside pumpage will increase migration of water from the lake. Based on the hydraulic properties beneath the north central portion of Washoe Valley and the lake area, it appears that ground water movement can occur from the western side to the eastern side as a result of eastside ground- water development. Without eastside pumpage, this ground water would normally discharge through ET processes at the wetlands or discharge to the lake. Water level declines on the eastern side appear to be attenuated under the influence of the lake.

Limitations of the model

This author suggests that the limitation of this model is largely in how the lake was simulated. For general analysis of present and future scenarios one must exercise caution in that the lake is modeled essentially as a constant head which can become an unlimited source of water. For small stresses placed on the model, this may work fine. For long term and large stresses placed on the model one can only qualify the impacts and trends that would develop.

Additional Work

This current modeling effort is primarily constrained by the lack of data that would allow better conceptualization of the lake-ground water interactions. Since ET is the greatest discharge process for ground water, a record of ET specific to Washoe Lake and the wetlands is also of primary importance in order to continue water resource quantification in a more accurate manner. To better calibrate a transient ground-water flow model, surveyed well elevations from the 1981 survey are necessary. These efforts are attainable and would not pose any serious problems to the next investigator.

In order to quantify the ground water-lake interactions, a surface water budget based on accurate measurements would need to be compiled. This would include the gaging of streams and ditches, better qualification of irrigation methods, historically irrigated areas and practices, precipitation records on the east side of the valley, an ET station near or at the lake that includes accurate wind information, and finally, year round outflow records at Steamboat Creek. By knowing an accurate budget of the surface water regime, difference calculations can be made with respect to the ground water component. These basic requirements could be augmented with measurements of vertical ground-water gradients and seepage measurements.

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APPENDIX I

Transient estimates of mountain front recharge, irrigation pumpage and lake levels.

STRESS PERIOD	MTN. FRONT RECHARGE percentage of normal recharge	IRR. WELLS percentage of normal pumpage	GHB lake level (ft)
1 winter 1966	74		5028
2 summer 1966	74	130	5028
3 winter 1967	122		5028
4 summer 1967	122	90	5028
5 winter 1968	74		5028
6 summer 1968	74	130	5028
7 winter 1969	167		5029
8 summer 1969	167	60	5029
9 winter 1970	113		5029
10 summer 1970	113	90	5029
11 winter 1971	122		5028
12 summer 1971	122	90	5028
13 winter 1972	55		5027
14 summer 1972	55	150	5027
15 winter 1973	106		5027
16 summer 1973	106	100	5027
17 winter 1974	122		5027
18 summer 1974	122	90	5027
19 winter 1975	113		5027
20 summer 1975	113	90	5027
21 winter 1976	58		5026
22 summer 1976	58	140	5026
23 winter 1977	61		5024
24 summer 1977	61	140	5024
25 winter 1978	103		5023
26 summer 1978	103	100	5023
27 winter 1979	71		5024
28 summer 1979	71	130	5024
29 winter 1980	103		5026
30 summer 1980	103	100	5026
31 winter 1981	55		5025
32 summer 1981	55	150	5025
33 winter 1982	184		5030
34 summer 1982	184	60	5030
35 winter 1983	200		5030

STRESS PERIOD	MTN. FRONT RECHARGE percentage of normal recharge	IRR. WELLS percentage of normal pumpage	GHB lake level (ft)
36 summer 1983	200	50	5030
37 winter 1984	142		5029
38 summer 1984	142	80	5029
39 winter 1985	87		5028
40 summer 1985	87	110	5028
41 winter 1986	190		5029
42 summer 1986	190	50	5029
43 winter 1987	67		5028
44 summer 1987	67	130	5028
45 winter 1988	55		5025
46 summer 1988	55	150	5025
47 winter 1989	103		5024
48 summer 1989	103	100	5024
49 winter 1990	74		5021
50 summer 1990	74	130	5021
51 winter 1991	68		5018
52 summer 1991	68	130	5018
53 winter 1992	71		5018
54 summer 1992	71	130	5018
55 winter 1993	74		5019
56 summer 1993	74	130	5021
57 winter 1994	57		5020
58 summer 1994	57	150	5019
59 winter 1995	180		5020
60 summer 1995	180	60	5026
61 winter 1996	150		5028
62 summer 1996	150	50	5030
63 winter 1997	200		5030

APPENDIX 2
Wells for Steady State Model

Mountain Front Recharge Wells

LAYER	ROW	COL	STRESS RATE	WELL NO.
1	2	11	10000.	1
1	3	11	9000.0	2
1	4	10	10000.	3
1	8	6	5000.0	4
1	9	6	5000.0	5
1	10	6	5000.0	6
1	11	6	15000.	7
1	12	6	25000.	8
1	18	3	20000.	9
1	19	3	30000.	10
1	20	2	25000.	11
1	21	2	20000.	12
1	22	2	20000.	13
1	27	2	10000.	14
1	28	2	24000.	15
1	35	2	12709.	16
1	40	11	3000.0	17
1	41	11	5000.0	18
2	28	27	.00000	21
1	29	2	10000.	22
1	20	29	5000.0	23
2	20	2	40000.	24
2	21	2	35000.	25
1	13	6	20000.	26
2	13	6	40000.	27
1	31	29	5000.0	28
1	17	29	10000.	29
1	15	28	5000.0	30
1	11	24	5000.0	31
1	13	27	5000.0	32
1	6	22	3000.0	33
1	7	22	3000.0	34
1	8	22	3000.0	35
1	37	2	5000.0	36
1	37	3	5000.0	37
1	37	4	5000.0	38
1	37	5	5000.0	39
1	14	5	20000.	40
2	14	5	40000.	41
2	37	2	5000.0	42
2	37	3	5000.0	43
2	17	29	5000.0	44
1	30	29	1500.0	45
1	29	29	1500.0	46
1	23	29	1500.0	47
1	25	29	1500.0	48
1	27	29	1500.0	49

LAYER	ROW	COL	STRESS RATE	WELL NO.
1	6	6	10000.	50
1	7	6	5000.0	51
1	6	7	5000.0	52
2	6	7	5000.0	53
2	7	6	5000.0	54
1	1	12	4000.0	55
2	37	5	10000.	56
2	12	6	20000.	57
1	37	6	5000.0	58
1	28	29	1500.0	59
1	37	7	5000.0	69
2	37	6	10000.	70
1	18	29	5000.0	71
2	37	4	5000.0	72
1	23	2	5000.0	73
1	24	2	5000.0	74
1	25	2	5000.0	75
1	26	2	7000.0	76
2	23	2	5000.0	77
2	24	2	5000.0	78
2	25	2	5000.0	79
2	15	4	10000.	80
1	17	3	5000.0	81
1	15	4	10000.	82
1	39	10	4000.0	83
1	38	8	5000.0	84
1	38	9	5000.0	85
1	34	27	1000.0	86
1	33	28	1000.0	87
1	37	25	1000.0	88
1	38	24	1000.0	89
1	41	19	1000.0	90
1	40	21	1000.0	91
1	9	22	5000.0	92
1	10	23	3000.0	93
1	5	22	7000.0	94
1	1	22	3000.0	95
1	2	22	3000.0	96
1	3	22	3000.0	97
1	32	1	12000.	104
1	30	1	10000.	105
2	30	1	3000.0	106
2	31	1	3000.0	107
2	32	1	3000.0	108
1	4	22	5000.0	109
1	42	11	2000.0	110
2	36	2	10000.	111
2	22	2	15000.	112
2	10	23	3000.0	116

LAYER	ROW	COL	STRESS RATE	WELL NO.
2	11	24	3000.0	117
2	13	20	10000.	118
2	16	23	5000.0	119
2	18	22	5000.0	120
2	20	21	5000.0	121
2	21	20	5000.0	122
2	19	19	5000.0	123

Irrigation Wells

LAYER	ROW	COL	STRESS RATE	WELL NO.
2	28	4	−32900.	113
2	36	7	−9900.0	114
2	18	19	−7700.0	115
2	20	4	−41770.	19
2	25	4	−27000.	20

Domestic Wells

LAYER	ROW	COL	STRESS RATE	WELL NO.
1	8	19	−430.00	98
1	9	19	−570.00	99
1	2	14	−570.00	100
1	3	13	−650.00	101
1	3	12	−720.00	102
1	5	12	−430.00	103
1	7	19	−430.00	60
1	10	20	−430.00	61
1	12	21	−720.00	62
1	12	22	−720.00	63
1	15	22	−1150.0	64
1	15	23	−1150.0	65
1	16	26	−1350.0	66
1	18	22	−1600.0	67
1	20	22	−1600.0	68